# Design and Control of Automated Truck Traffic at Motorway Ramps

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# Design and Control of Automated Truck Traffic at Motorway Ramps

Proefschrift

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*In the name of God*

*My God gave me life to learn the meaning of humanity and living with others. Thus, I have to learn from others, as much as I can. The findings could be either scientific results, or social communication skills. This contribution only indicates the scientific results of my research. However, it does not reflect my ability for communicating and working with others, necessarily. Maybe, it would be nice to include members in the doctoral evaluation committee, in future, to judge social characteristics of candidates, too! In such a case, there are more doubts for me to be able to become a doctor!*

*Masoud Tabibi*
*Delft- July 2004*

# Preface

The research presented in this thesis focuses on the implication of automation of truck traffic on existing infrastructures as one of the possibilities that might improve the efficiency of existing motorways. It was part of a multidisciplinary research program, initiated by the Dutch Research School on TRAnsport, Infrastructure and Logistic (TRAIL), and named as Freight Transport Automation and Multimodality (FTAM). For me, as an Iranian fellowship student, it was a great opportunity to carry out my research topic in the framework of such a programme.

Thus, I would like to express my sincere gratitude to Prof. Dr. Ing. Ingo Hansen who provided for me the chance to work with other friendly members of the Transport and Planning section of the faculty of Civil Engineering and Geosciences of TU-Delft, in a very friendly and enjoyable environment, during the last five years, which never to be forgotten. I derived lessons from the great patience and the freedom that Ingo provided for me in the research. In addition to all these attentions, he also offered to me and my wife the possibility to live in the first floor of his apartment during the whole period of my research study, in the very nice and lovely center of the city of Delft. It was the reason that why I never felt the major problem of other students for searching houses!

I wish to thank all members of the section and also the TRAIL members that I enjoyed being and working with them during the whole period of my research study. Among them, my special thanks should be devoted to Nicole who always helped me, regardless of all her own works. Her role in the section is like the heart in the body. I am also very thankful to Kees and Peter for their great assistances. For me, they were a great example of two wings of a flyer that never work alone! Among the TRAIL members, my sincere thanks is expressed to Mirjam, Esther and Rob (Konings) who continuously had contacts with me to recognize my requests and problems (as a foreigner Ph.D. student) and to try to solve them, so much as they could.

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In the Iranian side, I am very obliged to Mr. Fazel, the former fellowship officer of TTO, for his initial efforts to provide the possibility for me to come to TU-Delft as the first Ph.D. student of TTO. I am also grateful to Mr. Khansari, the head of TTO, Mr. Soleimani the former deputy of the head of TTO, and also the other members of board of directors of TTO for all their supports, and specially providing the possibility for me to stay for a longer time in the Netherlands to be able to finalize my research work successfully. I also should thank the embassy of Iran in The Hague and also the Dutch embassy in Tehran for their supports concerning my affiliated work to TTO to create a closer contact between Iran and the Netherlands in the field of road transport.

I owe much to my brothers, Amir and Said, and my sister in law, Fereshteh, who take care of our gray-haired mother, making me feel secure during my stay overseas. I also should thank my parent’s in law for their acceptance to be alone within the last five years to give my wife this opportunity to accompany me. I should not forget to appreciate all efforts of my uncle, Ali, who always has been as a supporting point for me, like a father. Of course, there are many others who due to limit of space I have not been able to address their names. I should apologize all of them and I wish all the best for all them.

And last, but certainly not least, my love and deepest appreciation should be assigned to my mother, Fatemeh, and my wife, Parisa.

My mother, you gave me the lesson of endurance. You summarized your life in taking care of your three sons. I hope the result of my research could compensate a bit of all your devotions. You were far from me during the last five years, but your benedictions were the most close to me. I never was able to reach to this degree without your spiritual supports. Thanks for all of them.

My wife, we started our common life here five years before, as two persons, and now we are two and half! During this long time, you learned me the meaning of common life more clearly by supporting me in all times, by missing all your opportunities, and by accepting to be far from your parents who really needed your patient. Certainly, without your full support and endurance, I was not able to accomplish my research, successfully. You really have had a great role in the provision of this thesis. I never forget all your lovely patients.

Finally, I would like to vitalize the memory of my father, who died when I was a child, by assigning this thesis to him. Of course, his memory is always alive in my heart. My main wish in my life is to be a person like him.

Masoud Tabibi
July 2004, Delft, The Netherlands

# Notation

## General notation for parameters and variables

| | | |
|---|---|---|
| $s_{intra}$ | : | intra-distance of trucks within a platoon (m) |
| $s_{inter}$ | : | inter-distance of two successive platoons of trucks (m) |
| $L$ | : | average length of a truck (m) |
| $N$ | : | number of trucks in a platoon |
| $v_{plat}$ | : | desired platoon speed (m/s) |
| $cap$ | : | capacity of uninterrupted flow of platooned trucks on a single lane (veh/h) |
| $N_{max}$ | : | maximum number of trucks in a platoon |
| $N_{initial}$ | : | initial number of trucks in a platoon |
| $a_{plat(+/-)}$ | : | maximum acceleration/deceleration of trucks in a platoon (m/s$^2$) |
| $[L_1, L_2]$ | : | a segment of the dedicated freight lane in which truck platooning is applied (m) |

| | | |
|---|---|---|
| $q_m^t$ | : | output flow of segment "m" of the road at time "t" (veh/h) |
| $q_{m-1}^t$ | : | output flow of segment "m-1" of the road (the input flow of segment "m" of the road) at time "t" (veh/h) |
| $r_m^t$ | : | exit flow from segment "m" of the road at time "t" (directed to the off-ramp) (veh/h) |
| $s_m^t$ | : | entrance flow to the segment "m" of the road at time "t" (directed via the on-ramp) (veh/h) |
| $\Delta t$ | : | assumed time interval (sec); |
| $k_m^{t+\Delta t}$ | : | flow density on segment "m" of the road at time "$t+\Delta t$" (veh/km) |
| $k_m^t$ | : | flow density on segment "m" of the road at time "$t$" (veh/km); |
| $L_m$ | : | length of segment "m" of the road (km) |
| $Iin_{bm}^t$ | : | flow directed from the road segment "m" to the buffer area "b" at time "t" (veh/h) |
| $Iout_{bm}^t$ | : | flow directed from the buffer area "b" to the road segment "m" at time "t" (veh/h) |
| $qq_{mm}^t$ | : | output flow of vehicles from segment "mm" of the on-ramp at time "t" (veh/h) |
| $v_{e,m}^t$ | : | equilibrium speed of vehicles on segment "m" of the road at time "t" (km/h) |
| $v_{f,m}^t$ | : | free flow speed of vehicles on segment "m" of the road at time "t" (km/h) |
| $k_{cr,m}$ | : | critical density of vehicles on segment "m" of the road (veh/km) |
| $v_m^{t+\Delta t}$ | : | speed of vehicles on segment "m" of the road at time "$t+\Delta t$" (km/h) |
| $v_m^t$ | : | speed of vehicles on segment "m" of the road at time "t" (km/h) |
| $\tau$ | : | relaxation factor, describing the convergence of the mean speed of a segment to its equilibrium value |
| $\nu, \kappa$ | : | anticipation constants, representing the impact of the change in density of vehicles in a segment of the road on the speed of vehicles in the previous segment |
| $k_{j,m}^t$ | : | jam density on segment "m" of a road at time "t" (veh/km) |
| $cap_m^t$ | : | capacity of segment "m" of a road at time "t" (veh/h) |
| $SD(t)$ | : | ideal (required) lag distance for crossing of manually driven vehicles by automatically controlled trucks at merging areas at time "t" (m) |
| $RT$ | : | average assumed reaction time for the ACTs (sec) |
| $f$ | : | coefficient of friction |

| | | |
|---|---|---|
| $g$ | : | gravitational acceleration (m/s$^2$) |
| $\alpha$ | : | percentage of non-clustered vehicles which arrive at on-ramp |
| $t_m$ | : | time headway for clustered vehicles at on-ramp area (sec) |
| $D^t_{ACT}$ | : | the generated volume of ACTs on the dedicated freight lane at time "t" (veh/h) |
| $D^t_{MDV}$ | : | the generated volume of MDVs on the on-ramp at time "t" (veh/h) |
| $\beta$ | : | reduction factors to translate the volume of generated vehicles to the capacity at merging (diverging) areas |
| $k_b^{t+\Delta t}$ | : | density of vehicles in buffer area "b" at time "$t+\Delta t$" (veh/km) |
| $k_b^t$ | : | density of vehicles in buffer area "b" at time "$t$" (veh/km) |
| $L_b$ | : | length of buffer area "b" (km) |
| $\alpha^t_{bm}$ | : | share of input flow to the buffer area "b" located on segment "m" which remains in the dynamic part of the buffer area at time "t" |
| $IoutP^t_{bm}$ | : | output flow from static part (parking area) of the buffer area "b" located on segment "m" of the road at time "t" (veh/h) |
| $IinP^t_{bm}$ | : | input flow to the static part of the buffer area "b" located on segment "m" of the road at time "$t$" (veh/h) |
| $k^t_{cr,bm}$ | : | critical density of vehicles within buffer area "b" located on segment "m" of the road at time "t" |
| $v^t_{f,bm}$ | : | free flow speed of vehicles within buffer area "b" located on segment "m" of the road at time "t" (km/h) |
| $NL^t_{bm}$ | : | number of lanes available in the parking area of the buffer "b" located on segment "m" of the road at time "t" |
| $\gamma$ | : | reduction factor for translating the total existing space of a parking area to usable space for parking of vehicles in the static part of the buffer area |
| $T$ | : | total time period of analysis (sec) |
| $NS^{M,R}$ | : | the number of road segments for user group "M" on road type "R" |
| $NT$ | : | the number of time intervals during the total time period of analysis |
| $\omega^{M,Rt}$ | : | assumed weight for running time of user group type "M" on road type "R" |
| $\delta^{M,R}$ | : | assumed weight for running time of user group type "M" in buffer areas on road type "R" |
| $\theta^{M,R}$ | : | assumed weight for waiting time of user group type "M" on road type "R" |

| | | |
|---|---|---|
| $q_{m=ii}^{M,R,t}$ | : | traffic flow of the user group type "M" on road type "R" at time "t" for a segment of the road which is located at the on-ramp (or off-ramp) area (veh/h) |
| $\varphi^{M,R}$ | : | assumed weight factor for the user group type "M" on road type "R" |
| $\sigma^{ACT\,/\,ACT}$ | : | assumed weight for speed synchronization in the intersection point between the mainline and the on-ramp flow of ACTs at the on/off-ramp |
| $\sigma^{ACT\,/\,MDV}$ | : | assumed weight for speed synchronization in the intersection point between the mainline flow of ACTs and the on-ramp flow of MDVs at the on/off-ramp |
| $\sigma^{MDV\,/\,MDV}$ | : | assumed weight for speed synchronization in the intersection point between the mainline and the on-ramp flow of MDVs at the on/off-ramp |

**Abbreviations**

| | | |
|---|---|---|
| ACC | : | Adaptive Cruise Control system |
| ACT | : | Automatically Controlled Truck |
| ADAS | : | Advanced Driver Assistance System |
| AHS | : | Automated Highway System |
| ATT | : | Average Travel Time |
| AVCS | : | Advanced Vehicle Control System |
| AVG | : | Automated Vehicle Guidance system |
| AVV | : | Transport research center of the Netherlands |
| CBS | : | Central office of the statistics of the Netherlands |
| CTT | : | Center of Transport Technology |
| DFL | : | Dedicated Freight Lane |
| DL scenario | : | Dedicated freight lane at the left-hand lane (median lane) |
| DRIP | : | Dynamic Route Information Panel |
| DR scenario | : | Dedicated freight lane at the right-hand lane (shoulder lane) |
| DTL | : | Dedicated Truck Lane |
| DVU | : | Driver-Vehicle Unit |
| ERTICO | : | European Road Transport Telematics Implementation Coordination Organization |
| EU | : | European Union |
| GA | : | Genetic Algorithm |
| GAMS | : | General Algebraic Modelling System |

| | | |
|---|---|---|
| HMI | : | Human-Machine Interface |
| HOV | : | High Occupancy Lane |
| ICC | : | Intelligent Cruise Control system |
| ISA | : | Intelligent Speed Adaptation system |
| ITS | : | Intelligent Transport System |
| JIT | : | Just In Time |
| LDWA | : | Lane Departure Warning Assistant system |
| LOS | : | Level Of Service |
| LP | : | Linear Programming model |
| MDV | : | Manually Driven Vehicle |
| NLP | : | Non-Linear Programming model |
| OPTION “i” | : | A truck platooning scenario in which the impact of the strategy “i” for the application of signals is evaluated |
| P-A sce. | : | Scenarios in which the impact of the maximum possible acceleration and deceleration of trucks in platoons are evaluated |
| P-COM sce. | : | Scenarios in which the impact of the simultaneous change of some characteristics of truck platooning are evalauted |
| P-INTER sce. | : | Scenarios in which the impact of the inter-distance of platoons of trucks are evaluated |
| P-INTRA sce. | : | Scenarios in which the impact of the intra-distance of trucks in platoons are evaluated |
| P-L sce. | : | Scenarios in which the impact of the implemenation of platooning of trucks on a certain length of the DFL are evalauted |
| P-MAX sce. | : | Scenarios in which the impact of the maximum number of trucks in a platoon are evaluated |
| P-MIN sce. | : | Scenarios in which the impact of the initial number of trucks in a platoon are evaluated |
| P-S sce. | : | Scenarios in which the impact of the desired speed of platoons of trucks are evaluated |
| R sce. | : | Reference case, in which there is no platoon of trucks on the DFL |
| RB scenario | : | Reference case, without lane change prohibition for trucks |
| RP scenario | : | Reference case, with lane change prohibition for trucks |
| TCC | : | Traffic Control Center |
| TP | : | Throughput |
| TRAIL | : | Transport, Infrastructure, and Logistic Research School |
| TTC | : | Time–To-Collision indicator |
| TTT | : | Total Travel Time |
| ULT | : | Ultra Long Truck |
| VMS | : | Variable Message Sign |

# Contents

# 1
# Introduction

Demand for freight transport is ever increasing. This demand in the European Union (EU) countries has increased about 3 times during the last three decades. Relatively, the same trend has been reported for the Netherlands (Table A.1- Appendix A).

Motorways have a more important role in the road freight transport than other categories of roads. It is estimated that they carry about 40 % of all vehicle-kilometers in the Netherlands (Brühning and Berns (1997)).The international haulage of goods transport on Dutch motorways during the years 1995-1999 has increased by about 21% which indicates an annual growth of 4%. This haulage mostly takes place on motorways (CBS[1]).

The length of the motorway network in the EU countries during the period 1970-1998 has tripled. Dutch motorways, however, were extended less than twice during the same period (Table A.2- Appendix A).

Taking into account both supply and demand, it can be concluded that the capacity of the motorway network in the Netherlands, during the last two decades, has been increased much less than the mobility of freight and passenger transport (total ton-km or passenger-km).

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[1] Centraal Bureau voor de Statistiek, The Netherlands

## 1.1 Congestion on Dutch motorways

The growing traffic congestion on motorways is characterized, commonly, in the public opinion as a waste of time and money that should preferably be eliminated by means of increasing the road capacity. However, the required high investment (for building the motorways and the acquisition of its right-of-way) and also the negative environmental impact can be considered as major opposite factors for developing Dutch motorways. Policy making issues and complicated legal process for issuing the permission of construction of new motorways can be encountered as other reasons which have limited the development of motorway networks in the Netherlands. The development of traffic congestion on the Dutch motorway network during the years 1995 and 2001 is shown in table 1-1 (AVV (2002), Bovy (2001)). It emphasizes the fact that the severity of traffic queues on Dutch motorways has nearly doubled within 1995- 2001. The economic loss by traffic congestion on Dutch motorways was estimated to be around 0.8 billion Euro’s in 1997[2] (AVV (1998), Hansen (2001)). The increase in level of congestion also has doubled the annual environmental costs within the period of 1990-1999[3] (CBS (2002)). Apart from time and environmental losses, traffic jams cause considerable reliability problems in the road system.

**Table 1.1. Congestion figures for the motorway network in the Netherlands**

| Criteria of congestion | Value | |
|---|---|---|
| | 1995 | 2001 |
| Number of queues each working day | 50 | 95 |
| Average queue duration (min) | 60 | 66-84 |
| Length of total daily queue (km) | 200 | 399-427 |

Extrapolating the above trend of demand and supply into the future, much more congestion on the Dutch motorways would be expected. Hence, for maintaining the pivot point function of the Netherlands in European goods distribution, increasing the efficiency of existing motorways for operation of trucks is one of the major challenges.

## 1.2 Target group preemption for freight transport

In order to increase the efficiency of freight transport, one of the possible ways is to offer better traffic conditions to trucks. This idea, however, would increase the cost of other user groups like cars. The rationale behind this idea is that freight transport is more important to the economy than other modes. In such a case, the target group (e.g. trucks) receives preferential treatment on the existing infrastructure.

The port of Rotterdam has an important international transport role in the goods transport network, which is vital for the Dutch economy. For this reason, a physically segregated truck lane is operated on the Rotterdam beltway (A16) for the operation of trucks only. However, such a measure may not be sufficient to answer to the growing demand of freight transport in future, because the exclusive truck lane is not

[2] The last year that the calculations of congestion costs are achieved.
[3] CBS: the annual environmental costs of traffic has increased from 400 mln Euro in 1990 to 800 mln Euro in 1999.

continuously connecting the major ports and freight transport terminals. Moreover, due to lack of space and high investment costs for the construction of exclusive truck lanes along the Dutch motorway network for connecting major ports and freight terminals, the construction of a fully segregated network of freight transport seems not to be feasible.

In brief, as future traffic demand increases, the alternatives to provide additional capacity are limited. Since heavy use of secondary roads for freight transport is not desirable, hence, either additional motorways or lanes should be built or the existing motorways need to become more efficient. As the prospect of building new motorways becomes increasingly difficult, the promotion of capacity of existing motorways becomes more relevant. Therefore, it is required to look for a set of means which might improve the efficiency of existing motorways for the goods transport. The proposed mean(s) should not lead to an unacceptable level of service for the operation of other user groups of motorways.

## 1.3 With automation towards increasing road traffic efficiency

One of the options available to decrease congestion and possibly to reduce costs is the proper use of new transport technologies such as Advanced Driver Assistance Systems (ADAS) and Automated Vehicle Guidance (AVG) systems (Hall and Tsao (1994), van Arem and van der Vlist (1994), Harvey (1995), van der Heijden et al (1995), van Arem (1996), van der Heijden and Wiethoff (1999), Marchau (2000), AVV (2001)). In fact, Automated control has the potential to remove the human error from the driving process and provide a higher level of efficiency. Benefits of vehicle automation may be more wide reaching with attitudes toward driving moving away from a stand-alone or free agent state to an understanding of the benefits of co-operative systems (Varaiya (1993), Hedrick et al. (2001)).

Review of literature (Shladover (1995), van Arem (1996), Ioannou (1997), van der Heijden and Wiethoff (1999), AVV (2001), (ADASE2 Consortium (2003)) indicates that ADAS/AVG systems can be implemented as Autonomous systems, with all instrumentation and intelligence on-board the vehicle, or as co-operative systems, in which assistance is provided from the roadway, or from other vehicles, or both (Varaiya and Shladover (1991), Hedrick et al. (2001)). Roadway assistance typically takes the form of passive reference markers in the infrastructure. Vehicle-vehicle co-operation enables vehicles to operate in closer proximity to each other for purposes of increased efficiency, usually by transmitting key vehicle parameters and intentions to following vehicles (Vahdati Bana (2001)). The general philosophy is that autonomous systems will work on all roadways in all situations at a useful level of performance, and take advantage of co-operative elements, as available, to augment and enhance system performance (Shladover (2001); European Commission (2001)).

In brief, ADAS/AVG systems can be segmented readily into three groups (ADASE2 Consortium (2003)):

(a) systems that provide an advisory/warning to the driver (*collision warning systems*);
(b) systems that take partial control of the vehicle, either for steady-state driver assistance or as an emergency intervention to avoid a collision (*collision avoidance*), and;
(c) systems that take full control of vehicle operation (*vehicle automation*).

Tables A-3 and A-4 in Appendix A refer to the major technologies belonging to each of the above groups, a summary description of them, and the main expected impacts of each technology on safety, comfort, congestion and environment. These impacts have been identified based on the review of current state-of-the-art (including Europe, Japan and US).

The selection of the proper technology of ADAS/AVG mostly depends on the following factors:

- the main objective(s) of the application of ADAS/AVG;
- the user class for which the system will be applied;
- the degree of autonomy;

For instance, to promote road safety, nearly all ADAS technologies can be applied. The selected type of technology depends on characteristics of accidents in the existing situation. However, to improve both safety and congestion, only certain ADAS technologies, like Adaptive Cruise Control (ACC), Lane Keeping Assistance, Forward Collision Warning and Fully Automated Driving will be taken into account, among which only a few would play a major role on decreasing congestion.

Moreover, each ADAS technology mostly has been deployed for a specific user class, like car, truck or bus. For instance, Lane Departure Warning Assistant (LDWA) technology mostly has been deployed for trucks and buses, rather than cars. Similarly, Fully Automated Driving has been deployed for trucks and public transport, since this technology might bring major reductions in costs of freight and public transport.

The other major factor for the selection of an ADAS technology is the expected level for taking over the driver's tasks (the degree of autonomy). Autonomy varies from complete autonomy that the vehicle can perform driver-supporting functions completely without external infrastructure intelligence, to completely external guidance of the vehicle. The higher the degree of external guidance, the less the shortcomings of human driver errors and consequently the higher the possibility for gaining co-operative systems.

Since the main aim of this research study is a possible increase of the efficiency of road freight transport by reducing the congestion on motorways, we will focus on ADAS technologies that play a great influence on reducing the congestion. Of course, the expected increase in capacity of bottlenecks should be provided in such a way that it promotes the safety, too, or at least do not reduce safety aspects. A review on table A.4 of Appendix A shows that Fully Automated Driving would be one of the major options to reach to such a purpose. This technology has been applied for trucks in two main directions: a fully automated one on dedicated lanes (guideways), and the platoon concept.

The first approach is illustrated by the CombiRoad project (Heere and van der Heijden (1997), Melcherts and Heere (1998)) in the Netherlands and more recently with the ULS (Underground Logistic System) (CTT (1997)), also in the Netherlands. The first project which used mechanical guidance and electric energy pickup to drive trailers has since then been halted. The second project is now at the preliminary stage and should link the Flower market with a major train station and the Schiphol airport with fully automated electric shuttles for small containers. A fully segregated route for the Automated Freight Transport is the essential need for applying this direction of freight transport automation. As was described earlier, the fully segregated route for the operation of Automatically Controlled Trucks (ACTs) on motorways would not be a proper option.

The second approach for automated trucks is illustrated by the CHAUFFEUR project (Berghese et al. (1997)). In this approach, a leading truck, manually driven on a regular highway infrastructure, "pulls" a number of electronically coupled driverless trucks. The technique is based on a vision system which localizes the previous truck through active targets. A communication is needed between the trucks to insure the stability of the platoon and prevent collisions in case of sudden braking. Demonstrations have been carried at the end of the first contract in 1999 and more work is now in progress to refine the techniques. Due to mix of automated trucks with Manually Driven Vehicles (MDVs) the realization of such an option needs more investigations to ensure safety and legal aspects. Moreover, due to variety of human behaviour, the mix of automated trucks and ordinary vehicles would reduce the expected gains caused by co-operative system of automated trucks.

In this research study we follow an intermediate approach. In this approach, it is assumed that Fully Automated Trucks are driving on Dedicated Freight Lanes (DFLs) in major parts of existing motorways. The introduction of DFL would segregate the flow of Fully Automated Trucks from ordinary cars and might facilitate the co-operative operation of Fully Automated Trucks. Since, the main aim is to avoid constructing new road infrastructures like new lanes on major segments or flyovers at bottlenecks like on-/off-ramp areas, the flow of Fully Automated Trucks would be hindered by the flow of MDVs at on-/off-ramp areas, necessarily. To deal with such an issue, the chosen approach of this research is to use optimization methods to minimize the hindrance of flow of Fully Automated Trucks by MDVs and vice versa.

Hence, this research seeks to reduce the level of congestion on motorways via operation of Fully Automated Trucks where the drivers remain on-board because it is assumed that completely segregated network for automated freight transport will not be available in the next decade. Thus, to ensure safety aspects, the role of driver in each Fully Automated Truck has been kept to take over the control of truck during emergency conditions. This specific degree of truck automation in whole of this contribution is defined as the Automatically Controlled Trucks (ACTs).

Actually, ACTs operate under automatic control: the distance an ACT maintains from the ACT in front, its speed, and its route from entry into the motorway to exit, are all determined by the ACT's feedback control laws. One may therefore compare the effect on the traffic of changes in ACT control laws, and seek to calculate the "optimum" control rules. By contrast, in MDVs the driver determines the vehicle's headway, its speed, its movement during a merge, etc. which may vary considerably among different drivers with different behavior.

A Traffic Control Center (TCC) could directly influence the flow of ACTs by issuing orders to ACTs regarding their speed and route. Those orders will be followed strictly because the ACTs are programmed accordingly. The TCC, could also influence the flow of MDVs by variable message signs, but drivers may ignore these suggestions or react to them in an unexpected manner. Thus the influence of TCC strategies on ACTs would be much stronger and more predictable than its influence on non-automated traffic; and so, one may again seek to determine the optimum TCC strategies.

Based on the above discussion, this research can be distinguished from other research in the field of application of ADAS/AGV by following points of view:

- Only one lane of *existing* motorways is assumed to be available for the operation of ACTs;
- It is focused on bottlenecks, namely on-/off-ramps of motorways, where the hindrance of flow of ACTs by crossing MDVs coming/going from/to on-ramp/ off-ramps takes place;
- It tends to introduce the application of optimization methods in order to determine the optimal design and control scenarios of automated freight transport.

## 1.4 Research questions and contributions

Throughout this thesis we will be addressing the major design and control requirements for the operation of ACTs at on-/off-ramps of existing motorways[4], as the most critical part of the motorway network, where hindrance of flow of ACTs and MDVs is expected. Although there are a lot of questions which might arise while describing the proposed solution from legal, human behavior, socio-economic and technological points of view, in this contribution we will be addressing the following questions that verify ‘why’ and ‘how’ the proposed solution might be applicable:

1. What are the main benefits of the operation of ACTs on motorways?
2. Which design and control requirements would be required to ensure a safe operation of ACTs at on-/off-ramps?
3. Which impacts on other road user groups will be expected?
4. How it would be possible to minimize the negative impacts on other road user groups (ordinary vehicles)?

It is clear that the operation of ACTs on DFLs which will interact with the flow of MDVs at entry/exit points of motorways is not the only option available for increasing the efficiency of road freight transport. Decisions to implement this scenario will only be made if it is considered to be safe and cost-effective for densely loaded freight transport corridors. The following alternatives may be considered as other competitive scenarios for the development of more efficient freight transport:

- dynamic traffic management of DFLs for the operation of ordinary trucks,
- operation of Ultra Long Trucks (ULTs) instead of the ACTs,
- increased use of intermodal rail freight,
- improved logistics information management and coordination.

However, these alternatives are not further discussed in this thesis.

In brief, this contribution can be characterized from other similar researches in the field of AHS from the following points of view:

[4] Since motorways carry about 40% of all vehicle-kilometers traveled on roads

a) it focuses on using the existing infrastructure (motorways) for the operation of automatically controlled trucks;
b) it concentrates on crucial time and space situations like focusing on peak hours and bottlenecks, among which the maximum level of hindrance between user groups would be expected;
c) it introduces the wide application of optimization methods in developing control strategies at bottlenecks;
d) it addresses new mean(s) of control which would be essential to avoid the hindrance of flow of ACTs by MDVs at bottlenecks.

## 1.5 Outline of the thesis

The structure of this thesis can be divided into three parts. The first part consists of chapters 2 to 4 which will give an overview of the operation of automatically controlled vehicles (with focus on trucks) in the literature (chapter 2) and will address the new (and major) concepts required for the operation of ACTs. Chapter 3 refers to the *design* requirements and introduces the major design implications required for the operation of ACTs affected by the flow of MDVs at on-/off-ramp areas of motorways. Then, chapter 4 describes the most promising *control* strategies for the operation of ACTs. These two chapters also will present the results of the analysis for assessing the impact of the proposed concepts of design and control, respectively.

The second part includes chapters 5 to 7. This part focuses more in detail on theoretical aspects of traffic flow modelling. First, chapter 5 describes a time-discrete traffic flow model applied in the literature for analyzing the human-behavior in traffic flow and describes the required model extensions for considering the proposed concepts of design and control of ACTs and MDVs (co-operative traffic flow of ACTs and MDVs). This section will present the development of a generic optimization model designed for assessing the impact of operation of ACTs hindered by the flow of MDVs at on-/off-ramps of motorways. Then chapter 6 will analyze the sensitivity of the proposed model quantitatively for a specific set of data and also for different design and control-related parameters. Later, chapter 7 indicates the utilization of the proposed design and control options while selecting different design objectives for a co-operative traffic flow control on motorways.

Finally, chapter 8 as the last part of this thesis will summarize the main findings and conclusions of this research. This chapter also outlines possible directions for future research in the field of truck automation operations.

# 2
# State-of-the-Art of Vehicle Automation With Focus on Trucks

## 2.1 Introduction

As future traffic demand will increase, the alternatives to provide additional capacity are limited. Either additional motorways and lanes must be built or the existing motorways need to become more efficient. As the prospect of building new motorways or lanes will be increasingly difficult, upgrading the capacity of existing motorways becomes more relevant. Thus, advanced technologies could be used to automate some of the basic elements of the system, such as the vehicle and the infrastructure control. Applying such technologies could increase the efficiency of roads during solitude hours (mostly night hours) and could avoid unpredictable and nonresponsive behavior of road users that have negative effects on efficiency.

The main purpose of this chapter is to show the deployment and benefits of Advanced Driver Assistant Systems (ADAS) technologies (with focus on trucks) along the time and to address an area of research, in this field, which might lead to a most dramatic change in efficiency. In addition, it addresses the major design and control requirements for applying the selected degree of truck automation along motorways. This chapter also overviews the results of previous researches in the literature to find existing gaps for applying their results to the questions of the existing research study.

ADAS or Advanced Vehicle Control Systems (AVCS) as they are known in North America, are being rapidly developed by vehicle manufacturers and others (Shladover (1995), Shibata and French (1998), van der Heijden and Wiethoff (1999), AVV (2001), ADASE2 Consortium (2003)). These technologies are intended to provide additional safety and comfort to drivers. In addition, the rapid advances in communication and sensor technology in accompanying with new motorway infrastructure and services may enable such technologies to operate more effectively to aim to broader criteria such as efficiency of operation or the environment.

Market introduction of ADAS can be considered to start in 1994 with the introduction of Collision Warning Systems[1] in the US (Marchau (2000), Shladover et al (2001), AVV (2001), STARDUST project team (2003), ADASE2 Consortium (2003)). The following step was the introduction of Advanced Cruise Control (ACC[2]) systems as optional for cars in Japan and Europe (Becker (1994), AHSRA (1998), ADASE2 Consortium (2003)). Following functions that are being introduced are Night Vision[3] and Lane Departure Warning[4], based on infrared and visible light cameras (AVV (2001), ADASE2 Consortium (2003)). Moreover, there are other functions which have been addressed in the literature, like pre-crash safety, Intelligent Speed Adaptation (ISA[5]) and parking support[6].

As the state-of-the-art shows, the emphasis in ADAS projects is mostly on informative or warning ADAS technologies in which the driver remains in control, rather than fully automated vehicles. Table 2.1 gives a brief overview about the major ADAS/AVG systems, the development and deployment of related technologies in Europe, Japan and US, separately. It should be noted that this table does not explicitly refers to all previous researches in the field of ADAS/AVG which have not led to practical implementations.

The following roadmap (figure 2.1) presented by AVV (AVV (2001)) provides a look at the current and expected deployment of ADAS technologies in the near future. In this figure, a simplified roadmap is given showing the systems to be marketed according to the *industry's scenarios*. While the roadmap may suggest that a system can only be introduced after the previous one is already available, this is not in fact the case. Furthermore, certain systems may only be introduced into certain market segments.

[1] A system warning the driver of an impending collision (See an example in the Appendix B- Figure B-1).
[2] A system ensuring that the speed of the vehicle is constant or adjusts to the speed of the preceding vehicle (See an example in the Appendix B- Figure B-2).
[3] A system assisting the driver in night conditions when road lighting is poor (See a visualization of this system in the Appendix B- Figure B-3).
[4] A system warning the driver when the vehicle threatens to leave the driving lane (See a figure in the Appendix B- Figure B-4).
[5] A system warning the driver of speed limitations (See a figure in the Appendix B: Figure B-5).
[6] A system helping the driver to do park or to do precision docking (see a figure in the Appendix B: Figure B-6).

**Table 2.1. Development and deployment of ADAS/AVG systems**

| System | Prototype/ Demonstration/ Field test | Market/ Deployment |
|---|---|---|
| Adaptive Cruise Control | - AHS operational Demo 1996 (Japan)<br>- Demo '1999 (US)<br>- PROMETHEUS BMM 94 (Europe) | - World first Production,1995 (Japan)<br>- Market avaiable in 1999 (Europe )<br>- Market avaiable in 2000 (US ) |
| Adaptive Cruise Control with stop-and-go function | - Smart Cruice 21 Demo 2000 (Japan)<br>- IVI technology showcase 2000 (US) | - Scheduled for deployment in 2003-2015 (Japan)<br>- Expected to be deployed in 2003-2015 (Europe and US) |
| Lane Departure Warning | - Operational prototype presented 1994 (Europe)<br>- Demonstration 1999 (Europe)<br>- AHS operational Demo 1996 (Japan)<br>- Smart Cruise 21 Demo 2000 (Japan)<br>- Demo '97, Demo '99 (US) | - Available for use on heavy trucks in 2000 (US)<br>- Market available for passenger cars, 2000 (Japan) |
| Lane keeping Assistance | - AHS operational Demo 1996 (Japan)<br>- Smart Cruice 21 Demo 2000 (Japan)<br>- Demo '97, Demo '99 (US)<br>- PROMETHEUS BMM 94 (Europe) | - Available for use on guided bus, 2000 (Europe)<br>- Market available, 2001 ( Japan) |
| Side-obstacle Warning | - Demonstrated on the VITA II from Daimler Chrysler<br>- Smart Cruice 21 Demo 2000 (Japan)<br>- Demo '97, Demo '99 (US)<br>- Generation 1 Field Operational Test of Transit in the 2001-2004 time frame (US) | - Available for use on trucks and buses, since early '90s (US)<br>- Market available for passenger cars, 2000 ( Japan) |
| Intersection Collision warning | - Smart Cruice 21 Demo 2000 (Japan)<br>- Driving Safety Supporting Systems, Fall 2000 (Japan)<br>- Ligh duty passenger cars IVI technology, showcase 2000 (US)<br>- Demonstration, 2005 (US) | - Scheduled for deployment 2003-2015 (Japan)<br>- Expected to be deployed for use in 2007+ (US) |
| Forward Collision Warning | - Smart Cruice 21 Demo 2000 (Japan)<br>- Demo '97 (US)<br>- Generation 1 Field Operational Test of Transit in the 2001-2004 time frame (US) | - Available for use on heavy trucks now. Expected to be deployed for other vehicles in 2003-2015 (US)<br>- Available for use on heavy trucks. Scheduled for other vehicle deployment in 2003-2015 (Japan)<br>- Expected to be deployed for use in 2003-2015 (Europe) |
| Intelligent Speed Adaptation | - Demo '98 (Europe)<br>- Demonstration at ITS World Congress, 2000 (Europe) | - Expected to be deployed for use in 2003-2015 (Europe)<br>- Scheduled for deployment, 2003-2015 (Japan) |
| Fully Automated Driving | - Truck application demonstration in CHAUFFEUR project, 1999 (Europe)<br>- Demo '97 (US), Demo '98 (Europe)<br>- Demo for fully automated buses and trucks on the HOV freeway lanes of I15, 2003 (US) | - A mass transit system based on a multi-articulated hybrid bus running on a dedicated lane developed in the Netherlands and due to start its operation in Eindhoven in 2003 (Europe)<br>- Public amusement park, 1999 (Japan)<br>- Initial market, 2003-2015 (Japan, US) |

**Source:** (http://www.trg.soton.ac.uk/stardust/).

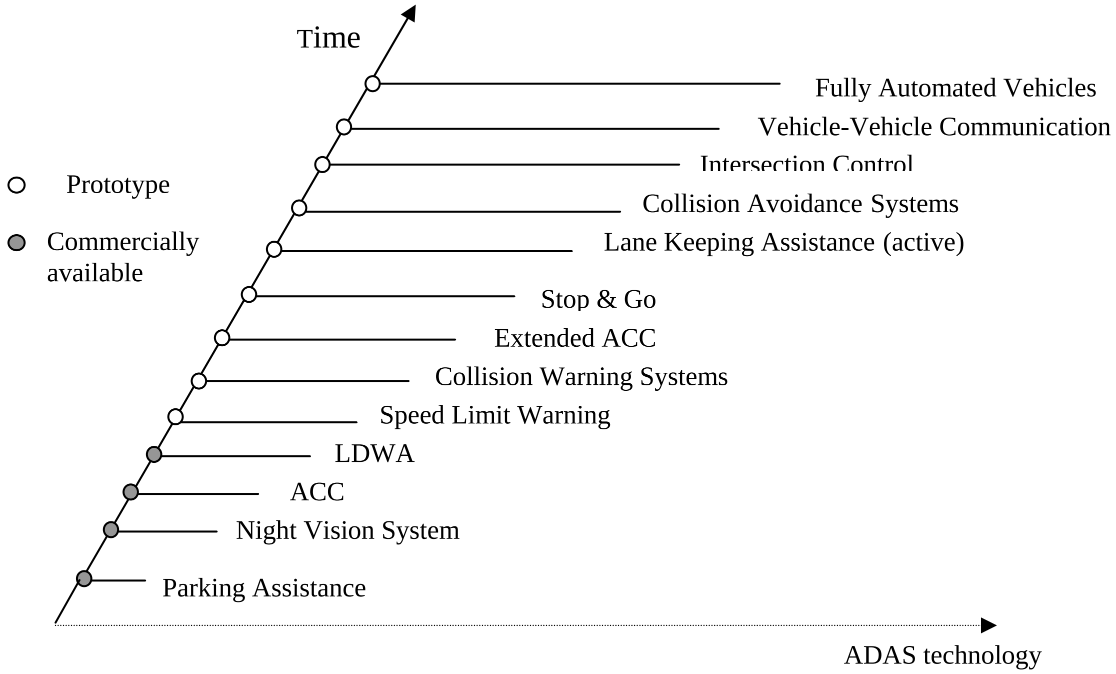


**Figure 2.1. Deployment of ADAS technologies along the time (**Source: AVV, 2001**)**

A survey achieved among 37 R&D projects on ADAS related technologies concluded that safety has become the main motivation for R&D into ADAS in the EU[7]. This survey concluded that increase in throughput, environment or comfort are pursued much less often. From this survey it also observed that most of the R&D researches in the EU within this time period have been assigned to the technological development of ADAS technologies, rather than other research areas like Human-Machine Interface (HMI), legal, social and even infrastructure (Appendix B: Figure B-7). The survey also indicated that most projects are demonstration type projects in which certain technologies are demonstrated.

The area, however, where the most dramatic changes in efficiency are expected is Fully Automated Driving (Varaiya (1994), Tsao (1995), Whelan (1995), Stevens (1997), Ward (1997), STARDUST project team (2003), ADASE2 Consortium (2003)). In Fully Automated Driving, all Intelligent Transport System (ITS) technologies would be integrated to generate a road system where fully automated vehicles are guided to their destinations and the flow of traffic is controlled and optimized for maximum efficiency and safety. Of course, due to taking over the whole driving tasks by the automatic system, the design of a Fully Automated Driving system is a challenging one and the issues involved are enormous from the technological, human factors, socioeconomic, legal, institutional and environmental points of view. The complexity to provide all required issues is the main reason why the Fully Automated Driving, so far, has not been used effectively, in spite of a broad range of researches achieved in this field.

## 2.2 Activities on Fully Automated Driving (with focus on trucks)

During 1990s specific organizations and groups have been established to further develop the concept of Fully Automated Driving. Among all, the Intelligent Transport Society in the US and European Road Transport Telematics Implementation Coordination Organization (ERTICO) can be enumerated. Within this decade, the PATH program[8] in the US has delivered a lot of research materials concerning the Fully Automated Driving concept[9], in which long term objectives are taken into account.

It has been recognized in the literature that research and development on AHS technologies to date has been primarily focused on passenger vehicles, while commercial vehicles such as trucks have been largely ignored (Ioannou (1997), Shladover (2001a)). The ADAS technologies that have been developed for trucks are mostly related to safety aspects, rather than efficiency (e.g. LDWA, Side Obstacle Detection, etc.).

In general, for a variety of reasons, the economics of automation would appear to be significantly more favorable for trucks than for passenger cars, making the prospects more encouraging for developing the truck automation (Shladover (2001a)):

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[7] A more descriptive state-of-the-art of ADAS technologies in the Europe can be found in: http://www.adase2.net.

[8] http://www.path.berkeley.edu/

[9] In the US-related literature this concept is introduced by Automated Highway System (AHS).

- Time is money for trucking operations, and travel time savings have direct economic benefits because of reduced operating costs (specially driver labor), improved utilization of capital equipment, and better ability to meet performance targets for “Just In Time” (JIT) deliveries. Reduction of travel time variance, even without a reduction in mean travel time, has a similar benefit because of the sensitivity of JIT systems to delays. If Fully Automated Trucks can avoid even some of the congestion experienced by conventional trucks, the benefits should be substantial and would increase the reliability of the freight transport system;

- The potential (but still uncertain) safety improvements from automation should have direct economic benefits in terms of reduced insurance costs and less time loss being created due to crash damage. The effects are much larger for trucks than for passenger cars because of their high economic value and high utilization rates;

- Operating Fully Automated Trucks at close longitudinal separations, enabled via platooning of ACTs, might reduce their aerodynamic drag, which translates directly into reductions in fuel consumption and exhaust emissions. Considering the much higher annually operated distances of each truck compared to cars will encourage the higher intention for operating the ACTs;

- Fully Automated Trucks could also be driven during night hours, since normally the driver has a limited role in it. This possibility could increase the efficiency of roads during night hours for the freight transport and may decrease the traffic demand on motorways during peak hours. This would result in decrease of total travel time of all user groups of roads ultimately (Tabibi & Hansen (2000));

- Operation of Fully Automated Trucks paves the way for optimizing the control of the traffic flow of vehicles more broadly. This capability could create a more smooth flow of trucks comparing the flow of ordinary trucks. The higher the smoothness of flow, the less the number of sharp accelerations and decelerations (shock waves), and consequently the less the consumption of fuel of trucks which would be effective in decreasing the costs of transport (Tabibi (2002)) ;

- The electronic equipment needed to automate a truck should not be very different from equipment needed to automate a passenger car, since its functions are essentially the same. It means that the cost of automated system for an ACT should be almost the same as a passenger car. However, a heavy truck would typically cost much higher than a passenger car. This factor makes the potential economic return from an investment in automation equipment significantly more attractive for a truck than for a passenger car.

Thus, from the mid-1990s, a part of the PATH program started to develop truck automation capabilities. The PATH program has been developing a truck automation capability since 1997, and has equipped one Freightliner tractor-trailer rig for fully automated testing (Tan et al. (1999), Hingwe et al. (2000)). In the summer of 2003, PATH and CALTRANS have a plan to hold a public demonstration of three automated tractor-trailers (Shladover (2001b))[10].

[10] No result with regard to this demonstration for trucks is reported, yet (Dec. 2003).

In Japan, the development of special lanes for automated trucks was considered, for the first time, as part of the New Tomei Expressway in the Tokyo-Osaka corridor. But, the research has not progressed beyond the planning stages (Yamada et al. (1996)). There has also been a study of the use of automated trucks for urban freight movement in tunnels located 60 m beneath major urban centers, but this concept faced construction cost and technology as well as vehicle automation difficulties, so it is still at the stage of concept definition (Highashi et al. (1997), Takahashi et al. (2000)).

In Europe, activities also focused on near-term implementations of truck automation. Among these, the Combi-Road project (van der Heijden and Heere (1997), Scrase (1998), Melcherts and Heere (1998)) and the CHAUFFEUR project (Schulze (1997), Fritz (1997), Berghese et al. (1997)) were the most prominent ones.

Programs and researches like PATH and CHAUFFEUR are still going on. The CHAUFFEUR research was extended beyond the development and testing of technology to the evaluation of the impacts of systems implementation with focus on trucks only, while the PATH program covers a broad range of research in different fields of operation of automatically controlled vehicles without any specific focus on special target groups. Within PATH a demonstration for the operation of heavy duty vehicles, like truck-trailers and buses in platoons for the summer 2003 (Shladover (2001b), Misener and Miller (2002)) was scheduled, however due to budget problems this demo was cancelled[11].

The innovation process necessary to come to automated truck lanes can be divided in four steps: in the first step, the *sensor technology* was introduced as the fundamental requirement to facilitate the recognition of objects, automatically; in the second step the *communication technology* was developed to facilitate the interaction of automated trucks with each other[12]; then in the third step *traffic control strategies* were developed to improve the interaction of partly/ fully automated trucks with each other and finally the *construction of dedicated freight lanes* (including dedicated on-/off-ramps) for fully automated trucks was distinguished as a major need for the operation of fully automated trucks.

### 2.2.1 Description of the Combi-Road project

In the Netherlands, the Combi-Road concept was developed as a bimodal, intermediate transport system between sea terminals and inland transfer points for standard road trailers and rail wagons which will be hauled by electrically driven, rubber-tired engines on an exclusive right-of-way (Project team Combi-Road (1994)). In the Combi-Road concept the vehicle will be manually controlled during interterminal transport or coupling/uncoupling at transfer points, whereas during the operation on open tracks it will be fully automated.

The automatic system of Combi-Road was planned to ensure a minimum headway of 12 sec and a minimum distance of 180 m between vehicles at a maximum speed of 54 km/h. Traction power for operation of Combi-Road system on the exclusive right-of-

[11] http://www.ivsource.net/archivep/2003/mar/030310_demo2003nomore.html (last update- March 2003)
[12] These trucks are not fully automated, necessarily.

way was designed to be fed by third rail, while at transfer points the diesel-electric drive was used.

It was estimated that the Combi-Road trucks would transport 20- and 40-feet containers from the port of Rotterdam to hinterland terminals within the Netherlands or until Belgium and Germany. The practical capacity was estimated to be 1.5 million container moves per year asuming a service of 24 hours per day.

Each Combi-Road truck was designed to receive instructions concerning stop-and-go at conflict points for vehicles coming from different directions. In the first stage of development of such a system, the mechanical guidance was tested while in the later stage the possibility for electronic guidance was introduced.

Combi-Road gave a public demonstration of a single automated truck guided by Magnet Marker Sensing System (MMSS) to provide the lateral guidance of the vehicle in the summer of 1998. This demonstration was performed on a special test track (Scrase (1998)), but there is little progress evident since that time.

With regard to the application of Combi-Road vehicles the comments of Hansen (Hansen (1996)) are worth noting. He argued this concept and concluded that the operation of Combi-Road vehicles, as bi-modal vehicles, may encounter a number of difficulties due to the inherent complexity of technical problems (e.g. very different weights, deceleration rates and design of super-structure[13]), which might cause negative economic impacts. The enormous required capacity for storing containers at the destination point of Combi-Roads, financial aspects for the construction of the exclusive lane for Combi-Roads, and possible technical failures due to electronic guidance of vehicles at intersections can be encountered as major reasons which led to little progress of the Combi-Road project.

### 2.2.2 Description of the CHAUFFEUR project

The most substantial body of research documentation on truck automation is associated with the CHAUFFEUR project, sponsored by the European Commission, with a variety of industrial partners (Schulze (1997), Fritz (1997), Berghese et al. (1997)).

This project tackled the problem of dramatic increase in freight transport by developing systems which safely may increase the density of freight traffic and enable better use of existing roads. In the proposed system of CHAUFFEUR two trucks will be linked electronically in which the second truck follows the dynamics of the first one. Therefore, there is no need for the second truck to be driven by a driver in normal traffic situations (excluding emergency conditions) (Figure 2.2). In the proposed system of CHAUFFEUR, all on-line information about the dynamics of the first truck is transferred to the Tow Bar installed at the backside of the leader truck. Then, by scanning this Tow Bar, the second truck is able to follow precisely the dynamics of the first truck.

[13] An integration of rail and road in one lane.

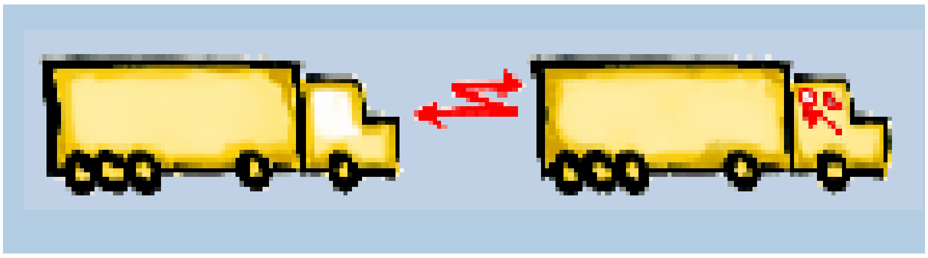


**Figure 2.2. A schematic diagram of CHAUFFEUR trucks**

In the CHAUFFEUR project, the system requirements were analyzed from different points of view:

a) *users*: to answer the needs of potential users, like road operators, freight forwarders, professional drivers, society.
b) *safety*: to assess the potential system failures including the CHAUFFEUR system itself and relevant conventional vehicle components and adverse effects from the environment,
c) *traffic operation*: to define the impact of the Tow-Bar system on traffic flow and assess its feasibility.

The CHAUFFEUR project is characterized by the following two main initial concepts:

- *Tow-Bar* is the kernel of the CHAUFFEUR project. Two trucks are coupled electronically. The leading truck is conventionally driven, the towed one follows automatically. Although, in this concept, the following truck will run automatically behind the leading one, some kind of human interaction, i.e. a driver on board, will be necessary to take the driving control in case of technical failures. Despite the presence of a driver on the following truck, the driver of the leading truck will be responsible to apply a suitable driving style to the whole Tow-Bar like with a traditional trailer;

- *Platooning* allows the electronic coupling of more than two trucks. However, as the research has progressed, it became evident that the Tow-Bar capability can be applied on existing motorways only to pairs of trucks (a leader and one follower), because lane change and merge into the gaps between truck platoons by cars could not be avoided. Platoons of three or more trucks could only be operated in dedicated truck lanes that are segregated from normal vehicle traffic.

The CHAUFFEUR project was continued within the time period of Jan. 2000-March 2003 with the name of CHAUFFEUR II, in which the Lane Keeping System and also the extension of number of platooned Tow-Bar trucks up to 6 trucks, were evaluated (Benz et al. (2003)).

The results of questionnaires distributed among freight forwarders and professional drivers indicated that the system for the electronic coupling of heavy goods vehicles would meet a widespread acceptance among forwarding agents, as a potential group of purchasers (Brockmann et al. (2001)). For the majority of those questioned, the system represented an innovative, professional and practical solution, which is in line with the requirements of the forwarding and haulage industry. In the case of companies with relatively frequent haulage in which a number of vehicles are driven at the same time, on the same route, to the same or nearby destinations, a significant reduction of personnel and fuel costs is anticipated (Table 2.2).

**Table 2.1. Distribution of similar trips among forwarders**

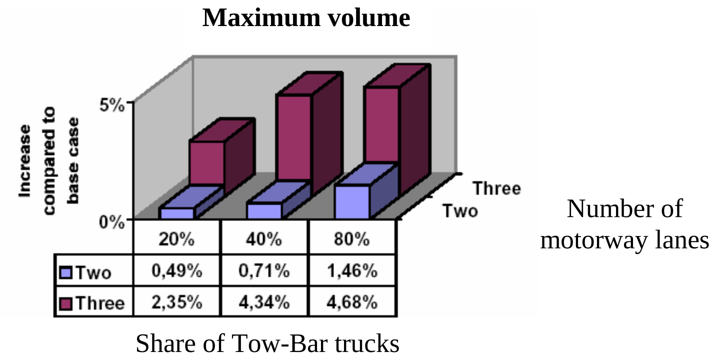
| Journeys with the same destination at the same time (%) | Forwarders (%) |
|---|---|
| 0 | 20.8 |
| 1-10 | 32 |
| 11-20 | 19.2 |
| 21-30 | 13.6 |
| 31-40 | 4.8 |
| 41-50 | 5.6 |
| 51-60 | 1.6 |
| 61-70 | 1.6 |
| 71-80 | 0.8 |

Source: CHAUFFEUR 2 Project- Final results

Lorry drivers and car drivers regarded electronic coupling as professional and innovative. For truck drivers, the system was evaluated neither practical nor requirement oriented. The main reason for the negative attitude of truck drivers was described as the worry of truck drivers for loosing their jobs and a low acceptance of electronic coupling on the part of their colleagues and on the part of unions. Both lorry drivers and car drivers expected advantages in reduced haulage costs, quicker execution of haulage and improved road utilization. On the other hand, riding in platoons was regarded as too long and consequently difficult to control. The research also reported that "*the use of electronic coupling seems to be problematic in relation to the existing infrastructure, specially at slip roads, on- and off-ramps*". It is interpreted as: "hardly surprizing" that both truck and car drivers believed that the system will tend to reduce road safety. However, the enquiry does not reflect any findings concerning the safety impacts of driving Tow-Bar trucks.

The results of the economic evaluation of Tow-Bar system indicated that independent from the CHAUFFEUR equipment rate the benefit-cost ratio would be higher than 4. The benefits are mainly caused by time cost savings due to the capacity effect (i.e. increase in road capacity) and by the lower fuel consumption caused by lee driving (Baum and Geissler (2000), Baum et al. (2003)).

Concerning the traffic flow impact, the results of simulations for two and three lanes motorways turned out that the CHAUFFEUR system would improve the traffic flow on motorways up to 5% in heavy traffic depending on the share of CHAUFFEUR equipped vehicles (Figure 2.3) (Brandenburg et al. (2000)). During normal traffic conditions no negative effects were found. Also, the Tow-Bar effects on traffic flow were investigated on motorway bottlenecks like lane drops. Here, the CHAUFFEUR system slightly led to a reduction in the traffic flow (10%-15%) because of less space available allowing vehicles (rather than towed trucks) on the closed lane to merge. Nevertheless the simulation runs showed that these effects are limited that they would not be recognized in real traffic.




Source: http://www.chauffeur2.net/final_review/Deliverables/D1_30.pdf

**Figure 2.3. Influence of Tow-Bar trucks on maximum flow**

With regard to capacity gains, the simulation studies carried out included Tow-Bar trucks in various percentages (e.g. 10%, 20% and 40% of all trucks). They focused on very dense traffic around the capacity of the motorway. In all cases, a positive traffic impact was found. Although small at only 10% penetration rate, a slight increase in capacity was established. With increasing number of Tow-Bar trucks, this effect became more prominent reaching a maximum of about 3.5% increased capacity. The positive effects were more pronounced for a three lane motorway than for two lanes (Benz et al. (2003-b)).

The results of platooning of more than two Tow-Bar trucks also led to this conclusion that in low traffic volumes at night platoons up to 6 vehicles or more can successfully carry out all necessary lane changing manoeuvres. In situations where the traffic volume increased further to normal daily traffic or even higher, a high degree of hindrance of flow of Tow-Bar trucks were reported. Therefore, it was recommended that platooning should be carried out during times of low traffic volumes like at night up to the early morning hours, if the road conditions in changing sections are not altered adequately for platooning (Benz et al. (2003-a)).

## 2.3 Mixed versus Dedicated Flow of Automated Trucks

Dedicated lanes are lanes for the exclusive use of certain kinds of vehicles. If trucks are operated as automated vehicles on these lanes, terms like Dedicated Freight Lane (DFL) or Dedicated Truck Lane (DTL) are applied here (Tabibi and Hansen (2000), Tabibi (2002)). Dedicated lanes may or may not physically be separated from manual traffic. In general, dedicated lane deployment could be accomplished by any of the following options:

- to convert an existing High Occupancy Lane (HOV) to a DFL,
- to separate an existing lane and convert the inside lane to a DFL,
- to build a new lane and convert the inside lane to a DFL lane,
- to build separate DFLs for fully automated trucks in the existing right-of-way.

Among the above options, the first two options would use the existing infrastructure, while the last two options would provide extra capacity for the operation of automated vehicles. Consequently, they need more space and particularly a higher investment to be built.

In difference to dedicated truck lanes, the mixed lane concept, in which both fully automated vehicles and manually controlled vehicles would share the same roadway exists. It would provide more flexibility for the traffic flow, however, from the safety point of view a mixed flow of manually controlled vehicles with automated trucks might create much more problems for the fully automated vehicles, particularly.

Van Arem et al. (1997) conducted research to explore the traffic flow impacts of a dedicated lane for "intelligent" vehicles on Dutch motorways. Since, they have assumed an exclusive lane for automated vehicles the results of that research are addressed here, however, they assumed the Intelligent Cruise Control (ICC) systems as the level of automation for vehicles. They addressed to results of their earlier study (van Arem et al. (1995)) in which a deterioration on the traffic performance was found at higher levels of demand for 40% penetration of ICC vehicles and a target headway of 1.5 s. The objective of the more recent study was to examine whether a lane available exclusively for 'intelligent' vehicles can increase the capacity of a bottleneck in the motorway network. A road configuration consisting of a motorway with a drop of the left lane of a four lane section was examined by means of the microscopic traffic simulation model MIXIC 1.3. They concluded that smaller distances and/or time headways between vehicles may be feasible, possibly at higher speeds by automating following behavior. The question is, whether and how such an 'intelligent lane' can be combined with manually driven vehicles on conventional roadways. In the approach to such a lane, a lot of lane changes would take place, which could potentially be the cause of a bottleneck themselves. The findings of their study indicate that:

- the introduction of ICC in the bottleneck situation was found to result in a reduction in the number and severity of shock waves and a throughput improvement of several percent with respect to the maximal throughput of approximately 7570 pce/h for the reference situation (3-lanes);

- the introduction of ICC lane resulted in a slight decrease in speed (at a slightly higher volume);

- the introduction of short headways on the ICC lane led to some problems of merging at the approach to the ICC lane, but also to a slightly higher throughput (e.g. 5%-10%) with respect to the reference case without ICC.

In brief, the nature of the hindrance of flow of fully automated trucks by manually driving vehicles on dedicated lanes at on-ramp areas might be very similar to the mix of two groups of vehicles at lane dropping sections. Thus, the results of this research confirm the potential of a higher efficiency by the operation of fully automated vehicles on dedicated lanes, too.

Hearne and Siddiqui (1998) also compared dedicated and mixed traffic lanes for fully automated vehicles, mixed traffic lanes present two significant problems: (1) in mixed traffic lanes driver errors (as the main cause of 90% of accidents) continues to be a problem; (2) potential problems with computer inability to predict human intervention at any time in the driving scenarios remain unexplained. However, in dedicated lanes automated vehicles are equipped with a compatible system and vehicles know the capabilities of the vehicles around them. Therefore, unpredictable events due to human intervention are minimized. Moreover, the application and maintenance of AHS equipment can more easily be achieved in dedicated lanes. They performed some simulation runs by using the SmartCap program, developed by PATH. They also concluded that the dedicated lane configuration has many advantages, mainly in terms of increased safety and increased throughput. Moreover, they recognized the automated detection of obstacles is a difficult problem for the dedicated lane.

In the Prometheus project, also, the possibility of fully automated driving on regular highways (and hence among MDVs) with the demonstration of the VITA II prototype from Daimler was pursued (Ulmer (1994)). Since then, fully automate driving has taken a more realistic approach with *dedicated* applications[14].

Research of Minderhoud and Hansen (2001), with focus on trucks, also led to the conclusion that a dedicated lane with flow control near the motorway intersections is the most promising approach to prevent future problems on heavy loaded motorways with a high share of trucks as the traffic composition per lane becomes more heterogeneous. Almost all criteria indicating the performance of scenarios with dedicated lanes for trucks, like traffic operation, comfort and safety indicators, showed an improved performance applying the dedicated lane scenarios.

In a more recent study, the same authors (Minderhoud and Hansen (2003)) showed that in a mixed flow of manually and automatically controlled vehicles, the application of an externally controlled headway system for selected parts of the motorway can increase bottleneck capacity and speed, as well as safety downstream of an on-ramp. They addressed that at 80% system penetration the throughput gain would be about 4%. They have concluded that an external control headway system for automated vehicles, by creating more equally sized gaps directly upstream the on-ramp, can improve the efficiency in merging on-ramp traffic and consequently increase downstream capacity. A maximum reduction of 9% in average travel time of all vehicles is reported in scenarios in which the automated vehicles with a time headway of 1.2 s and 1.4 s were driven. It should be noted that the automated vehicles addressed in this study were not fully automated. A study conducted by TNO in the Netherlands (Hogema (2003)) indicated that a time headway of 1.3 s-1.6 s would be the most relevant time headway selected by truck drivers.

[14]Addressed by: http://www.trg.soton.ac.uk/stardust/d1_exec.htm

Thus, the current state of knowledge with regard to the operation of fully automated trucks in mixed traffic or on segregated lanes indicate that the application of dedicated lanes for fully automated trucks is essential. Since the construction of additional lanes for fully automated trucks is not considered within the framework of this thesis, the application of dedicated freight lanes would mean a reduction of the number of lanes for ordinary vehicles. Thus, one of the aims of the current research is to investigate whether the creation of a dedicated freight lane for fully automated trucks could increase the efficiency of motorways at on-/off-ramps in case of absence of fly-overs. It also would be needed to estimate in detail to what extent the creation of such a DFL would change the efficiency of both automated and non-automated vehicles.

## 2.4 Transition Area versus Dedicated On-/Off-ramps

The previous section cited the necessity for providing a dedicated lane for the operation of automated vehicles, when the longitudinal and lateral control and steering of vehicles becomes the main task of the system, instead of control by drivers. This section overviews the existing ways, described in the literature, to provide the access to dedicated lanes for automated vehicles.

Stevens et al. (1995) defined two ways to provide access to dedicated lanes. In the first way, the access can be through existing on-/off-ramps with use of a transition lane to transfer control from manual to automated control, or vice versa. In the second way, the access can be achieved by on- and off-ramps dedicated to fully automated vehicles only. Transition lanes are lanes between the 'manual lanes' and 'automated lanes'. Vehicles enter and exit the automated lane via this transition lane. On the transition lane they request access to the automated lane, after which the control system 'pulls' the vehicle into the automated lane (Figure 2.3). Given the fact that also manual vehicles could drive on the transition lane and that entry and exit maneuvers require a high speed, problems of safety were expected, unless the transition lane is exclusively used for either entry or exit. Dedicated ramps are for exclusive use by automated vehicles, and will segregate the flow of automated vehicles from the manual ones. Such a dedicated ramp requires a grade-separated infrastructure, like a bridge or tunnel, at on-/off-ramps to provide a safe access of on-/off-ramps to the dedicated lane.

Smith and Noel (1995) compared a three-lane motorway section with an off-ramp followed by an on-ramp, with a similar situation in which the left lane is allocated to AHS traffic. The left lane is physically separated from the other lanes, and has an egress point just before the off-ramp and an access point after the on-ramp. Both the egress and access points have a deceleration and acceleration transition lane into and from the remaining motorway lanes. The authors have reported that the AHS results differ especially as function of the percentage of AHS vehicles. Clear improvements in traffic performance (measured as average and standard deviation of speed) are reported for AHS percentage of 65% and higher.

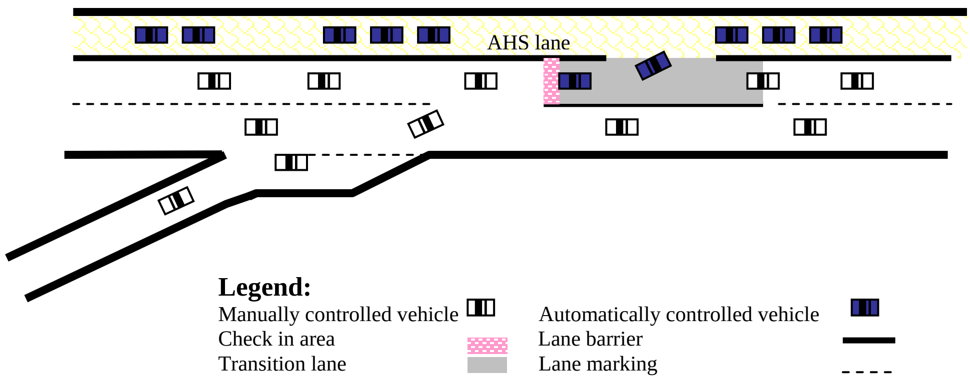



**Figure 2.3. A typical transition lane at on-ramps for dedicated lanes of automated vehicles (Source: Yim et al. 1997)**

Rao and Varaiya (1993) also considered an AICC lane without physical separation from the other lanes. On such lanes, vehicles try to form platoons which drive at 8 m mutual distances. The authors concluded that the transition lane is sensitive to vehicles entering or leaving the AICC lane. At 40% AICC vehicles, the authors report that a capacity of 2700 veh/h/lane is feasible. It is remarked however, that the distance of 8 m between AICC vehicles, at high speeds, is quite optimistic. Because, at a speed of 80 km/h, such a distance would only provide a reaction time of 0.36 s which seems to be too short for processing data and sending the appropriate commands for stopping automated vehicles.

Youngblood et al. (1995) have reported an other study on alternative entry/exit strategies. Their conclusion is that dedicated entries/exits are the most effective and safe with regard to automated lane's operation. A direct exchange between manual and automated lanes is considered to be the least effective. Transition lanes are considered to be 'moderately' effective, either continuous or in designated entry/exit zones. Barriers between the manual and automated lanes are recommended for reasons of safety. Further, in entry/exit zones it is recommended to have a special acceleration lane contiguous to both the manual and automated lane just before the entry point is provided, and similarly a deceleration lane just after the exit. Most of all, Youngblood et al. (1995) found that gaps in the available theories exist with respect to knowledge of interacting traffic streams at entries/exits to automated lanes.

Yim et al. (1997) defined a similar concept for accessing to the dedicated lane of automated vehicles. They referred to different design layouts, like at-grade or grade-separated access of dedicated lane for automated vehicles. They concluded that at-grade AHS facilities would be most compatible with the existing environment (California motorways). Compared with at-grade AHS facilities, grade separated facilities would typically be more costly to construct and would introduce greater environmental hazards. Yim et al. (1997) also emphasize that “in terms of safety and operational efficiency, the complete separation of manual and automated traffic appears to be preferable. However, there are trade-offs between these two concepts that should be examined further. Comparisons between the two concepts that should be investigated further include cost, safety, land-use, displacement, motorway traffic operations, impacts on secondary roads, and accessibility to the automated facility by emergency vehicles".

In conclusion, the above evidences suggest applying dedicated on-/off-ramps to provide safe merge/diverge of automated vehicles to the mainline flow of automated vehicles on the dedicated lane. Thus, in such cases, at least two lanes would be required to ensure an efficient and safe merging at on-ramps. Concerning the possibility of operation of automated trucks on heavy loaded motorways with a high share of freight traffic, the following remarks should be taken into account:

- in case of operation of automated trucks on one lane of the existing motorways, all ordinary vehicles drive on the remaining lanes (mostly 2 lanes). Thus, the provision of a transition lane would be inefficient and may create safety hazards to manually driven vehicles, because of possible technical failures of the automated system for taking over the control mode of driving of ACTs from manual to automatic and vice versa;

- the location of the dedicated lane for automated vehicles, e.g. on the right (shoulder) or left (median) lane, has a great impact on the traffic flow, as it is influenced by the selection of either dedicated on-/off-ramps or transition areas. When trucks are the main users of these lanes, the higher difference in dynamics of trucks compared to cars would be a safety issue. This would require fly-overs or traffic signals on the mainline, in case of dedicated lane on the left side. Alternatively, in case of dedicated lane on the right side, the application of transition lane seems to be still possible and needs further investigations.

## 2.5 Traffic Flow Theory in AHS

Automation of the driver task not only supports the safety and comfort of the equipped vehicle, it can also improve traffic flow efficiency. Therefore traffic flow theory plays an essential role in the design and assessment of automatically controlled vehicles.

*In an AHS* vehicles are under automatic control: the distance a vehicle maintains from the vehicle in front, its speed, and its route from entry into the highway until the exit, are all determined by the vehicle's feedback control laws. One may therefore compare the effect on the traffic by changes in vehicle control rules, and seek to determine the "optimum" control rules. By contrast*, in non-automated traffic flow theory*, the driver determines a vehicle's headway, its speed, its movement during a merge, etc. Each driver has his/her own preference which varies so much among various drivers depending on age, sex, education, etc. Thus, such a variation in driving behavior makes it difficult to provide a co-operative driving style which makes benefits for the whole vehicles driving on a segment of the road.

A traffic control center (TCC) for the AHS could directly influence the flow by issuing orders to vehicles regarding their speed, gap acceptance and route. Those orders would be followed because the vehicles were programmed to do so. The TCC for the non-automated highway can only make speed and route suggestions, but drivers may ignore these suggestions or react to them in an unexpected manner. Thus, the influence of TCC policies in the AHS is much stronger and more predictable than its influence on non-automated traffic; and so, one may again seek to determine the optimum TCC policy. Because it is possible to exercise much greater control over the movement of individual vehicles and the traffic as a whole, a theory of AHS traffic flow will tend to be *prescriptive*. Non-automated traffic flow theory is more *descriptive*, by contrast.

The prescriptive nature of flow of automated vehicles may provide the opportunity to extend the scope of work of optimization algorithms for the design of road layouts and control of automated vehicles in order to minimize the travel time spent in the whole road network.

Basically, in the literature, three different levels for the description of driver-vehicle interactions are considered: (sub)microscopic, mesoscopic, and macroscopic levels (Hoogendoorn (1999), Hoogendoorn and Bovy (2001), Tampere and van Arem (2001)).

Every *(sub-) microscopic model* distinguishes between longitudinal and lateral steering tasks of a Driver-Vehicle Unit (DVU). The longitudinal tasks consist of speed and acceleration choice during congested and uncongested traffic, as well as interaction with vehicle equipment; while the lateral steering task involves lane changing behavior, merging behavior, and interaction with vehicle equipment. Car following models, micro-simulation models, and cellular automation models are available for this class of models.

Alternatively, the *mesoscopic model* deals with probabilities and distributions in Phase Space Density (PSD). The PSD is the probability distribution of finding a DVU on lane 'j' at location 'x' at time 't' driving with speed 'v'. Mesoscopic models describe how distribution changes and provide a way to translate microscopic model assumptions into a macroscopic model formulation. By doing so the mesoscopic models benefit from the many numerical techniques that are available for solving the macroscopic traffic flow equations.

The third class of models are *macroscopic models* which describe the dynamics of traffic flow on an aggregate level, i.e. without distinguishing individual vehicles. For this description macroscopic variables like flow rate, average speed and density are used. The basic rule for every macroscopic model says that the density increases in time as the flow rate decreases in space (conservation law or 'continuum equation'). To this continuum equation macroscopic dynamic equations are added that describe the evolution of the average vehicle speeds. Macroscopic models differ from each other depending on the type of assumptions that are made for the dynamic estimation of the speed. Models that assume a static empirical equilibrium relation between the average speed and the density are called first order models. A second order model assumes a dynamic equation for the speed as a function of time or space derivatives of density and speed. Typically the speed variance appears as one of the terms in this equation. Another option is to establish another dynamic equation for the speed variance, which yields a third order model. However, most common macroscopic models are first or second order.

In this connection it is worth noting the comments of Tampere and van Arem (2001). In their overview about traffic flow theory and its application in automated vehicle control they argue "The (sub-)microscopic approach to traffic flow modelling is appealing because of high level of detail allows virtually all control measures to be implemented. Moreover, the correspondence with the real world makes the approach comprehensible to outsiders. However, this approach is less suited when the detailed specifications of the traffic flow control measures are not precisely known. In this case the macroscopic approach might be the better choice. Here the problem is how to include the behavioral changes of the DVU's without a priori limiting the model's outcome to a predictable solution. The number of traffic flow control policies that can be modelled macroscopically is therefore limited to relatively simple strategies with influence on those few parameters that occur in the macroscopic model". They also found that the mesoscopic models have not been used so far for these purposes.

Thus, the microscopic and macroscopic approach respectively for the analysis of flow of automated vehicles depends on the specific objectives that are followed. While the microscopic models will provide the possibility to distinguish among different combinations of trucks platooning more clearly, the macroscopic models provide the possibility to assess the impact of distribution of flow of automated trucks over all hours of the day. The review of the literature reveals a lack of knowledge with respect to combination of (micro-) simulation models and optimization models describing accurately the dynamic characteristics of flow on the macroscopic level. It is hypothesized that due to the prescriptive characteristics of flow of automated trucks, the utilization of optimization methods for traffic control may be beneficial. The application of micro-simulation tools like SiMoNe (Minderhoud (2001)) may help to recognize the DVU interactions more clearly and to use the results of micro-simulation analysis for simplifying the structure of the optimization model aimed at controlling the mixed flow of automatically controlled trucks and manually driven vehicles. In such a case, the results of a micro-simulation model would act as input for the proposed optimization models.

## 2.6 Application of Optimization Methods in Capacity Measurement of On-/Off-ramps

In saturated traffic flow conditions, a merging or diverging area is considered as a bottleneck because of the conflict between the flow of mainline motorway and the ramp flow that enters the motorway and the reduced capacity due to the lane drop. There was a considerable amount of work done on estimation of capacity to specific user groups at on-/off-ramp areas, either in AHS concepts or in traffic flow of ordinary vehicles.
A majority of researches with respect to capacity estimation at on-/off-ramps in the AHS is devoted to concepts like platooning or inter-vehicle communications, as addressed by Hall et al. (2001). The impact of these concepts, as explained in the previous section, is mostly evaluated by using micro-simulation tools. Therefore, the application of optimization methods, so far, is widely neglected in the literature concerning AHS.

Among these, Hall (1995) developed an analytical model that assigns traffic to lanes on the basis of trip length with the objective of maximizing the highway throughput. This is accomplished by minimized capacity losses associated with lane changes. In follow-up works Hall (1996) and Hall and Caliskan (1997) extended the static and dynamic models to highways with varying traffic flows by on ramp and off ramp, through the use of a linear programming model. In the proposed model in this study capacities are defined by bundle constraints, which are functions of the flow entering, leaving, continuing and passing through lanes in each highway segment. The objective function of the proposed model is to maximize total flow, subject to a fixed origin-destination pattern, expressed on a proportional basis. The model was tested for highways with up to 80 segments, 20 destinations, 5 lanes and 12 time periods.

Broucke and Varaiya (1995) also created a related model that optimally assigns traffic to lanes, and optimizes other maneuvers such as platoon formation. Another methodology was applied by Park and Ryu (1999) to estimate the capacity of on-ramp areas through applying Neuro-Fuzzy control of converging vehicles for automated transportation systems. In this study, the authors proposed an unmanned vehicle-merging algorithm that consists of two procedures: First, a longitudinal control algorithm was designed to keep a safe headway between vehicles in a single lane. Secondly, a 'vacant slot and ghost vehicle' concept was introduced and a decision algorithm was designed to determine the sequence of vehicles entering a converging section considering the total traffic flow. The sequencing algorithm was based on fuzzy rules. The authors concluded that the developed algorithm could be used for a Personal Rapid Transit (PRT) system and for IVHS, as well as and also for a real-time system for human driver controlled automobiles.

As explained in the previous section, due to the descriptive nature of traffic flow of ordinary vehicles, the application of optimization methods in traffic flow of ordinary vehicles mostly is restricted to the development of ramp metering algorithms. However, a clearly different view is presented by Lertoworawanish and Elefteriadou (2003). They developed a method for estimating the capacity of ramp weaves based on gap acceptance and linear optimization. The proposed methodology provides estimates of the capacity of ramp weaves, as a function of the capacity of the equivalent basic freeway segment lane, and for given proportions of origin-destination demands within the weave. Thus, the objective function in this optimization model is to maximize the total flow of vehicles which change their lane or go forward in a weaving area. Figure 2.4 indicates a flowchart describing their methodology for estimating the capacity of weaving areas. The authors concluded that the framework is robust enough to be applied to other types of time headway distributions, which can be obtained whenever field data are available.

Shim and Kim (1998) examined the characteristics of merging lane capacity and improved the ramp-metering algorithm to consider the time varying characteristics of ramp volume and the merging lane capacity. According to the results of their study, a Linear Programming (LP) model considering a *variable merging capacity* model is

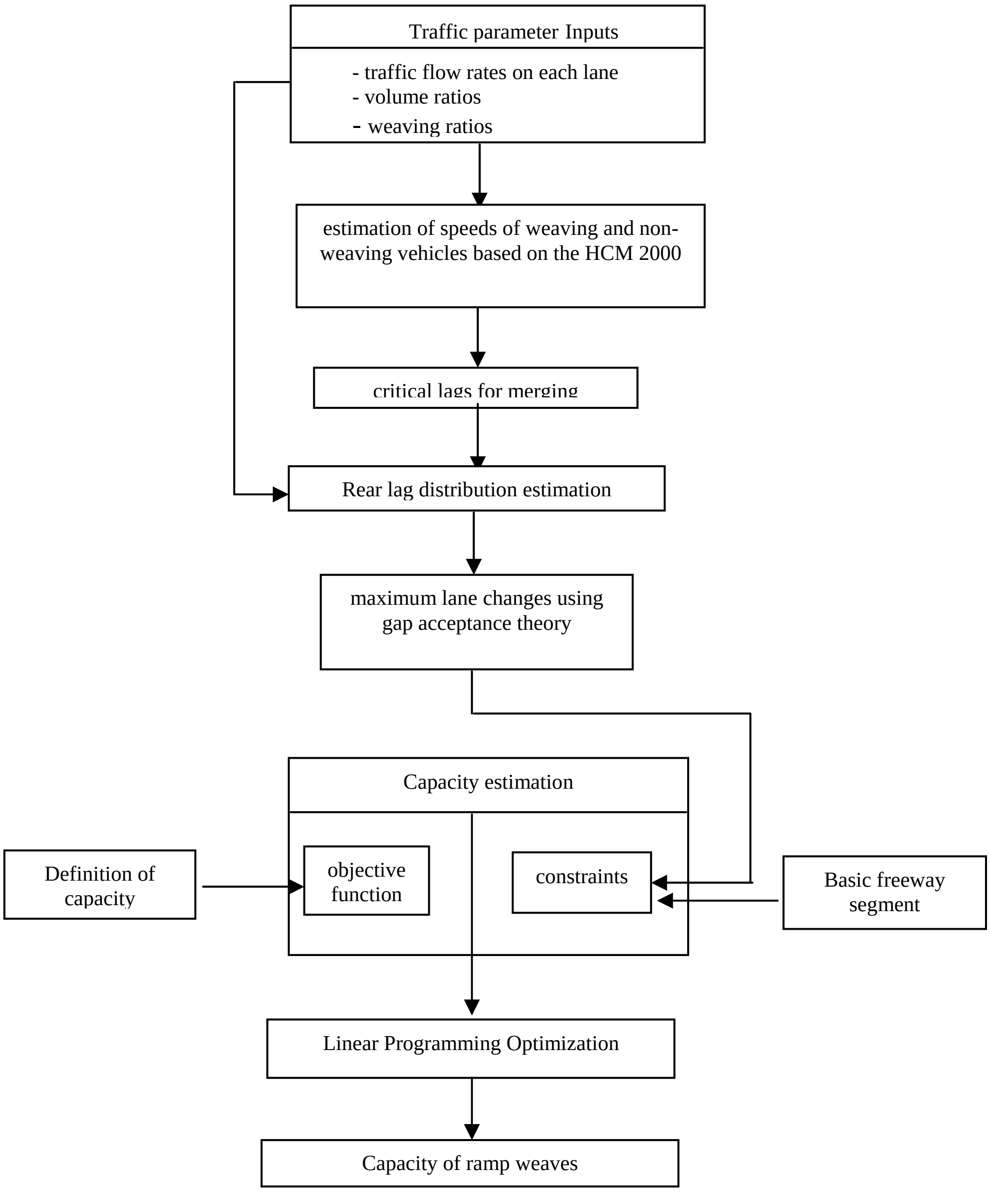



**Figure 2.4. Flowchart of the proposed methodology for the estimation of capacity at weaving sections (Source: Lertoworawanish and Elefteriadou (2003)).**

superior to the existing models in terms of good adaptability to the variation of traffic pattern at merge areas and the effectiveness of traffic operation due to less breakdown occurrences. A similar approach for estimating the capacity at merging areas based on the effective factors (e.g. on-ramp flow, flow of shoulder lane of mainline, critical gap, length of acceleration/deceleration lane) is proposed in this thesis. In such a case, micro-simulation tools, like SiMoNe (Minderhoud (1999)), will help to explore the impact of each of the individual factors on the capacity of merging/ diverging area.

## 2.7 Summary

This chapter gave an overview of the state-of-the-art of AHS with focus on truck automation. It addressed PATH and CHAUFFEUR as two major research projects focusing on AHS concepts. While the first research program considers trucks as a part of the integrated AHS concept, the second research study focuses on the operation of automatically controlled trucks (Tow-Bar trucks which are electronically coupled).

Review of the literature about the operation of automated trucks in mixed or segregated flow indicated that the application of dedicated lanes for automated trucks is essential. Then, in order to assess the access to the dedicated truck lane, it addressed two major options namely transition lanes and dedicated on-/off-ramps. Based on the main requirements for the operation of automatically controlled trucks on *existing motorways*, it came up with the conclusion that a dedicated on-/off-ramp would be more beneficial compared to applying transition lanes.

Then, we described the main difference between the traffic flow theory of automated vehicles and non-automated vehicles. It was explained that since the vehicles are under automatic control, a theory of AHS traffic flow will tend to be *prescriptive*. While, in non-automated vehicles the driver determines the vehicle's headway, its speed, its movement during a merge. Therefore, non-automated traffic flow theory is more *descriptive*, by contrast. Based on the benefit of operation of automated vehicles, this chapter addressed the possible extensions of the application of optimization algorithms in the design of road layouts and traffic flow control of automated vehicles.

We also then argued that the selection of microscopic or macroscopic approach of modelling the flow of automated vehicles depends on the specific objectives to be taken into account. It was addressed that the microscopic models will provide the possibility to distinguish among different combinations of trucks platooning more clearly, whereas, the macroscopic models provide the possibility to assess the impact of distribution of flow of automated trucks over all hours of the day. Thus, the integration of micro-simulation tools and optimization models was proposed as the proposed assessment tool in this thesis to provide adequate answers for key questions of this study. The proposed tool must meet the safety requirements of control of different kinds of vehicles and should demonstrate its potential to improve the efficiency of operations.

Briefly, the implications of the findings from the literature review for the current research are as follows:

- The high potential (but still uncertain) safety and throughput improvements from automation of trucks and the economic gains of the Tow-Bar system in the CHAUFFEUR project justifies more detailed analysis of impacts of operation of *fully automated trucks*;

- The results of the Combi-Road project implies the importance of the operation of fully automated trucks on existing motorways instead of the construction of an additional lane for the operation of fully automated trucks;

- In order to avoid the negative impacts of technical failures of the operation of fully automated trucks on motorway network links, the dedication of a lane to fully automated trucks is necessary;

- In order to ensure safety aspects at motorway network nodes (e.g. on-/off-ramps) additional traffic control measures needs to be investigated;

- The prescriptive nature of AHS traffic flow aims to extend the application of optimization models in the design of road layouts and traffic flow control of automated vehicles.

# 3
# Comparison of Motorway Ramp Design Options

## 3.1 Introduction

Automation of trucks can provide opportunities for a more efficient freight transport network. Continuous traffic flow, high reliability and savings on personnel costs for freight transport would be some of these advantages. In order to reach these purposes we need to provide the required facilities from different points of view. Otherwise, it may result in negative impacts on both traffic flow of MDVs and ACTs (Kanellakopoulos and Tomizuka (1997), Shladover (2001b)).

The previous chapter addressed the major studies performed in the ground of vehicle automation. It was indicated that nearly all of the previous researches have focused on isolated network of roads, in which the flow of automatically controlled vehicles are segregated from the flow of manually driven vehicles. Actually, a completely dedicated network of DFLs for transport of containers or other kinds of load-units seems infeasible in a larger network because of its extremely high costs and the risk of insufficient expected load.

Alternatively, automatic control of trucks on DFLs and assigning one lane of *existing ordinary motorway* to them might endanger the continuity of traffic flows and increase the risk of accidents at on-/off-ramps while merging or diverging the ACTs.

Therefore, the main aim of this chapter is to assess some major infrastructural requirements for controlling the traffic flow of ACTs upstream of on-/off-ramps while confronting with flow of MDVs. It will seek to provide adequate answers to the following questions:

- In what extent the dedication of a lane of existing motorways to the operation of ACTs would affect the flow of ordinary vehicles?

- Which lane of existing motorways (right lane or left lane) would be more efficient to be assigned to ACTs only?

- Which other infrastructural requirements would be needed for optimizing the flow of ACTs while interacting with the flow of MDVs at on-/off-ramps of motorways?

## 3.2 Creation of dedicated freight lane: The first key factor

Dedication of special lane(s) along existing sections of motorways to specific user groups such as ACTs could be achieved by converting a lane of the existing motorways. Figure 3.1 indicates a schematic layout of such a dedicated freight lane along an existing motorway including three lanes of which the shoulder lane is assigned to ACTs. Actually, a physically segregated truck lane is operated on the Rotterdam beltway (A16) in the Netherlands for the operation of ordinary trucks only.

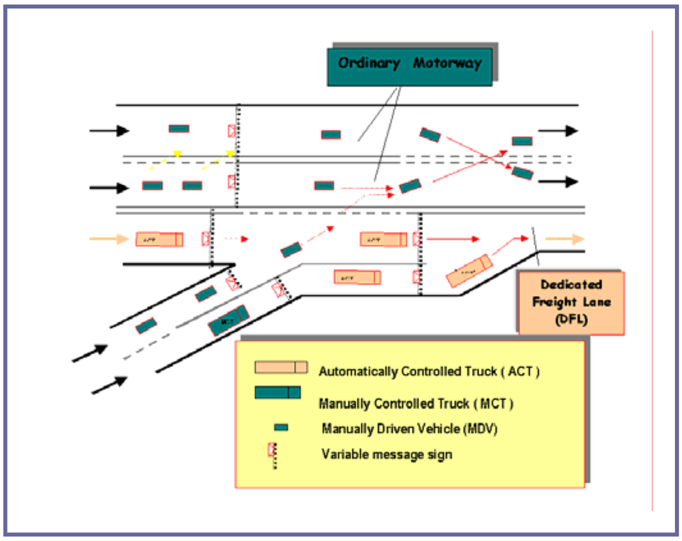



**Figure 3.1. A schematic layout of a dedicated freight lane**

Dedication of a lane to trucks would increase the flow homogenity for both users and non-users of Dedicated Freight Lanes (DFLs) on motorways, namely trucks as users of DFLs and the other user groups (mostly cars) as users of the rest of lanes. This segregation also would decrease the risk of collisions between trucks and cars in major parts of motorways. Moreover, it would lead to less hindrance of flow of ACTs by MDVs in major segments of motorways and consequently provide the required background for developing the specific control strategies applied for the operation of

ACTs (Minderhoud and Hansen (2001)). These control strategies will be discussed in the next chapter.

However, by converting one lane of an existing motorway to trucks only, the existing capacity for the traffic operation of other user classes would be decreased. This situation would increase the flow density of other user groups on non-DFL lanes and may decrease the level of service (LOS) of ordinary vehicles. In addition, since near bottlenecks (such as on-/off-ramps) traffic enters or exits, the other user classes may hinder or are hindered by the trucks. This process will differ for a dedicated lane on the left side (truck must cross the mainline) or on the right side (other user groups must cross the dedicated truck lane).

Therefore, it would be necessary to assess to what extent the performance, for instance total travel time of vehicles or total throughput, would be changed due to the assignment of one lane of motorway to the operation of trucks. Certainly, this dedication should be achieved in such a way that safe merging and crossing of vehicles can be assured. The assignment of the right hand lane to trucks would facilitate entering/exiting trucks to/from dedicated lane, but will increase the hindrance of flow of trucks travelling on DFL by cars using the on-ramp or the off-ramp, respectively. Conversely, considering the left hand lane as the dedicated freight lane may result in less interruption of flow of passing ACTs by other user classes, whereas the merging/diverging trucks would hinder the flow of passing MDVs on the mainline or will be hindered by them in successive on/off-ramps. Therefore, the assignment of the left lane to trucks may result in more dangerous situations due to frequent crossing/weaving of trucks with approaching cars on the mainline.

On current Dutch/European motorways trucks are not allowed to drive on the left (median) lane because they may hinder the flow of other user groups considerably. However, this would be a matter of discussion to what extent this hindrance would be expected if trucks drive on the dedicated lanes at the median lane and interrupt the other user groups only at on-/off-ramps of motorways while entering/exiting motorways. Moreover, if the speed of trucks could be harmonized with that of the other user groups upstream of on-/off-ramps then it might improve the level of safety in scenarios where the dedicated freight lane is located at the median lane. This synchronization of speed could be achieved by reducing maximum speed of cars to 80 km/h upstream on-/off-ramps. It seems that operation of fully automated trucks could facilitate such an opportunity.

In brief, the main aims of this chapter are:

(1) to determine whether a dedicated freight lane would improve the efficiency of existing motorways;

(2) to compare the effectiveness of the dedicated freight lane by assigning the right or left hand lane of existing motorways to the trucks;

(3) to assess the safety impacts of a dedicated freight lane, either in the right side or in the left side of existing motorways.

The first aim tends to determine the effectiveness of *creation* of a DFL, while the second aim will seek to specify the more appropriate *location* of a DFL (assignment of the shoulder lane or the median lane to trucks). At last, the third aim will assess *the safety aspects* of the assumed designs of DFL to ensure the required safety of road design and operation.

Concerning each of the above aims, in the next section, some scenarios have been developed and are evaluated by means of a microscopic simulation tool, named SiMoNe (Minderhoud (1999, 2001)). Throughout this thesis, SiMoNe is used as the main simulation tool because of the availability and proven performance from earlier research (Minderhoud (1999) which was validated and calibrated with regard to traffic characteristics of manually controlled vehicles and possibilities for inclusion of characteristics of advanced driver assistance systems (Minderhoud (2001)).

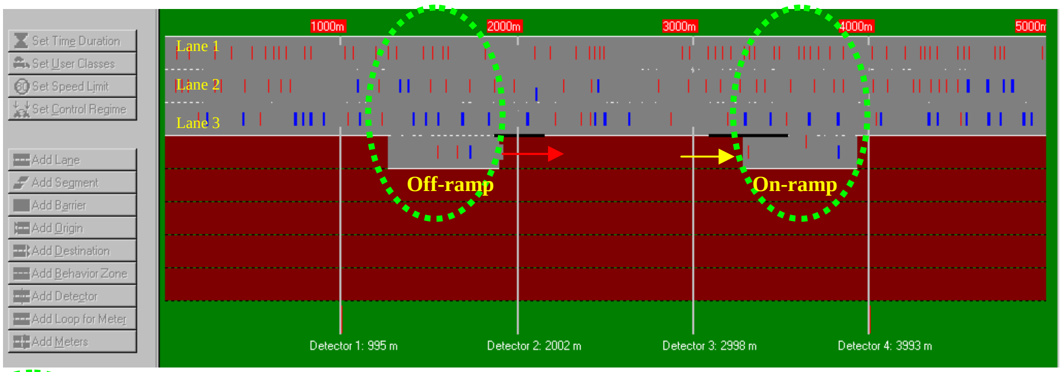
### 3.2.1 The proposed scenarios

The simulation study focuses on four different scenarios:

(I) Reference case, without lane change prohibition for trucks (RB scenario);
(II) Reference case, with lane change prohibition for trucks (RP scenario);
(III) DFL at the right-hand lane (shoulder lane) (DR scenario);
(IV) DFL at the left-hand lane (median lane) (DL scenario).

We focus on a motorway bottleneck (a section including an off-ramp and an on-ramp) with a three-lane mainline, since this layout is often found in the Netherlands. We also have assumed that all trucks driving on the DFL are automatically controlled (fully automated trucks). It means that a penetration rate of 100% is assumed for trucks, instrumented by automatic control systems. The lower penetration rates are not evaluated in this research study because in such a case the ordinary trucks will be driving on two remaining lanes (since the fully automated trucks should be completely segregated from other ordinary vehicles). Consequently, the expected economic gains would be too low to justify the operation of ACTs on DFLs.

The reference scenario represents the current situation with respect to road geometry. The geometric layouts of deceleration and acceleration lanes, as well as the location of detectors, as presented by SiMoNe, are shown in figure 3.2. Reference scenarios are applied in order to compare the other scenarios with a 'do-nothing' case. We have distinguished two types of reference scenarios: *with* and *without* a lane change prohibition for trucks. Both types will be evaluated in this analysis. We also have assumed that all trucks are




Possible bottleneck

**Figure 3.2. Road layout in reference case (screen picture from SiMoNe)**

*(I) Reference case without lane change prohibition for trucks (RB scenarios)*
This scenario represents the most usual situation of truck operations on motorways in most of the countries. In this scenario, trucks may drive on the right and center lane, so lane changes are allowed. Since trucks have the possibility to use the second lane then this scenario provides the maximum freedom of movement for trucks. Hence, the most uniform distribution of trucks and cars on the right and center lanes would be expected in this scenario.

*(II) Reference case with lane change prohibition for trucks (RP scenarios)*
This scenario represents the actual situation on a part of the motorway network in the Netherlands. In this scenario, the lane change prohibition is mandatory for all trucks driving on the right lane. Only passenger cars are allowed to pass trucks. In the simulation model this behavior has been modeled accordingly. Among the proposed scenarios, this scenario gives more freedom to the ordinary user groups (cars).

Contrary to the reference cases, in scenarios including a DFL, one lane of the motorway layout is assigned to trucks. In order to evaluate the impact of location of dedicated lane on the results of analysis, two scenarios are distinguished. In the first one, the shoulder lane is assigned to the trucks, while in the second scenario the median (left) lane will act as a dedicated lane for trucks.

*(III) DFL at the right-hand lane (shoulder lane)* ***(DR scenarios)***
In these scenarios the right hand lane (lane 3) of the motorway is dedicated to trucks. Therefore, cars can not use this lane and trucks can not use the other lanes. Consequently, the assumed flow of cars on this lane would be shared between the rest of lanes (lanes 1 and 2 in figure 3.3) and it may increase the level of congestion on these lanes. It is expected that this scenario only would facilitate the flow of trucks, but would have some negative impacts on the flow of cars. Segregating the flow of trucks from other user groups might produce a homogenous flow in major parts of the layout for trucks. Whereas, a higher number of crossings would be expected for the flow of passing trucks by other user groups diverging/ merging from/to mainline at off-/on-ramp sections (corresponds to actual situation or the other scenarios explained in the section b-2).

Moreover, each exit or entrance of other user groups would take place in two steps in a short distance: first diverge to the off-ramp at exits and then crossing the DFL (or vice versa for the mainline flow at on-ramps). This also would hinder the flow of passing trucks heavily and may cause congestion for the approaching trucks on the dedicated freight lane at these sections.

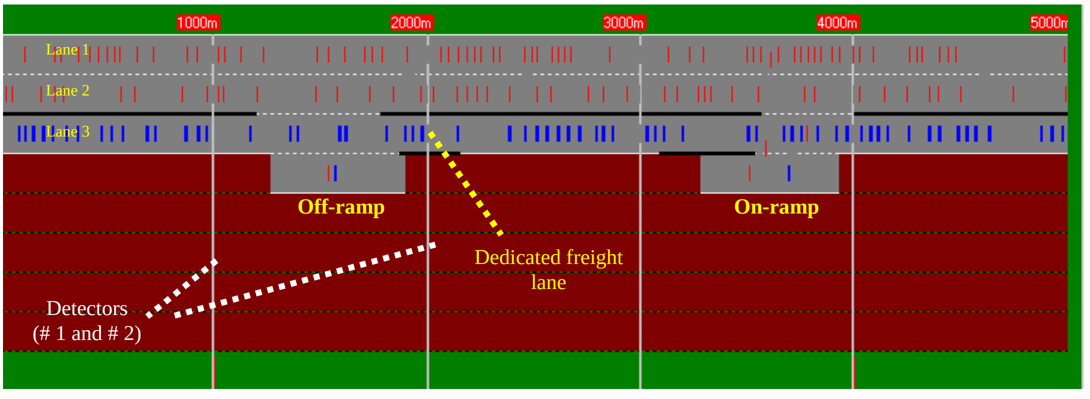



**Figure 3.3. Road layout of dedicated freight lane at the right-hand side of motorway (screen picture from SiMoNe)**

*(IV) DFL at the left-hand lane (median lane)* ***(DL scenarios)***

In these scenarios the left-hand lane is assigned to trucks, instead of right-hand lane. Therefore, cars can not use this lane and trucks can not use the other lanes. Figure 3.4 shows a schematic layout of these scenarios.

In such a case, only a few trucks leaving/entering the dedicated freight lane will affect the flow of cars. This design would certainly have a negative impact on the safety of approaching cars to the off-/on-ramp areas (conflicting with trucks exiting/entering the dedicated freight lane). Because, in these scenarios weaving of trucks of lower speeds from the left side/on-ramp (at off-/on-ramp areas respectively) compared to a higher speed of cars on the middle lane would increase the risk and severity of accidents. This lack of safety, due to high difference in speed of weaving trucks and cars, might be avoided by harmonizing the speed of trucks and cars upstream of on-/off-ramp areas. The reduction of maximum allowable speed of MDVS on mainline upstream of these sections, the application of variable message signs (VMS), and enhanced control of MDVs via applying an Intelligent Speed Adaptor (ISA) system would help to reach to this goal. Operation of automatically controlled trucks also would simplify to handle such a situation.

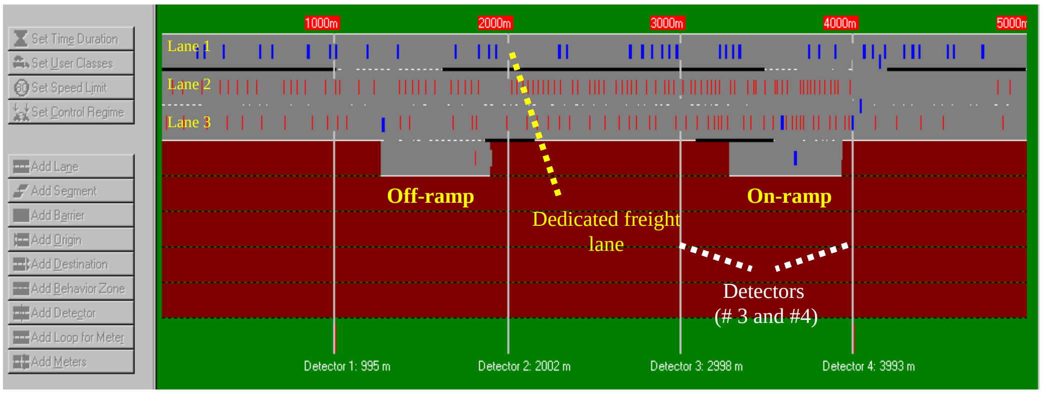



**Figure 3.4. Road layout of dedicated freight lane at the left-hand side of motorway**

In order to assess the impact of creation and location of DFLs and to describe the safety aspects of each of the proposed scenarios of design of DFLs, the next section presents a quantitative example in which all scenarios are analyzed by using a micro simulation program. It then evaluates the proposed scenarios from different points of view, like traffic operation, energy consumption and safety and comfort indicators.

### 3.2.2 Simulation setup

*Input data*

For reasons of simplicity it is assumed that there are only two user groups: cars and trucks. The total demand in vehicles is the same in all scenarios. Owing to the fact that in the scenarios with a dedicated freight lane the total number of cars should be assigned to two lanes, the total input flow (demand) on the mainline is assumed to be equal to 4000 veh/hr. This amount of flow is near the capacity of two lanes (since one lane will be dedicated to trucks in scenarios where there is a dedicated lane for trucks) and indicates a dense traffic (I/C=0.83 when the share of truck in the mainline flow is limited to 5%). The on-ramp flow is assumed to be equal to 1000 veh/h. To evaluate the impact of on-/off-ramp flow of trucks, different shares of trucks, e.g. 5, 10, 15, 20, and 25 %, in the mainline flow are tested. This heavily assumed traffic demand would reflect the expected traffic flow situations in which the potential benefits of automation of trucks need to be investigated. It also would provide the possibility to compare the scenarios with dedicated freight lanes with reference scenarios, more accurately.

The total simulation time is 4 hours per scenario to ensure reliable results of simulations. Moreover, detectors are provided to aggregate the recorded data per 5 minutes intervals. It means that during 4 hours simulation runs per scenario, there is a possibility to calculate the capacity about 48 times at bottlenecks (on-/of-ramps) to ensure reliable results of simulations.

The first part of the analysis is designed to assess the impact of change in share of trucks in both the mainline flow and the on-ramp flow. Thus, different shares of trucks (e.g, 5, 10, 20, and 40%) in the on-ramp flow are analyzed for each assumed share of trucks in the mainline flow (e.g. 5, 10, 15, 20 and 25%). In this part of analysis it is assumed that 10% of the mainline trucks exit the mainline flow at the off-ramp.

The second part of simulations assesses the impact of off-ramp flow of trucks on the efficiency of the proposed scenarios. Therefore, for each share of trucks in the mainline flow (e.g. 5, 10, 15, 20 and 25%) it is assumed that different percentages of trucks will exit from the mainline (e.g. 5, 10, 20, and 40 %). In these groups of scenarios, a share of 10% has been assumed for trucks in the on-ramp flow.

*Output data*

In order to evaluate each of the scenarios different performance indicators can be distinguished. These indicators can be categorized into three groups:

- the first group of indicators give information about the impact of the respected scenario on *traffic operation.* Measurement of queues during a run means that the demand has reached capacity. However, as it is possible that no queues are occurring *the total number of counted vehicles* during the simulation time is considered as an indicator for the throughput. *Total travel time* of vehicles over the road section or the average travel time of each user class may determine clearly the advantages or disadvantages of scenarios from this point of view;

- the second group provides more information about the comparison of scenarios from the *consumption of energy* point of view. In order to evaluate the scenarios, the criteria of 'average consumption of energy' for all vehicles and also for each user group have been calculated for each of the scenarios. Since this indicator is expressed by the absolute cumulative value of accelerations and decelerations during the total time of simulation, it also relates to the 'driver comfort'. It should be emphasized that the real consumption of energy is not sufficiently indicated by the above indicator. There may be some other indicators like variance of speed deviations which describe the consumption of energy in a better way, however, these indicators are not included here;

- the third group demonstrates the evaluation of each scenario from the *safety* point of view. In order to quantify the safety impact, the performance indicator of Time-To-Collision (TTC) has been determined for all scenarios. The frequency of creation of shock waves would be another indicator that can give a good sense for comparing the proposed scenarios from the safety point of view. However, this indicator is still not considered here.

### 3.2.3 Simulation results

The main simulation findings about all of scenarios will be discussed in this section. The analysis has been divided in two parts as explained before. The first part compares the proposed scenarios for different shares of trucks in the mainline flow and the on-ramp flow to assess the impact of flow of on-ramp trucks on the creation and location of a dedicated freight lane. The second part describes the results of simulation for scenarios in which the impact of change in share of trucks, in the mainline and also in the off-ramp flow of trucks, has been evaluated. All of the comparisons are made based on three groups of indicators: traffic operation indicators, energy and comfort indicators, and finally the safety indicators.

*Part 1- The impact of the on-ramp flow of trucks*

♦ **Traffic operation indicators**

*a) Capacity*
The results of simulation indicate that the assumed flow does not reach the capacity at most of the scenarios, which is a desired situation. The only exceptions are the following scenarios:

- RP scenario with simultaneously high shares of trucks in the mainline flow (25%) and the on-ramp flow (>20%);

- DR scenario with simultaneously high shares of trucks in the mainline flow (25%) and the on-ramp flow (>40%).

- DL scenario with a high share of trucks in the on-ramp flow (>20%);

- DL scenario with a moderate share of trucks in the on-ramp flow (10%) but low share of trucks in the mainline flow (5%);

In the DL scenario the capacity decreases about 8% - 40% depending on share of trucks in the mainline and the on-ramp flow. In these scenarios, the worst case would be related to situations where the share of trucks in the mainline flow is low (5%) and simultaneously a high share of trucks intend to merge to the DFL from the on-ramp (40%). In such a case the maximum hindrance of the on-ramp flow of trucks by the approaching cars on the mainline can be expected.

Comparing the DR scenario with the RP scenario indicates that the first scenario generally represents a higher capacity, especially in case of high share of trucks in the on-ramp flow (>20%).

Moreover, findings of the simulation indicate that none of the proposed scenarios lead to a higher capacity compared to the RB scenario.

Tables C.1 and C.2 in the Appendix C give more detailed information about the results of simulations for all proposed scenarios. In summary it can be concluded that:

- In case of low shares of trucks in the on-ramp flow (e.g. 5%), there is no meaningful difference among all proposed scenarios;
- In case of high share of trucks in the on-ramp flow (>200 trucks/h) the DL scenario can not compete with the other proposed scenarios;
- Generally, the DR scenario represents a competitive capacity compared to the reference scenarios.

*b) Travel time*

The results of simulation indicate that any RB scenario in combination with a low share of trucks on the on-ramp (< 5%) proves to be competitive. Generally, in case of a low share of trucks in the on-ramp flow (< 5%) the maximum increase in average travel time of vehicles in all scenarios would be limited by about 9%.

The results of simulations also indicate that in case of high shares of trucks in the on-ramp flow (>20%) the competitiveness of the DL scenario with other scenarios depends on the share of trucks in the mainline flow. In case of a low share of trucks in the mainline flow the DL scenario can not compete with the other scenarios, whereas in case of a high share of trucks in the mainline flow, the DL scenario even would represent a lower average travel time compared to the RP scenario (Figure 3.5).

The results of simulation also confirm that the DR scenario would allow less travel time of the vehicles compared to the RP scenario, at high shares of trucks in the mainline flow (> 20%). For instance, in case of a share of 20% trucks in the on-ramp flow and 25% in the mainline flow, the average travel time of vehicles in the DR and BP scenarios would increase by about 8% and 24%, respectively, compared to the RB scenario.

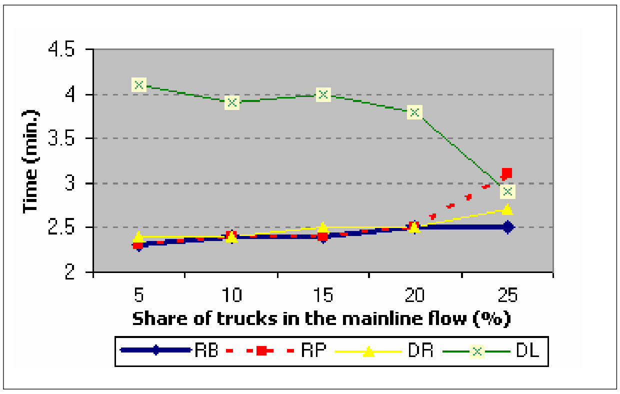



**Figure 3.5. Average travel time of vehicles in all scenarios**

Taking into account all scenarios and all percentages of trucks in the mainline and the on-ramp flow, the average travel time of vehicles for passing the assumed section of motorway (5 km.) would change between 2.3 to 6 minutes.

Taking into account trucks alone, it can be concluded that in case of low and moderate shares of trucks in the mainline flow (<20%), the RP, DR, and DL scenarios represent very similar results to the RB scenario. Whereas, at a higher share of trucks in the mainline flow (e.g. >20%), these scenarios can not compete effectively with the RB scenario (Figure 3.6).

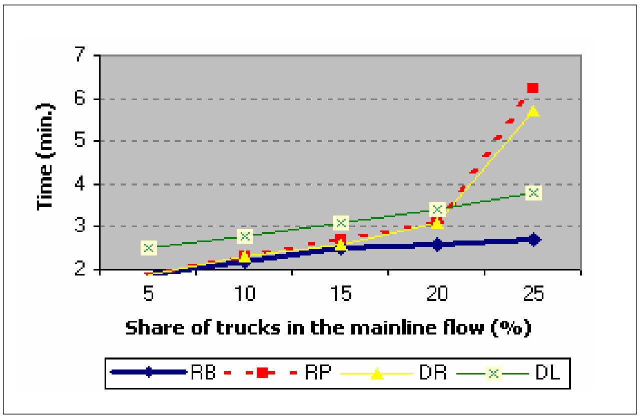



**Figure 3.6. Average travel time of trucks in all scenarios**

As it is indicated in the figure 3.6, in case of simultaneous high shares of trucks in the mainline and the on-ramp flow, the DL scenario requires less average travel time of trucks, compared to the BP and DR scenarios. It is due to less hindrance of flow of mainline trucks (trucks on the DFL) by cars which intend to exit the mainline.

*c) Throughput*

The throughput is a measure for the efficiency of a scenario. This indicator is, in ideal conditions, equal to the specified input, which is equal to 20,000 vehicles in 4 hours of simulation. However, due to the saturated traffic upstream the specified traffic input could not always be generated completely. Vehicles in the simulation are not generated at origins when there is no sufficient physical space (e.g. queuing). Figure 3.7 shows the results of simulation concerning this indicator for a high percentage of trucks in the on-ramp flow (e.g. 20%).

The results of simulation indicate that in case of low and medium shares of trucks in the on-ramp flow, independently from the share of trucks in the mainline flow, there is no considerable difference in throughput among all proposed scenarios. The maximum difference in throughput among all scenarios is limited to only 3%. By increasing the share of trucks in the on-ramp flow to 20%, the DL scenario would lead to a reduction of 8%-14% in total throughput compared to the RB scenario, whereas at a very high share of trucks in the mainline flow (25%) it achieves a higher throughput than the DL and RP scenarios.

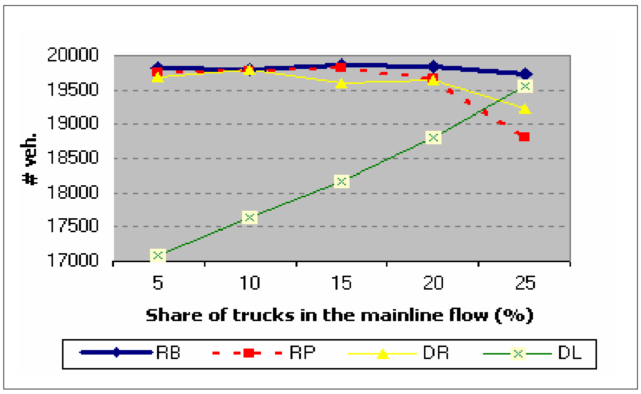



**Figure 3.7. Total throughput of vehicles in all scenarios (input = 20,000 veh.)**

This indicates the high degree of sensitivity of each of the proposed scenarios with regard to the share of trucks in both mainline and on-ramp flow. When the share of trucks in the on-ramp flow reaches about 25%, the DL scenario is not able to compete with other proposed scenarios. Interesting point is that in nearly all of the cases in which the share of trucks (in both the mainline and the on-ramp flow) reaches about 15%, the DR scenario leads to a higher throughput than the RP scenario. Moreover, in almost all cases the RB scenario still represents a higher throughput than the rest of the scenarios.

Comparing the same indicator for only trucks, it can be stated that in case of a low or moderate share of trucks in the on-ramp flow (5%-10%), the DFL scenarios (e.g. DR and DL) increase the throughput of trucks by about 10%, compared to the RB scenario. But, at high shares of trucks in the on-ramp flow (e.g. > 20%) the DL scenario mostly represents a lower throughput than the RB scenario. It is due to the higher frequency of hindrance of flow of on-ramp trucks by the approaching cars on the mainline. However, the DR scenario is really sensitive to the share of trucks in the mainline flow. The DR scenario can not compete with the RB scenario, in case of a simultaneous high share of trucks in the mainline flow and the on-ramp flow (e.g. 25% and 40% respectively).

As expected, in nearly all cases, the RP scenario represents a lower throughput of trucks than the DR scenario (by about 7%). It is due to the fact that the RB scenario creates the maximum constraint in freedom of movement of trucks (Figure 3.8).

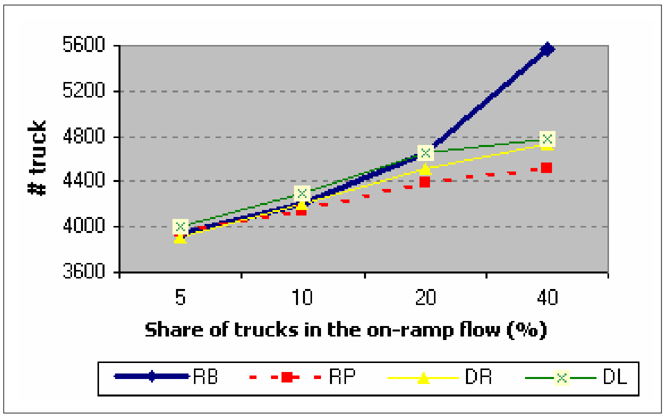



**Figure 3.8. Total throughput of trucks in all scenarios**

- **Energy and comfort indicators**

Another output of the simulation model is the total of summed absolute accelerations, on average per vehicle. This indicator gives a general idea about the changes of energy consumption and the comfort of the occupants of the vehicles; however, the rates of changes of acceleration and deceleration do not fully represent the degree of energy consumption. Tables C.1 and C.2 in the Appendix C give more detailed information about the absolute and comparative results of simulations for all options of analysis. Figure 3.9 indicates the average number of accelerations and decelerations of all vehicles (including both trucks and cars) for an option of analysis in which a low share of trucks in the on-ramp flow (e.g. 5%) is simulated.

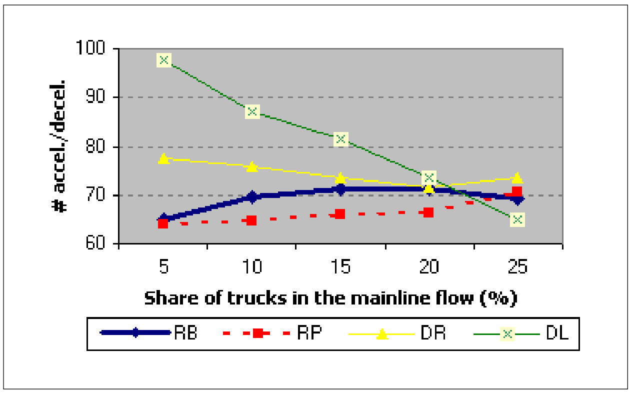



**Figure 3.9. Average number of accelerations and decelerations of vehicles in all scenarios**

This figure indicates that by increasing the share of trucks in the mainline flow, all related graphs of scenarios converge to each other. While in a low share of trucks in the mainline flow (e.g. 5%), the DFL scenarios (e.g. DR and DL) result in a higher number of changes in the accelerations and decelerations of vehicles compared to the reference scenarios (e.g. RB and RP), in a high share of trucks in the mainline flow (e.g. 20%-25%) all scenarios lead to a (relatively) equal number of accelerations and decelerations of vehicles (e.g. 70 times change). It also can be seen that the RP scenario mostly leads to minimum number of acceleration and deceleration changes of vehicles.

The results of simulation also reveals that the DL scenario only results in a reasonable number of acceleration and deceleration changes in case of a simultaneous high share of trucks in the mainline flow (e.g. 25%) and a low share of trucks in the on-ramp flow (e.g. 5%). Else, this scenario can not compete with the other scenarios.

Finally, it should be stated that except the case of simultaneous (very) high share of trucks in the mainline and the on-ramp flow, the DR scenario results in an increase of the average number of acceleration and deceleration changes by about 10%, compared to the RB scenario. It means that the dedication of the shoulder lane of the motorway to the operation of trucks only can be considered as a competitive solution for the reference scenarios.

Figure 3.10 indicates the findings of simulation for trucks, separately, in case of a high share of trucks in the mainline flow (e.g. 20%). Focusing on the DR scenario indicates that in nearly all cases the respected graph of this scenario has been located between the graphs of two reference scenarios. It means that the DR scenario provides a better result compared to the RP scenario, while it would not act better than the RB scenario.

Results of simulation also reveal that in case of low shares of trucks in the on-ramp flow (e.g. 5%- 10%) the DL scenario acts as the best scenario. Since, in such a case, a minimum hindrance of flow of trucks by cars would be experienced. However, by increasing the share of trucks in the on-ramp flow (e.g. 40%) this scenario becomes the worst scenario.

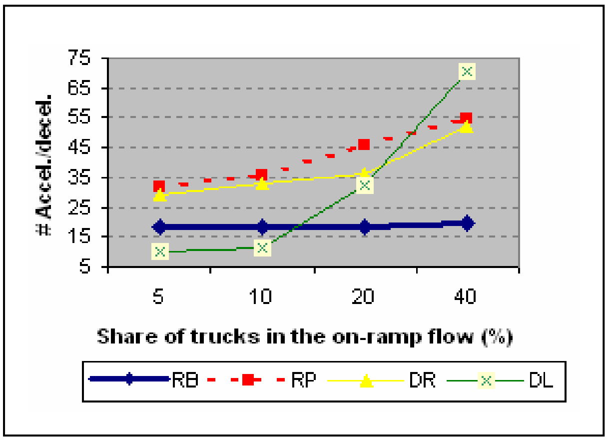



**Figure 3.10. Average number of accelerations and decelerations of trucks**

- **Safety indicator**

The TTC indicator is used to compare different scenarios from the safety point of view. According to Hoogendoorn and Minderhoud (Hoogendoorn and Minderhoud (2001)) TTC values smaller than 1.5 seconds can be considered as an unsafe situation, while TTC values between 1.5 and 3 seconds may be interpreted as uncomfortable. The higher the frequency of smaller values of TTC the higher the risk of an accident. Hence, the total time during a simulation in which the TTC values become less than 1.5 s (or similarly between 1.5 s and 3 s) can be compared in all scenarios.

The results of simulation indicate that in case of a low share of trucks in the mainline flow the DL scenario results in the most unsafe scenario. Whereas, by increasing the share of trucks in the mainline flow (e.g. >15%) the competitiveness of this scenario with the other scenarios depends on the share of trucks in the on-ramp flow. Figure 3.11 shows that in a case of 25% share of trucks in the mainline flow, the DL scenario only could compete with the other proposed scenarios when the share of trucks in the on-ramp flow is limited by about 10%.

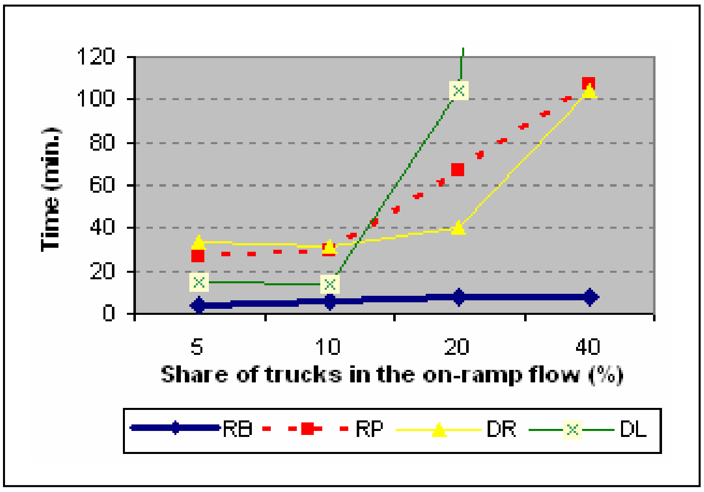



**Figure 3.11. Total times of simulation with TTC<1.5 sec.**
**(in case of a high share of trucks in the mainline flow)**

The above figure also indicates that the DR scenario represents a safer situation compared to the RP scenario in case of higher percentages of the on-ramp flow of trucks. However, the RB scenario in all cases represents the safer situation.

A similar order of graphs is achieved when the TTC values between 1.5 s and 3 s are reported. Therefore, a similar explanation can be applied to compare all scenarios from this point of view.

Tables C.1 and C.2 in the Appendix C present an overview of the results of simulation (absolute and comparative values) for all above indicators.

The following part of this section represents the results of simulation for the analysis of the impact of off-ramp flow of trucks. All proposed scenarios are compared with each other with respect to the different indicators described in the previous section. This analysis is made to evaluate the impact of the off-ramp flow of trucks on the performance of each of the proposed scenarios.

*Part 2- The impact of the off-ramp flow of trucks*

- **Traffic operation indicators**

*a) Capacity*

The results of simulation indicate that even at a very low share of trucks in the mainline flow (e.g. 5%) the assumed flow in the DL scenario reaches capacity. It is noted that the first hindrances start at the merging area (Figure 3.12). Then the queue of cars, hindered by the crossing flow of trucks at the merging area, is extended to the off-ramp area. Consequently, the exit of trucks at the off-ramp becomes more difficult.

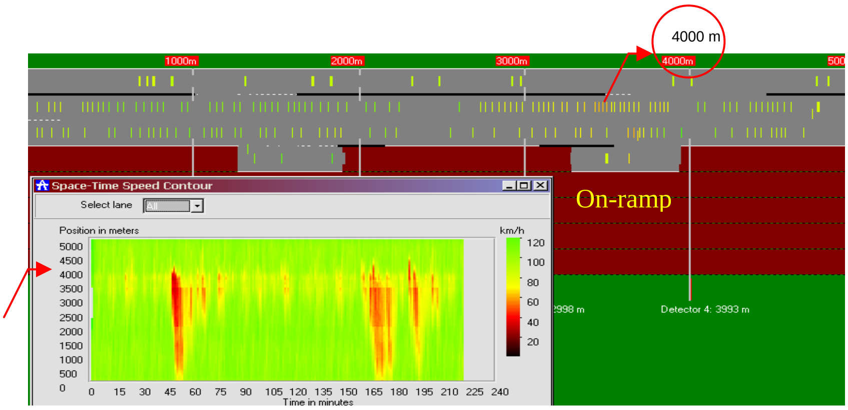



**Figure 3.12. The speed-space graph for the DL scenario**
(at a low share of trucks in both mainline and off-ramp flow of trucks)
**(screen picture from SiMoNe)**

Also, in case of a very high share of off-ramp trucks (e.g. 40%) the flow in the DL scenario reaches the capacity. The high number of trucks leaving the DFL causes a queue of vehicles in the off-ramp area (Figure 3.13).

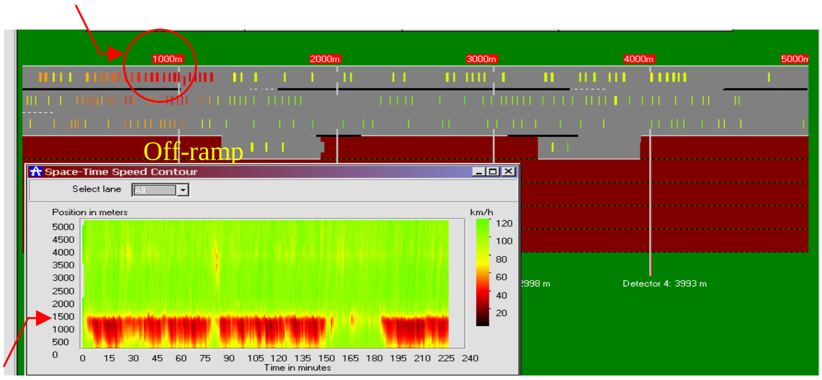



**Figure 3.13. The speed-space graph for the DFL-L scenario**
(at a high share of off-ramp trucks (e.g. 40%)
**(screen picture from SiMoNe)**

Hence, the DL scenario is not a competitive scenario in the two following cases: (a) at a very low share of trucks in the mainline flow; and (b) at a very high share of trucks exiting from the mainline (DFL). Generally, a decrease of 8% - 23% in capacity, compared to the RB scenario is then expected.

The results of simulation also indicate that in nearly all cases the flow in the DR scenario does not reach the capacity. The only exception is related to the case in which high percentages of trucks in the mainline flow are expected (e.g. 25%), while a low share of the trucks is going to exit from the DFL (e.g. 5%). In this case, a higher number of trucks passing the off-ramp area are hindered by the flow of cars exiting from the mainline. Similar results exist for the RP scenario, where the capacity decreases by about 10%.

An overview of results of simulation for all options of analysis (different percentages of trucks driving on the DFL and exiting from the DFL) is given in tables C.3 (absolute values) and C.4 (comparative values) in the Appendix C.

*b) Travel time*
The results of simulation indicate that at a low share of trucks in the mainline flow (e.g. 5%) the DL scenario leads to an increase of 4% - 22% in average travel time of vehicles, independently from the share of trucks exiting the mainline (DFL) flow. In such a case, the DR scenario also shows higher values of average travel time of vehicles. However, by increasing the share of trucks in the mainline flow by about 20%, as it is indicated in figure 3.14, the average travel time in almost all scenarios is more or less the same, specially at lower shares of off-ramp trucks (e.g. <10%).

The comparison of travel time of each user group indicates:

*for cars*

- the higher the share of trucks in the mainline flow, the less the difference in average travel time of cars between the DFL scenarios and the reference scenarios;

- in case of a high share of trucks in the mainline flow (e.g. >20%), the DR scenario acts very similar to the reference scenarios.

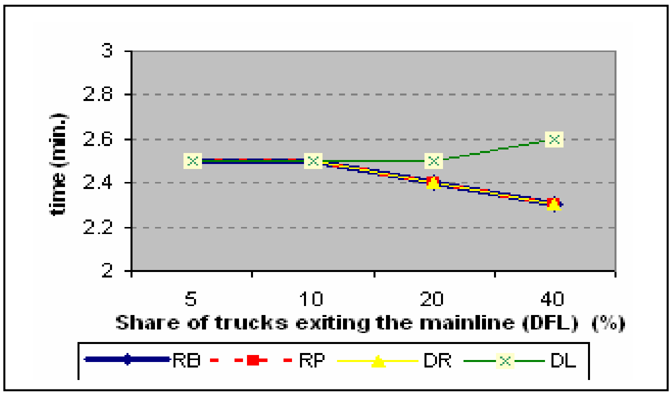



**Figure 3.14. Average travel time of vehicles**
**(at a high share of trucks in the mainline flow)**

*for trucks*

- in case of a low share of trucks in the mainline flow (e.g. 5%), by increasing the share of off-ramp trucks, the DL scenario is not competitive with the other scenarios, since in such a case the off-ramp flow requires more time to exit from the DFL. However, when increasing the share of trucks in the mainline flow, the DL scenario causes less hindrance for those trucks which pass at the off-ramp area.
- in case of a high share of trucks in the mainline flow (for instance >20%), the DR scenario results in a higher travel time of trucks compared to the DL scenario if there is a lower share of trucks exiting the DFL (e.g. <20%). In case of a high share of trucks exiting the DFL (e.g. >20%) the DR scenario leads, of course, to a lower average travel time of trucks compared to the DL scenario.

*c) Throughput*

Figure 3.15 provides the results of simulation concerning the throughput indicator for a high percentage of trucks in the mainline flow (e.g. 25%).

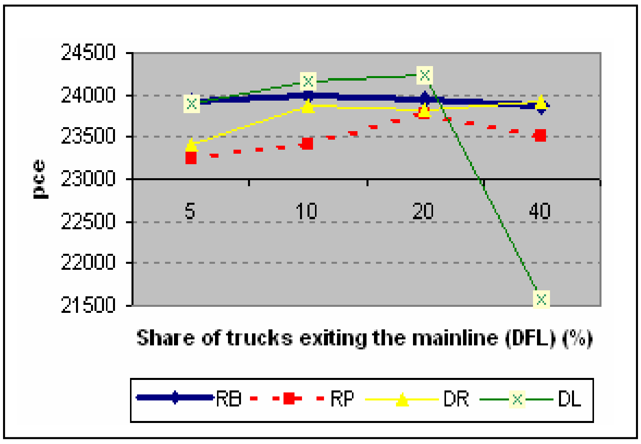



**Figure 3.15. Throughput of vehicles**
**(at a high share of trucks in the mainline flow)**

The above figure illustrates that in case of a high share of trucks in the mainline flow (e.g. 25%), the DL scenario mostly results in a competitive throughput, compared to other scenarios. However, by increasing the number of trucks exiting the mainline (DFL) by about 40%, this scenario leads to a decrease of 10% in total throughput (compared to other scenarios). The results of simulation show that in case of a low share of trucks in the mainline flow (e.g. 5%) the DL scenario can not compete with other scenarios, too.

The findings of simulation also indicate that nearly at all percentages of trucks in the mainline and exiting flow of trucks from the DFL, the DR scenario presents a similar throughput, compared to the reference scenarios.

Taking into account trucks alone, the results of simulation indicate that by increasing the share of trucks in the mainline flow by about 15%, the DFL scenarios lead to an increase of 9% in the throughput of trucks, compared to the RB scenario. However, in a simultaneous high share of trucks in the mainline flow (e.g. 25%) and the off-ramp flow (e.g. 40%) the DL scenario results in a decrease of 9% compared to the RB scenario.

- **Energy and comfort indicators**

Figure 3.16 indicates the results of simulation indicating average number of accelerations/ decelerations per vehicle, for a low share of trucks exiting the mainline flow (DFL) (e.g. 10%) in all scenarios.

When the share of trucks leaving the mainline (or DFL) is limited to about 10%, the DL scenario is not competitive with the rest of the scenarios. Only when the share of trucks in the mainline flow reaches about 25%, it represents a similar number of changes in accelerations and decelerations.

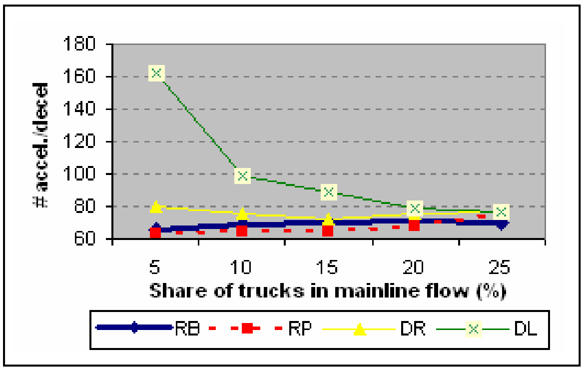



**Figure 3.16. Average number of changes in accelerations and decelerations of vehicles**

The findings of simulation also indicate that the DR scenario is not competitive with the reference scenarios, only in cases with a very low share of trucks in the mainline flow (e.g. 5%). In such cases, the DR scenario leads to an increase of about 25% in the number of changes in the accelerations and decelerations of vehicles, compared to the reference scenarios.

Table 3.1 provides an overview of the comparative results of simulation for a case of low share of trucks in the exiting flow (e.g. 10%). It provides the possibility to compare the effectiveness of each of the scenarios compared to the RB scenario, for options in which *all vehicles* or *trucks* (separately) are taken into account. It reveals that while a scenario may not lead to the competitive results with the other scenarios in cases which all vehicles are taken into account, it might lead to the best results when a specific user group (e.g. trucks) is the main focus of design. For instance, in case of a share of 15% for trucks in the mainline flow, the DL scenario leads to the worst result, compared to other scenarios. This table indicates that the average number of acceleration and deceleration changes of all vehicles in this scenario increases about 26%, compared to the RB scenario. Whereas at the same share of trucks in the mainline flow (e.g. 15%) this scenario results in the minimum number of changes of acceleration and deceleration of trucks, compared to other scenarios. This table reveals that a reduction of 34% of changes of accelerations and deceleration of trucks in this scenario can be expected (compared to the RB scenario).

**Table 3.1. Changes in accelerations and decelerations of vehicles and trucks compared to the RB scenario (RB Scenario Index= 100)**

| Indicator | Share of trucks in the mainline flow (%) | Share of trucks leaving the mainline flow (%) | | | |
|---|---|---|---|---|---|
| | | 10 | | | |
| | | RB sce. | RP sce. | DR sce. | DL sce. |
| Average energy consumption of **vehicles** | 5 | 100 | 97 | 122 | 246 |
| | 10 | 100 | 93 | 109 | 143 |
| | 15 | 100 | 92 | 103 | 126 |
| | 20 | 100 | 96 | 106 | 110 |
| | 25 | 100 | 108 | 111 | 111 |
| Average energy consumption of **trucks** | 5 | 100 | 105 | 104 | 141 |
| | 10 | 100 | 129 | 118 | 71 |
| | 15 | 100 | 155 | 155 | 67 |
| | 20 | 100 | 197 | 183 | 64 |
| | 25 | 100 | 322 | 232 | 78 |

♦ **Safety indicator**

The findings of simulation indicate that in case of a low share of trucks in the mainline flow (e.g. 5%), the DL scenario leads to much more dangerous situations compared to the other scenarios. Only in case of a high share of trucks in the mainline flow (e.g. 25%), the DL scenario may be considered safer than the RP and DR scenarios except when very high percentages of trucks intend to exit from the DFL (figure 3.17). The higher the share of trucks leaving the mainline, the less the number of dangerous situations in the DR scenario in case of a higher share of trucks in the mainline flow. The simulation findings indicate a similar trend for the TTC values between 1.5 s and 3 s which represent the uncomfortable gaps between vehicles in all options of analysis.

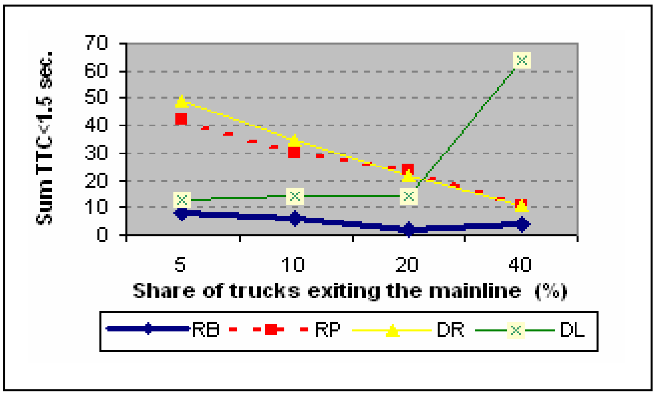



**Figure 3.17. Total times with TTC<1.5 s**
**(at a high share of trucks in the mainline flow, e.g. 25%)**

A more detailed information about the results of simulation for all above indicators (absolute and comparative values respectively) can be found in tables C-3 and C-4 of Appendix C.

### 3.2.4 Impact assessment: conclusions from simulation study

Taking into account the different measures of effectiveness and shares of trucks in the traffic flow (the mainline, on-ramp and off-ramp), the evaluation of design alternatives concerning the creation and location of dedicated freight lanes should be based on the following:

- In case of low shares of trucks (<10%), the construction of DFL for trucks only, does not make sense;
- The location of the DFL at the median (left) lane of the motorway is disadvantageous if dedicated (grade-separated) on-/off-ramps for trucks are missing, specially at high rates of on- and/or off-ramp flow of trucks;
- The location of the DFL at the shoulder (right) lane of the motorway is the most competitive solution with the reference scenarios if no grade-separated on-/off-ramps for trucks can be provided, specially in case of a high share of trucks in the mainline flow (e.g. >20%) and at higher flows of on- and/or off-ramp flow of trucks (150-200 trucks/hour).

Although the construction of ramps for ACTs alone would be expensive, it might avoid waiting time of ACTs at on-/off-ramps due to secondary congestion at on-/off-ramp areas. It also should be noted here that a dedicated lane for trucks, alone, will not be sufficient for an efficient operation and control of ACTs. The next section will introduce another key facility required for the operation of ACTs on DFLs aimed at reducing the hindrance of flow of MDVs at on-/off-ramps.

## 3.3 Buffer areas: The second key factor

### 3.3.1 Definition

Originally, buffer areas were introduced as a new element in Dutch motorways in order to reduce congestion (Schuurman and Westland (1996), Rijkswaterstaat (1997)). A buffer is a section of a motorway locally widened by one or more lanes in order to provide additional space for vehicle queues by increasing its density. The reduction of (secondary) traffic congestion stems not only from the capacity of additional lanes, but also from the higher density in the queues. The packing of vehicles at low speed shortens the length of queues and prevents the spill back to upstream on-/off-ramps and junctions. One of the main advantages of buffer areas consists in a much easier creation of dedicated lanes for specific user groups (Hansen and Westland (1998)). Figure 3.18 indicates schematically how a buffer area would reduce the congestion, caused by the propagation of queues to the previous on-/off-ramps on motorways.

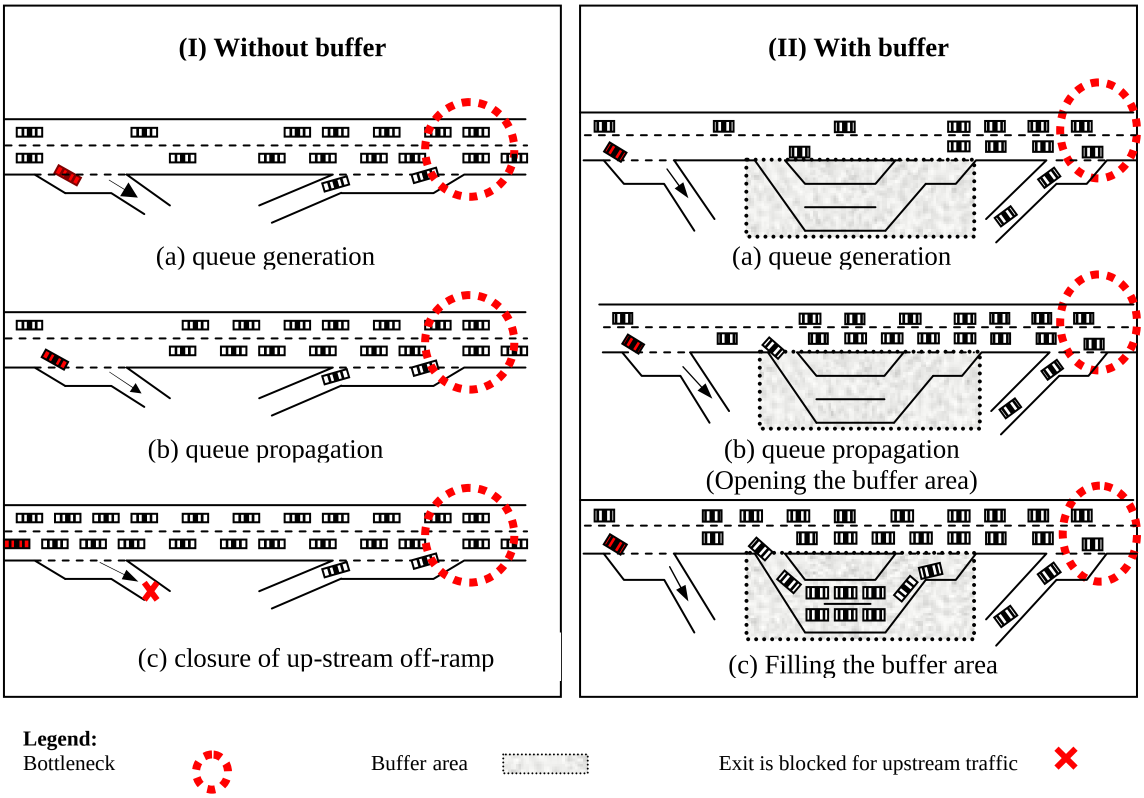



**Figure 3.18. Basic function of a buffer area**

The required length of a buffer area, corresponding to a time loss of 15 minutes in traffic congestion, is given in table 3.2 (AVV (1997)).

**Table 3.2. Length of a buffer area, corresponding to a time loss of 15 minutes (Source: AVV (1997))**

[Km]

| Number of lanes in buffer | (Number of lanes in the bottleneck) Capacity of bottleneck (veh/h) | | | |
|---|---|---|---|---|
| | (1) 1800 | (2) 4200 | (3) 6500 | (4) 8400 |
| 1 | 3 | 5 | 9 | 10 |
| 2 | 1.6 | 3 | 4.5 | 6 |
| 3 | 1.1 | 2 | 3 | 4 |
| 4 | 0.8 | 1.6 | 2.5 | 3 |
| 5 | 0.65 | 1.3 | 2 | 2.5 |
| 6 | 0.5 | 1.1 | 1.7 | 2.1 |

Figures 3.19 presents two different arrangements of a mainline buffer area, based on available space (length or width) along motorways. The mainline buffer provides the possibility to control the input flow approaching to a bottleneck to reduce the congestion severity. A mainline buffer can be assigned to all user groups, or to a specific user group like trucks. Since a mainline buffer normally includes more than one lane, it would be necessary to apply traffic signals at exit points of the buffer area to control the input flow of vehicles to the bottleneck section. This control on the mainline will be achieved by applying Variable Message Signs (VMS) or traffic lights.

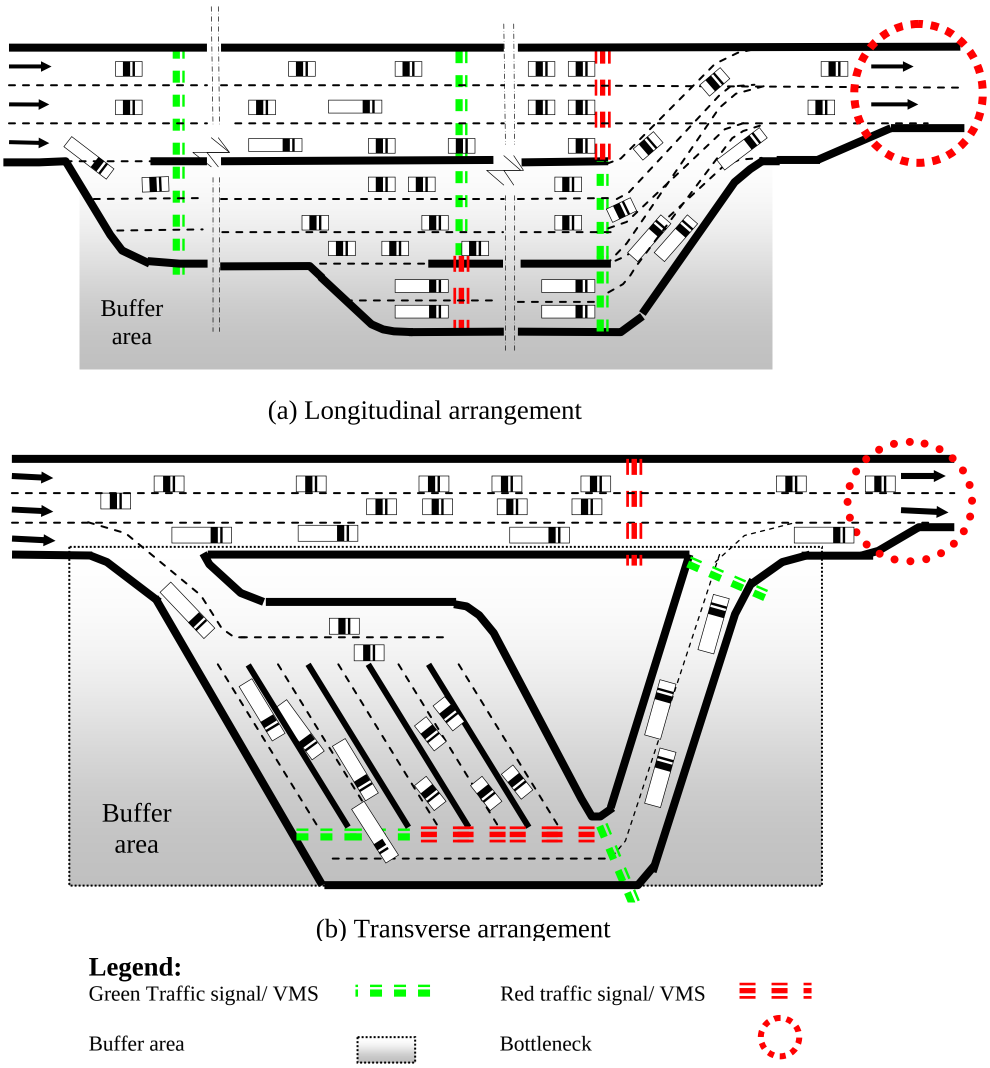



**Figure 3.19. Schematic layouts of buffer areas**

Thus, in traffic flow of ordinary vehicles, a buffer area would only avoid the propagation of a queue to the previous on-/off-ramps. It would not be able to avoid congestion at bottleneck, since the input flow to the bottleneck would not change.

### 3.3.2 Buffer areas for Automatically Controlled Trucks

The ACTs approaching on a DFL to a bottleneck like on-/off-ramps may hinder (or be hindered by) the flow of MDVs at on-/off-ramp areas. Therefore, the input flow of vehicles to the on-/off-ramp areas has to be controlled by traffic means in order to avoid accidents and minimize congestion.

The main difference to the operation of buffer areas for manually controlled vehicles is that here a group of vehicles (ACTs) can automatically be controlled (ACTs) with respect to volume, speed and density. This may enable to decrease traffic congestion upstream bottleneck.

Actually, in the ordinary state of traffic flow, traffic control messages (like VMS or DRIPs[1]) and decisions of the drivers are two mutually interfering processes with different objectives. While traffic control messages aim at creating optimal conditions for a whole network (or at least the optimum local situation), drivers mostly try to look for their personal benefit and do not follow always the instructions of the traffic control center. It is one main reason why a buffer area in the ordinary state of traffic flow has no influence on the capacity of the bottleneck itself.

The existence of buffer areas for the operation of vehicles on both DFLs and on-ramps may control efficiently the input flow of vehicles approaching to on-/off-ramps and will provide the possibility to split the traffic flow into different user groups which may be processed separately. To reach to such a goal, three kinds of buffer areas can be distinguished:

- *Mainline buffers* for ACTs located on the DFL nearby on-ramps,
- *On-ramp buffers* located on on-ramps for ACTs and MDVs separately,
- *Off-ramp buffers* for ACTs located on the DFL upstream off-ramps.

A *mainline buffer* aims to provide the possibility for reserving a part of the ACTs approaching upstream of on-ramps in order to control the total flow of ACTs on the DFL at individual on-ramps according to the desired level of service. In such a case, the mainline buffer acts as an intermediate parking area for a part of ACTs (Figure 3.20). During off-peak periods, when the volume of MDVs on the on-ramp is lower, ACTs that are parked in the buffer area enter directly (in form of platoons[2] or individual ACTs) to the DFL. Of course, these ACTs may experience delays before entering the DFL.

A mainline buffer consists of three parts: the entry, the platooning section, and the exit. When an individual ACT enters the buffer area, first the automatic control system of the ACT is checked whether it works correctly or not. If the communication system of the ACT works well, then the ACT gets permission to proceed to the platooning section. Otherwise, the ACT could not operate on the approaching DFL. In case of proceeding to the platooning section, according to a pre-defined slot that depends on the trip destination of the ACT, it joins one of the platoons of ACTs waiting for merging to the DFL. The slots of platoons of ACTs are determined on the basis of an analysis of the actual traffic flow (for both ACTs and MDVs) and the available capacity at the merging area as well as the downstream links. If a platoon receives the green signal for merging to the DFL, the platoon of ACTs will be checked out at the exit section of the buffer area and merge into a gap between passing platoons of ACTs. A maximum limit can be defined for waiting time of ACTs in buffer areas. This maximum assumed waiting time

[1] Dynamic Route Information Panels

[2] In platooning operations, vehicles are clustered together in groups of vehicles, in which vehicles within each group follow each other with a very short spacing, whereas a longer spacing between two successive groups of vehicles is maintained. This concept and its benefits will be explained more in detail in the next chapter.

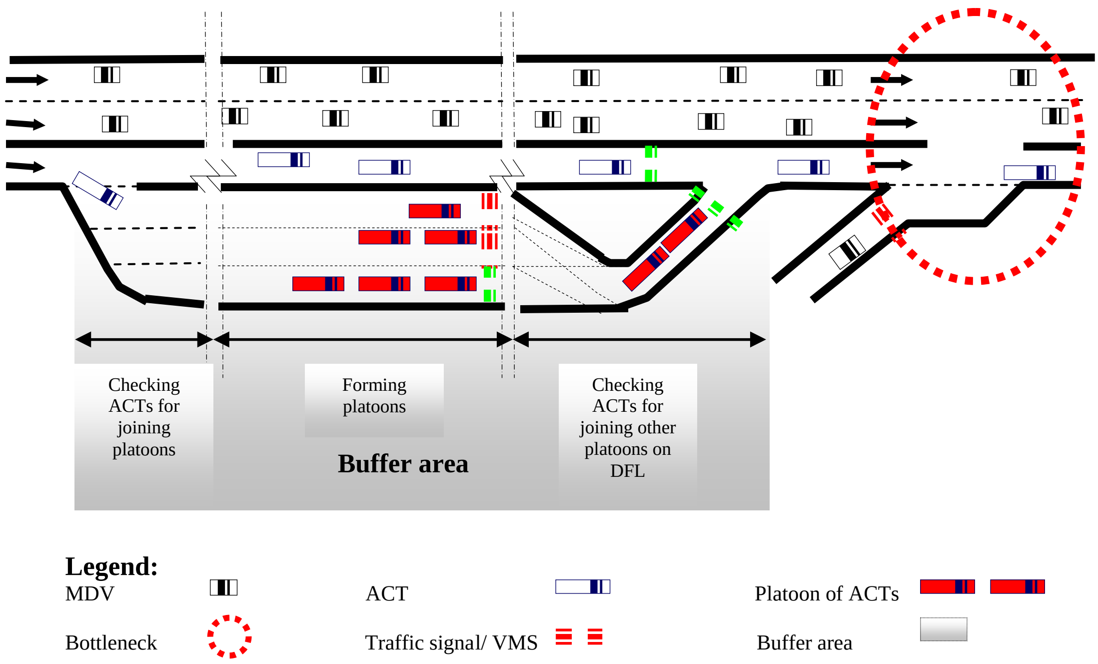



**Figure 3.20 A typical layout of a mainline buffer for ACTs**

of ACTs in buffer areas depends on various factors like the traffic demand of ACTs and MDVs upstream of a bottleneck, the provided capacity at the on-/off-ramp, etc.

The mainline buffer may also be combined with a buffer area located at the entrance point of on-ramps. In such an *on-ramp buffer*, would help to control the input flow of ACTs which were operated manually on the trip from their origin to the on-ramp via ordinary roads, would be controlled before entering to the mainline (DFL). The on-ramp buffer for ACTs also acts as a transition area for changing the mode of driving of ACTs from manual to automatic mode. Similar to the ordinary buffers, an on-ramp buffer can be applied for MDVs on the on-ramp to avoid spill back of queues of MDVs waiting on the on-ramp for merging to the mainline flow.  Figure 3.21 indicates a schematic layout of on-ramp buffers for ACTs and MDVs.

In order to avoid or reduce traffic congestion at off-ramps, a similar design of buffer areas is possible for off-ramps. The *off-ramp buffer areas* may be located directly at the off-ramp or on the DFL just upstream of the off-ramp. Since in the off-ramp buffers a part of the ACTs would leave the DFL in order to continue its trip via the off-ramp and ordinary roads to their final destination, the mode of driving of the ACTs, from automatic to manual needs to be changed. The other part of ACTs continuing their trip on the DFL, might be hindered by the flow of exiting cars from the mainline. Therefore, it might necessary to accommodate extra space in the off-ramp buffer (or the mainline buffer located further upstream of the off-ramp) to split the platoons of ACTs approaching to the off-ramp area. Figure 3.22 indicates a typical layout of an off-ramp buffer.

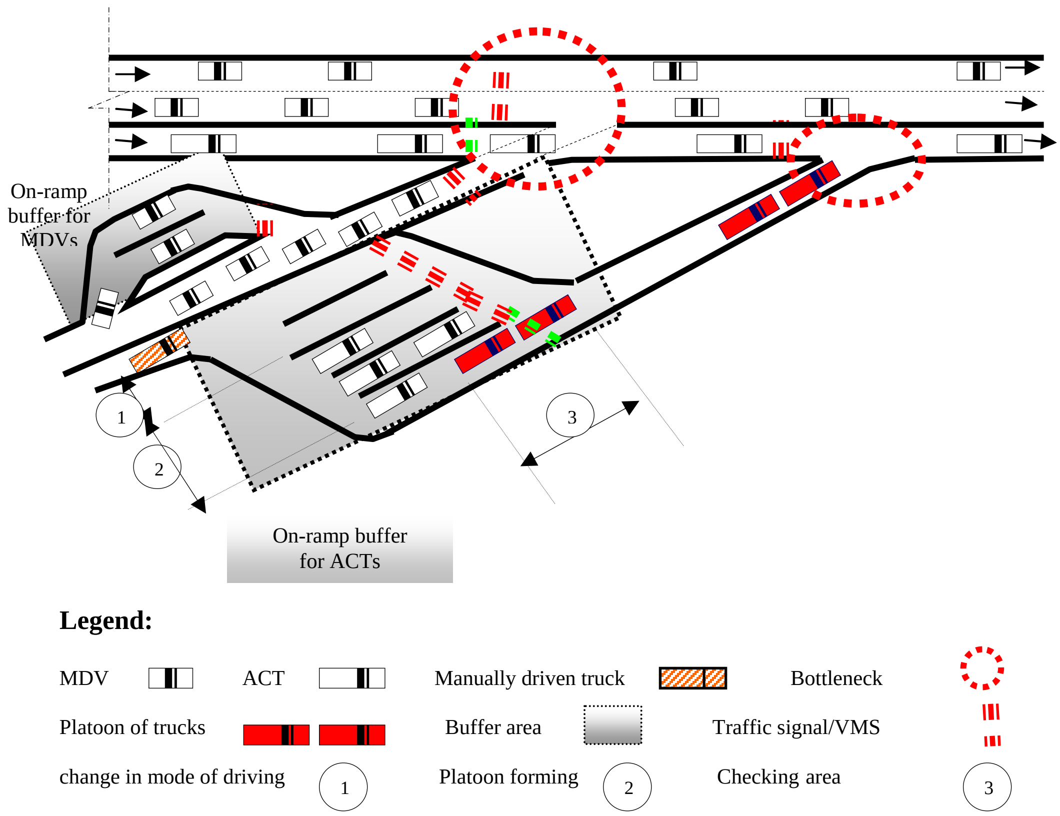



**Figure 3.21. A typical layout of the on-ramp buffer for ACTs and MDVs**

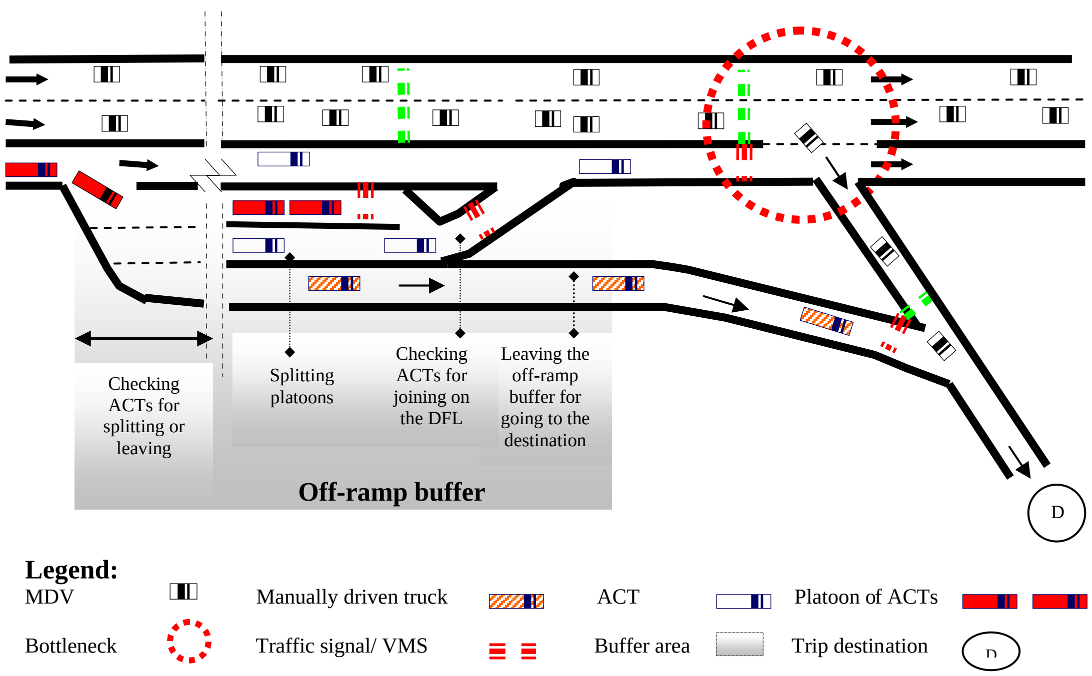



**Figure 3.22. A typical layout of an off-ramp buffer for ACTs**

Thus, all kinds of buffer areas aim to minimize the delay for the whole of traffic (including ACTs and MDVs) at on-/off-ramps of motorways. The buffers designed for ACTs also provide the possibility for changing the control mode of driving of ACTs from manual to automatic and vice versa. At the same time, buffer areas could simplify the dynamic traffic management of the ordinary motorway during peak periods. They may allow MDVs to use them, temporarily, during peak periods of freight traffic or reserve ACTs, temporarily during peak periods of ordinary traffic, to allow MDVs drive on the DFL for a certain time period. Mixed operation of ACTs and MDVs on DFL is not investigated in this thesis.

## 3.4 Summary

In brief, this chapter addressed two major design options for the operation of ACTs driving on DFLs and control of traffic flow of ACTs and MDVs at on-/off-ramp areas. The first design option is the possibility of creating a dedicated lane of existing motorways for ACTs, while the second one is the suitability of buffer areas for changing the control mode of ACTs and minimizing[3] traffic congestion at on-/off-ramps.

Dedicated lanes for ACTs prevent a mix of automated trucks with manually driven vehicles on motorway links. The segregation of flow of ACTs and MDVs would minimize the hindrance of flow of ACTs by MDVs, ensure traffic safety and simplify the operation of ACTs. Moreover, the creation of DFLs on existing motorways would save investment costs for the construction of additional lanes for the operation of ACTs. However, the reduction of the number of lanes for other vehicles than trucks would reduce the remaining capacity of the motorway and lead to even more congestion if the access at on-ramps is not controlled by additional means. The results of the analysis indicate that in case of a high share of trucks in the traffic flow (e.g. >20%) the creation of a dedicated freight lane at the shoulder lane of existing motorways is the most efficient option. The location of DFL on the median lane only might be considered in case of dedicated on-/off-ramps, e.g. by means of fly-overs.

The creation of buffer areas, as complementary means, provide the opportunity for regulating the flow of ACTs upstream of on-/off-ramps (by platooning[4] and splitting the flow of ACTs). Buffer areas for ACTs may be situated close the DFL on the mainline just upstream on-/off-ramps on the mainline or at on-ramp. The application of ordinary buffer areas for MDVs at on-ramps also would be beneficial. The buffer areas for ACTs facilitate the synchronization of the speed and density of ACTs while approaching to on-/ off-ramp areas, the switch of the control mode of ACTs from manual to automatic and vice versa, and dynamic traffic management of operation of ACTs and MDVs nearby on-/off-ramps.

The creation of DFL for ACTs and buffer areas would certainly have a significant impact on efficiency of operation of motorways. The question is whether optimal traffic

[3] In chapter 7 it will be explained for whom the flow optimization would be applied.
[4] The benefits of platooning of ACTs will be addressed in the next chapter.

control measures can provide competitive travel times for all user groups and sufficient capacity as well as safety at the most critical sections of off- and on-ramps. The impact of different control strategies such as ramp metering or platooning of ACTs on the DFL will be estimated and discussed more in detail in the next chapter.

# 4
# Impact Assessment of Truck Platooning

## 4.1 Introduction

In the previous chapter we addressed two major design requirements for the operation of ACTs. The necessity for the operation of ACTs on *dedicated lanes* was introduced as the first design requirement for safe operation of ACTs in major segments of motorways. Moreover, a complementary means was developed for on-/off-ramp areas to minimize the hindrance of flow of ACTs by MDVs, and vice versa. This new design requirement, named buffer area, would provide enough space for intermediate parking of some ACTs to arrange platooning and/or splitting ACTs upstream of on-/off-ramps and even would be suitable for MDVs at on-ramps.

Analysis of the simulations, reported in the previous chapter, indicated that dedication of a lane to ACTs alone would not be sufficient to justify the expected efficiency of the operation of ACTs, instead of ordinary trucks. It may even lead to a lower efficiency, if additional control strategies are not applied. Therefore, it is necessary to focus on the capabilities of ACTs, compared to ordinary trucks, to improve the expected hindrance of flow of MDVs, merging to the mainline flow at on-ramps or diverging the mainline flow at off-ramps, caused by approaching ACTs on DFLs at on-/off-ramp areas. The main aim of the present chapter is to develop suitable control strategies for the operation of ACTs and to assess how their application could improve the performance of traffic operations at on-/off-ramp areas.

First, the concept of platooning of ACTs will be described, as a key factor for achieving a higher throughput of ACTs compared to the flow of ordinary trucks. Then, different scenarios of truck platooning will be evaluated by using the simulation tool SiMoNe. It will be assessed to what extent the platooning of ACTs would improve the traffic performance for the assumed motorway layout. Further, it will refer to additional traffic control measures that are required to ensure a safe and reliable operation of MDVs mixed with the flow of ACTs at on-/off-ramps. Finally, this chapter will come up with some conclusions and recommendations.

## 4.2 Platooning operations

In platooning operations, vehicles are clustered together in groups of vehicles, in which vehicles within each group follow each other with a very short spacing (intra-distance), whereas a longer spacing between two successive groups of vehicles is maintained (inter-distance). Figure 4.1 refers to the concept of platooning of vehicles.

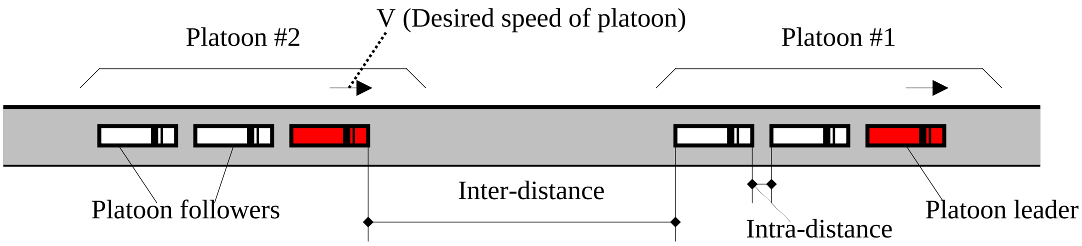



**Figure 4.1. Concept of vehicle platooning**

In order to ensure the safe operation of vehicles while platooning, a safe speed and intra-distance between vehicles within a platoon is to be maintained. Moreover, a certain (inter-)distance between two successive platoons should be provided. The severity of collision between two vehicles following each other in a single lane is proportional to the square of the relative speed of vehicles at the time of collision. Figure 4.2 illustrates the relation between the severity of collision and following distance of vehicles. This figure depicts that both very close and very far following distances would be safer compared to moderate following distance of vehicles.

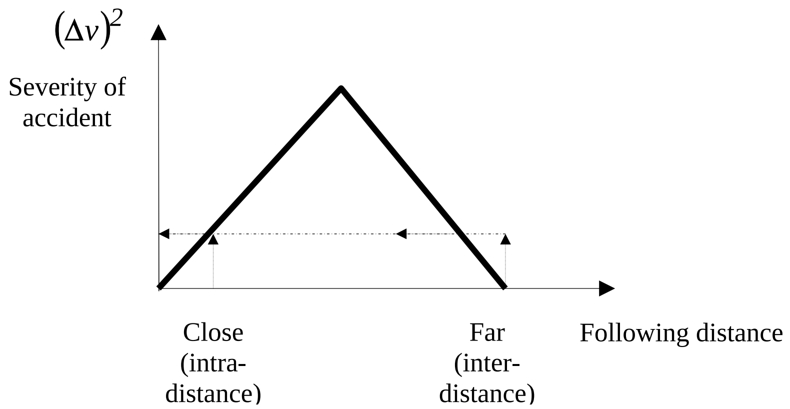



**Figure 4.2. Collision curve (Source: Ioannou (1997))**

Automatically controlled vehicles follow each other with a very close distance but keep the same desired speed does not create a higher risk of accident if the distance between the platoons or to obstacles on the roadway is sufficiently long. Indeed, this is the main reason underlying the introduction of platooning concept.

Let us denote:

$s_{intra}$ : intra-distance of trucks within a platoon (m)
$s_{inter}$ : inter-distance of two successive platoons of trucks (m)
$L$ : average length of a truck (m)
$N$ : number of trucks in a platoon
$v_{plat}$ : desired platoon speed (m/s)
$cap$ : capacity of uninterrupted flow of platooned trucks on a single lane (veh/h)

Then, capacity can be formulated as:

$$cap = \frac{3600 \cdot N}{s_{intra}(N-1) + L \cdot N + s_{inter}} v_{plat}$$

From the performance point of view the capacity should be as high as possible, which implies a high speed $v_{plat}$ and small values of $s_{intra}$ and $s_{inter}$. This, however, may have an adverse effect on safety because a high value $v_{plat}$ implies shorter time for the corrective actions to take place at a given distance $s_{intra}$, while small values of $s_{intra}$ and $s_{inter}$ imply shorter distance at a given speed to ensure no collision of trucks within a platoon and between two successive platoons, respectively. Thus, the upper bound of the speed $v_{plat}$ and the lower bounds of the distances $s_{intra}$ and $s_{inter}$ depend on safety constraints.

Thus, a theoretical capacity of about 2300 trucks/h may be estimated for an uninterrupted flow of automatically controlled trucks operating in platoons on a dedicated lane under ideal conditions supposing the following values:
$s_{intra}$ = 10 m; $s_{inter}$ = 150 m; $L$ = 14 m; $N$ =10; $v_{plat}$ = 88 km/h. The default values have been selected based on the following rules:

- to ensure a minimum safe distance between two successive trucks in a platoon;
- to provide the adequate and safe braking distance for the follower platoon while sudden (emergency) stop of the leading platoon (according to dynamic characteristics of braking of trucks) to avoid a collision;
- to let a certain number of trucks join together to form a platoon in a specific length of motorways which possibly should be splitted to platoons with a lower number of vehicles at on-/off-ramps.

Practical results indicate that a maximum flow of 3000 veh/h can be achievable on the most left lane of a motorway (Dijker et al. (1997)). Assuming a passenger car unit (pcu) equal to 2 for trucks, results in an equivalent flow of 1500 trucks/h on an exclusive lane for ordinary trucks. Hence, operation of (automatically controlled) trucks in platoons may result in an increase of capacity by about 53% in an uninterrupted flow, compared to ordinary trucks. Empirical data on the capacity of a lane with trucks-only is unfortunately not available.

It is clear that the interruption of flow of trucks operating in platoons on a DFL by crossing cars and merging/diverging ACTs at on-/off-ramps would reduce the maximum flow of platooned trucks. The next sections describe to what extent this hindrance is expected to happen at on-/off-ramps separately, and what effects the change in platoon characteristics (e.g. number of trucks in each platoon, intra-distance of trucks within platoons, inter-distance of platoons, desired speed of platoons, etc.) would have on the traffic performance.

ACTs in platoons receive commands from roadside-based control. Therefore, for each time instant (or actually time period) the desired speed of ACTs in a platoon, the intra-distance of ACTs within a platoon, and also the required inter-distance of platoons from each other will be estimated by the traffic control center and be transmitted to ACTs via tele-communication systems.

Detectors embedded in roads and also other vehcle recognition systems provide the required traffic information for the traffic controller to select the optimal strategy of control of ACTs in platoons during a certain time period. It is also assumed that ACTs can not overrule their automatic system in a controlled area in which the platooning strategy is applied. After leaving a platooning segment, the automated system switches back to the normal mode.

## 4.3 Evaluation of truck platooning at on-ramps

As it was described in the previous section, the impact of truck platooning on traffic performance at on-ramp areas of motorways is different than on continuous segments of motorways. This is due to hindrance of flow of platooned trucks caused by crossing movements of cars or merging of trucks to the mainline (DFL). Both the crossing of cars and merging of trucks may require a reconfiguration of truck platoons at on-ramps. Therefore, the impact of the main characteristics of truck platoons, like intra-distance of trucks within platoons or inter-distance of truck platoons must be analyzed in order to determine the optimal characteristics of platoons of trucks.

In order to estimate the impact of truck platooning characteristics at on-ramps on traffic performance, a simulation study is conducted. Based on the results of the previous chapter, the layout of the motorway includes three lanes in which the right lane is assigned to trucks (ordinary trucks or platooned trucks). Figure 4.3 indicates the assumed road layout of the assumed motorway including an on-ramp, located at a distance of 2 km from the origin of traffic on the mainline.

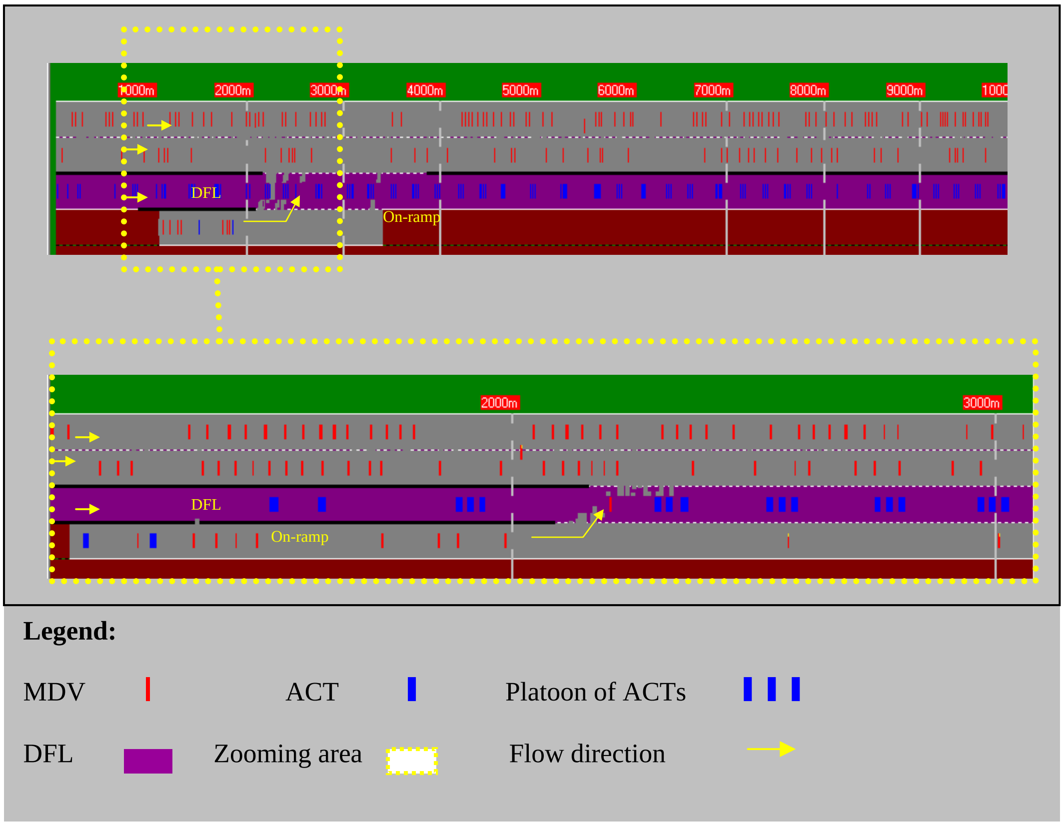



**Figure 4.3. The on-ramp layout with truck platooning**
**(screen picture from SiMoNe)**

### 4.3.1 Simulation setup

*Input data*

For reasons of simplicity it is assumed that there are only two user groups: cars and trucks (ordinary or automated trucks depending on the scenario[1]). The total traffic demand is the same in all proposed scenarios. Ordinary vehicles will drive on lanes 1 and 2, whereas trucks (ordinary trucks or platooned trucks) will drive on the DFL located at the shoulder lane of the existing motorway. As it was described in the previous chapter, a total simulation time of 4 hours per scenario is selected to achieve reliable results of the simulations. Six detectors are provided to aggregate the recorded data per 5 minutes intervals, among which detector 3 records the volume of the assumed layout of the motorway at the on-ramp.

In order to reach capacity at the on-ramp during platooning of trucks, compared with the case in which the trucks are not platooned, a high flow of cars and trucks on both motorway and on-ramp is generated as follows, while a share of 10% of trucks in the on-ramp flow is assumed (figure 4.4).

[1] Due to safety reasons a combination of ordinary trucks and ACTs on the DFL has not been taken into account. Also it is assumed that a DFL would be economically beneficial if all trucks be instrumented by automated systems.

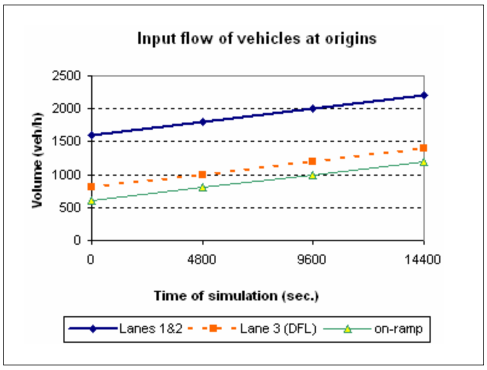



**Figure 4.4. Change of traffic flow generated at the origin**

*Output data*

Similar to the simulations reported in the previous chapters, three categories of traffic performance indicators, e.g. traffic operation, energy and comfort, and safety are measured to provide a basis for comparing the impact of different scenarios.

### 4.3.2 The scenarios

The simulation study focuses on two main options of scenarios:

- Reference case, in which there is no platoon of trucks on the DFL (scenario R);
- Platooning case, in which trucks in form of platoons will drive on the DFL (scenario P);

In the platooning cases, the following characteristics of the traffic of platoons of trucks are analyzed separately:

- the maximum number of trucks in the platoon (scenarios P-MAX),
- the initial number of trucks in the platoon[2] (scenarios P-MIN),
- intra-distance of trucks in platoons (scenarios P-INTRA),
- inter-distance of platoons of trucks (scenarios P-INTER),
- desired speed of platoons of trucks (scenarios P-S),
- maximum possible acceleration and deceleration of trucks in platoons (scenarios P-A),
- length of platooning of trucks (scenarios P-L).

The chosen values for the platoons of trucks are indicated in the table 4.1. In each part of the analysis, the impact of change in one of these values is evaluated.

In the next section, the simulation results of each of the proposed scenarios are described.

[2] The initial number of trucks in platoons upstream of a merging area before merging new vehicles to the platoon.

**Table 4.1. The basic values for the platoons of ACTs in the simulation**

| The chosen characteristics of platoons | Notation | Value |
|---|---|---|
| Max. number of ACTs in platoons | $N_{max}$ | 8 |
| Initial number of ACTs in platoons | $N_{initial}$ | 2 |
| Intra-distance of ACTs | $S_{intra}$ | 10 m |
| Inter-distance of ACTs | $S_{inter}$ | 150 m |
| Desired speed of platoons of ACTs | $v_{plat}$ | 85 km/h |
| Maximum acceleration/deceleration of ACTs in platoons | $a_{plat\,(+/-)}$ | -2,2 m/s^2 |
| Location of the platooning operation | [L1,L2] | [0,10000] m* |

* Throughout whole of the DFL

### 4.3.3 Simulation results

The analysis is done separately for each group of scenarios representing the main characteristics of a platoon:

*Analysis of 'P-MAX' scenarios*
This analysis is performed in order to assess the impact of the change of the maximum number of trucks in the platoons on traffic performance indicators. In this analysis, a maximum number of 4, 6, 8 and 10 respectively trucks in a platoon, is considered. Figure 4.5 indicates the major simulation results of the reference scenario and all platooning scenarios. More detailed information about results of simulations can be seen in table D.1 of the Appendix D.

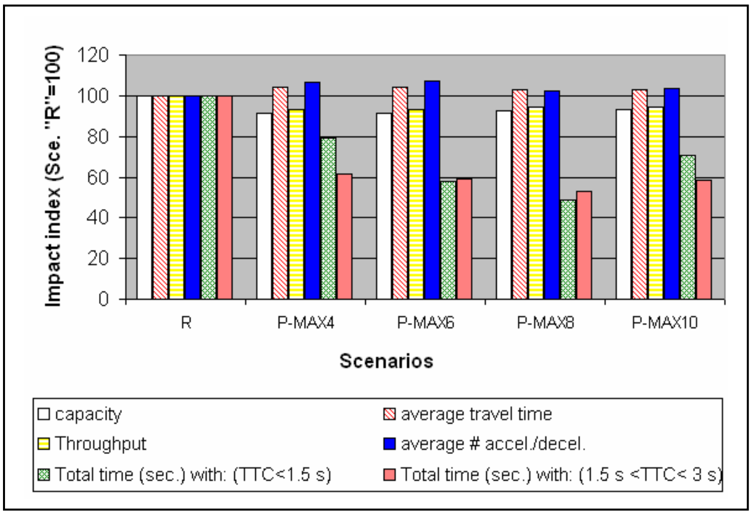



**Figure 4.5. Impact of the maximum number of trucks in platoons at on-ramps**

The major simulation findings can be summarized as follows:

- none of the platooning scenarios lead to a higher traffic performance, compared to the reference scenario. For instance, the capacity is decreased by about 10%, average travel time is increased by about 4%, and total throughput is decreased by about 7%. This may be due to the low value selected for the initial number of trucks in platoons, e.g. 2. In the next section the impact of the initial number of trucks in platoons will be discussed more in detail;

- All performance indicators concerning the platooning scenarios have improved by increasing the maximum number of trucks in platoons. The only exception is related to the P-MAX10 scenario in which the increase of the number of trucks from 8 to 10 has led to some adverse results compared to the P-MAX8 scenario. This seems plausible, because the creation of a platoon of 10 trucks may cause very big problems for the crossing flow of cars. The considerable increase in TTC values less than 1.5 s measured is indicating that a platoon size of 10 trucks does not comply with a higher traffic volume at on-ramps;
- The indicators representing the comfort and safety like the number of times of change of acceleration or deceleration of trucks or TTC values are improved considerably by platooning of trucks compared to the reference scenario.

*Analysis of 'P-MIN' scenarios*

The main aim of this analysis is to compare the impact of the initial (minimum) number of trucks in platoons. For instance, the scenario P-MIN2 represents an option of truck platooning in which the minimum number of trucks within a platoon is variable between 2 (the assumed initial number of trucks in platoons) and 8 (default value selected as the maximum possible number of trucks in a platoon). Figure 4.6 indicates some major results of simulations concerning the performance of such platoons. More detailed information about the simulation results can be found in table D.2 of the Appendix D.

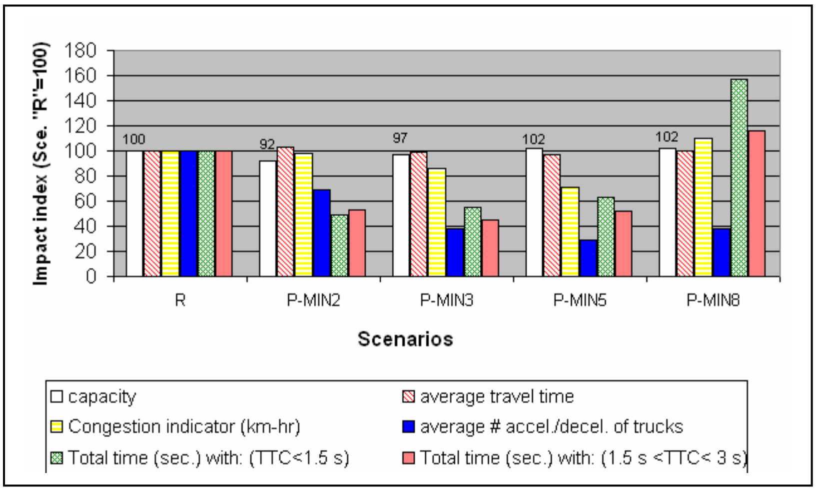



**Figure 4.6. Impact of initial number of trucks in platoons at on-ramps on some major performance indicators**

The results of simulation indicate that:

- By increasing the initial number of trucks in platoons from 2 to 5 the capacity is increased by about 10%, the congestion indicator[3] is decreased by about 25%, and

[3] This indicator shows the total times in which a speed of less than 50 km/h is measured in any of the roadway sections.

the average number of accelerations and decelerations of trucks is decreased by about 70%;

- in almost all platooning scenarios the safety indicator (represented by TTC < 1.5 s) is improved considerably, compared to the reference scenario. It indicates that the number of dangerous situations when cars are crossing reduces by about 40% in case of trucks are operating in platoons of 5 trucks. The only exception is the P-MIN8 scenario in which the initial and maximum number of trucks are the same, e.g. 8. In this case, the ability of reconfiguration (splitting and forming) of platoons is decreased and the number of small TTC values is increased again.

A trade-off between capacity, travel time and safety indicators show that a platoon size of 5 (trucks) can lead to a higher performance compared to the reference scenario and all other platooning scenarios.

*Analysis of 'P-INTRA' scenarios*

This analysis is carried out to assess in what extent a decrease of intra-distance of trucks in a platoon leads to a higher capacity of motorways at on-ramp areas. The default value assumed for the intra-distance of trucks is 10 m, whereas a shorter (e.g 5 m) and two longer distances (e.g. 15 and 20 m) are applied to be compared with the default value. figure 4.7 shows some major results of simulation concerning the impact of this characteristic of trucks platooning at merging areas. Table D.3 of Appendix D presents an overview of results of simulation concerning the impact of the intra-distance of trucks on all performance indicators.

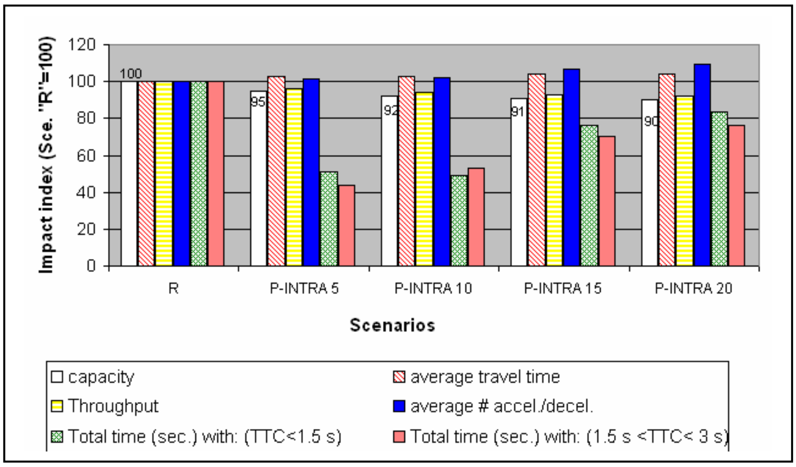



**Figure 4.7. Impact assessment of intra-distance of trucks in platoons at on-ramps on some major performance indicators**

It clearly indicates the negative impact of increase in intra-distance of trucks in platoons on capacity. However, it should be noted that from a safety point of view applying a minimum intra-distance for automated trucks in platoons is necessary in order to ensure a minimum reaction time of data communications and braking devices between the trucks. In the CHAUFFEUR II project, this minimum intra-distance of trucks in platoons is varied between 6 m as minimum and 12 m at a speed of 90 km/h depending on the vehicle speed (Brockmann et al. (2001)). The results of the present study (simulation runs) turn out that a reduction of the intra-distance of trucks from 10 to 5 m would lead only to a 3 % increase in capacity of motorways at on-ramps which is insignificant.

Moreover, the results of simulation indicate that increasing the intra-distance of trucks from 10 to 20 m leads to an increase of the number of dangerous TTC values continuously. It means that an optimal intra-distance for trucks may be determined at which any change would reduce the traffic performance. The selection of the optimal intra-distance of trucks depends e.g. on the volume of crossing traffic flow of cars, the layout of the motorways on-ramp and the required safety level.

In general, similar to the results of the previous analysis, all platooning scenarios lead to better results compared to the reference scenario with regard to traffic safety (up to 50 %).

*Analysis of 'P-INTER' scenarios*

This analysis has been carried out to assess the impact of inter-distance of platoons at on-ramp areas. An adequate inter-distance between platoons of trucks ensures safety aspects and causes a lower risk for the collision of two successive platoons due to instantaneous brake of the leading platoon which might happen in emergency cases. Figure 4.8 provides a comparison of all platooning scenarios with the reference scenario to indicate the impact of inter-distance of platoons at on-ramps more clearly (see table D.4 in the Appendix D for more detailed information).

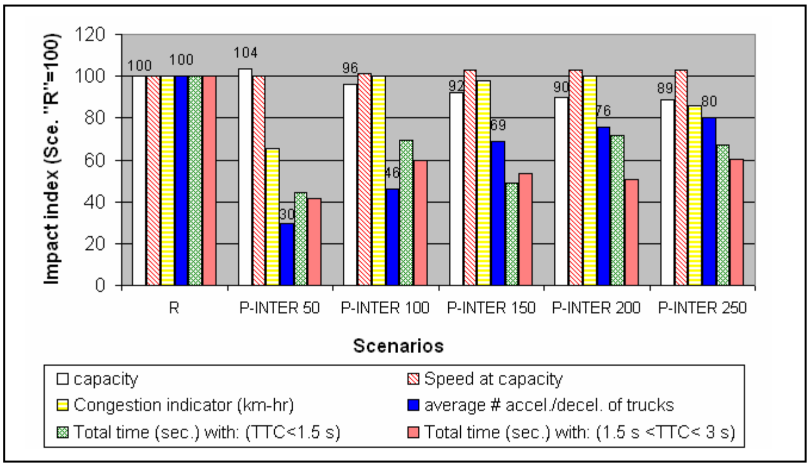



**Figure 4.8. Impact assessment of inter-distance of platoons at on-ramps on some major performance indicators**

The main findings can be summarized as follows:

- an inter-distance of 50 m of platoons of trucks on the DFL (Scenario P-INTER 50) represents better results compared to the reference scenario, with respect to almost all measured indicators (except for the 'speed at capacity'). It supports the effective role of inter-distance of platoons on traffic performance indicators. Although the initial number of trucks is limited to 2 trucks (default value), a reduction of the inter-distance of platoons compensates the negative impact of the low value selected for the initial number of trucks in platoons. In fact, this scenario is among few scenarios in which nearly all indicators are improved, compared to the reference scenario;

- by increasing the inter-distance of platoons from 50 to 250 m, a reduction of 15% in the on-ramp capacity may be expected. It also leads to an increase of up to 50% in the average number of accelerations and decelerations of trucks.

*Analysis of 'P-S' scenarios*

Another simulation is conducted in order to verify the impact of the change in desired speed of platoons of trucks at the on-ramp area on traffic performance (figure 4.9). As expected, by increasing the desired speed of platoons, capacity, throughput and average travel time improve. However, if the platoon speed is increased from 55 to 85 km/h (~ 60%), then the mentioned indicators improve marginally by only about 5, 5 and 7%, respectively. Table D.5 in the Appendix D indicates the impact of desired speed of platoons at on-ramps on some other major indicators.

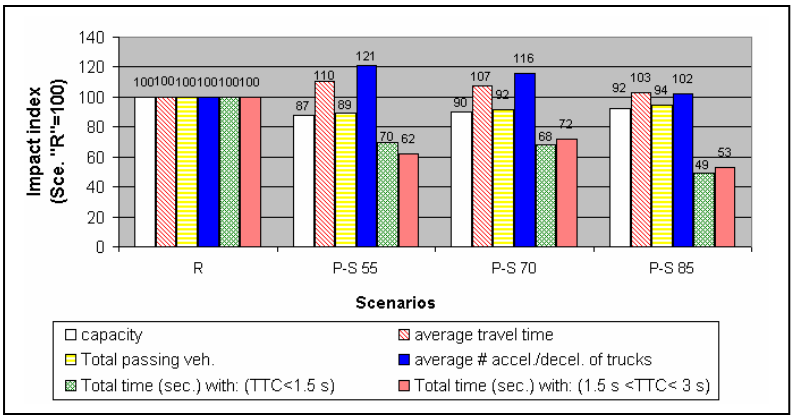



**Figure 4.9. Impact assessment of desired speed of platoons at on-ramps on some major performance indicators**

Surprisingly, the simulation findings indicate a major reduction (e.g. about 21%) of dangerous situations (e.g. TTC < 1.5 s) by increasing the desired speed of platoons from 55 to 80 km/h. Indeed, by increasing desired speed of platoons of trucks up to 85 km/h, the speed of trucks will be synchronized more effectively with the speed of crossing cars, coming from the on-ramp. This synchronization would help cars to cross the flow of trucks more smoothly and safely. Thus, a desired speed of 85 km/h for the platoons of trucks at on-ramps is more efficient in cases which no traffic signal is applied at on-ramps.

*Analysis of 'P-A' scenarios*

A similar analysis is carried out to assess the impact of the desired acceleration and deceleration of trucks in platoons. The deceleration of trucks is assumed to change between –1 and –4 $m/s^2$, and the same is selected for the acceleration of trucks in platoons. Then, different combinations of accelerations and decelerations are selected and analyzed. The results of simulation indicate no meaningful difference among the different rates of acceleration and deceleration, compared to the default value (e.g. –2 and +2 $m/s^2$) (see table D.6 in the Appendix D).

*Analysis of 'P-L' scenarios*

Trucks can be platooned along the total length of the DFL at on-ramp areas, or on a limited segment of the DFL (figure 4.10), either at one side (upstream or downstream of on-ramp area) or at both sides of the on-ramp area (total length of DFL excluding the on-ramp area). As before, due to the interruption of the flow of platoons of trucks at on-ramps (or similarly at off-ramps) it is expected that the performance of truck platooning is reduced heavily. The major results of analysis are shown in figure 4.11. In addition to the reference scenario, in this figure three different possibilities for trucks platooning are evaluated. In the first option, on the total length of the DFL trucks are platooned, named 'scenario P-L 0,10000'. In the second scenario, trucks are platooned only at upstream of the on-ramp (scenario P-L 0,2000). The last scenario refers to a situation in which trucks are platooned only at down stream of the on-ramp (scenario P-L 4000,10000). Table D.7 in the Appendix D gives more detailed information about results of simulations.

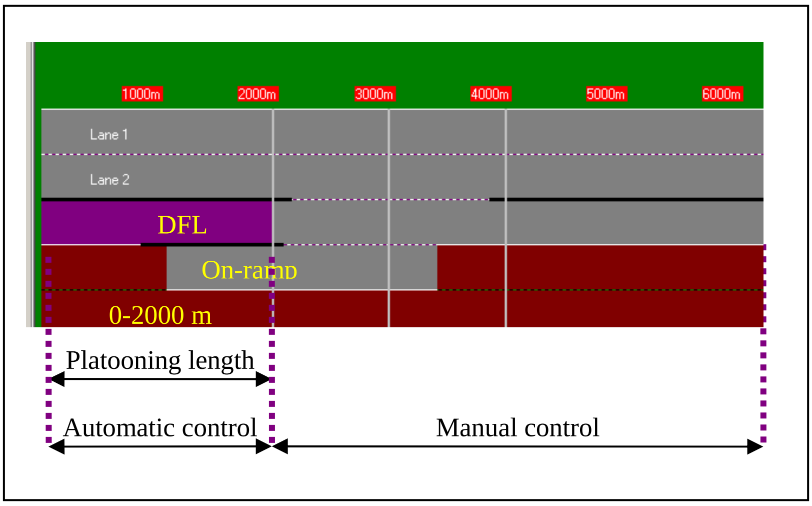



**Figure 4.10. Platooning of trucks only at upstream of the on-ramp within the road distance 0- 2000 m** **(screen picture from SiMoNe)**

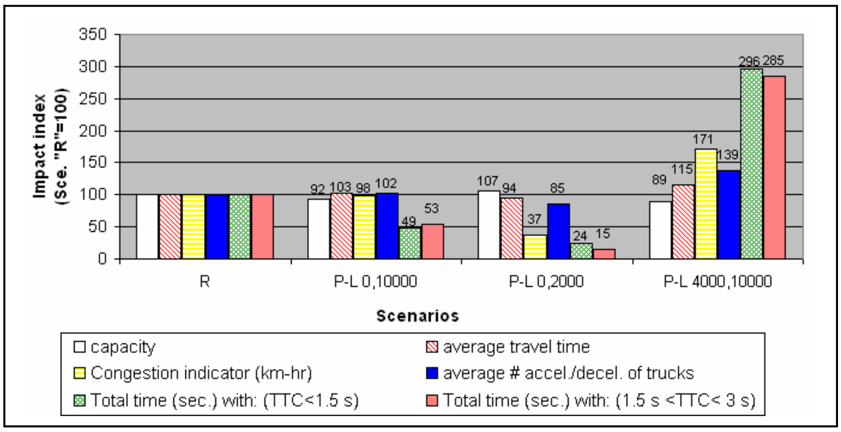



**Figure 4.11. Impact assessment of continuous or discontinuous platooning of trucks at on-ramps**

The results of analysis clearly show that:

- The discontinuation of platooning of trucks upstream of an on-ramp area results in an increase in capacity, equal to 7 % and 15% compared to the reference scenario and the continuous platooning scenario, respectively. This scenario leads to better results with regard to almost all described indicators. Thus, it can be assumed as a competitive option for applying platooning at all length of the DFL. A decision about the location and the optimal length for applying the platooning control strategy depends, too, on the density of on- and off-ramp areas. The closer the distance between on-/off-ramp, the lower the performance of the discontinuous platooning option compared to the continuous platooning scenario;

- Surprisingly, the scenario in which the platooning of trucks starts downstream of the on-ramp does not seem to be competitive. Specially, the dangerous situations (represented by TTC < 1.5 s) in this scenario is almost 3 times higher than the reference scenario. This is due to shock waves caused at the starting point of the platooning segment. Indeed, an inadequate space between the starting point of the platooning segment and the nose of the on-ramp affects the flow of vehicles entering from on-ramp.

In the above analyses, each of the characteristics of a platoon of trucks was considered separately. However, a combination of changes of some characteristics of platoons may have multiple impact on the traffic performance. Therefore, in the following analysis some of the default values of the platoon characteristics are changed simultaneously. The platooning scenarios in which several characteristics of platoons of trucks are changed simultaneously are shown in table 4.2.

**Table 4.2. Scenarios with multiple changes of platoon characteristics at on-ramps**

| Platoon characteristics | Default value | Scenario P-COM I | Scenario P-COM II | Scenario P-COM III | Scenario P-COM IV |
|---|---|---|---|---|---|
| $N_{max}$ | 8 | 8 | 3 | 3 | 3 |
| $N_{initial}$ | 2 | 5 | 5 | 5 | 5 |
| $S_{intra}$ | 10 | 5 | 15 | 15 | 15 |
| $S_{inter}$ | 150 | 50 | 100 | 100 | 100 |
| $V_{plat}$ | 85 | 85 | 70 | 85 | 70 |
| $a_{plat}$ (+/-) | +/- 2 | +/- 2 | +/-1 | +/-1 | +/-1 |
| Platooning distance | [0,10000] | [0,2000] | [0,2000] | [0,2000] | [0,10000] |

Table 4.3 illustrates the simulation results for all these combined platooning scenarios (P-COM I to P-COM IV). As this table indicates, a combination of optimal single characteristics (Scenario P-COM I) does not necessarily lead to optimal collective characteristics. For instance, the P-COM I scenario generates more dangerous TTC values, compared to the reference scenario, whereas in most of previous scenarios the safety indicators of platooning scenarios had represented better results, compared to the reference scenario. It is due to a combination of high desired speed (e.g. 85 km/h), a high acceleration/deceleration rate (e.g. +/- 2) and a short intra-distance of trucks (5 m) assumed for the P-COM I scenario which might be dangerous.

**Table 4.3. Comparison of P-COM scenarios with the reference scenario**

| Absolute values | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 5434.2 | 94.5 | 6.8 | 335.6 | 20626 | 4.9 | 16759 | 3867 | 24493 | 6.4 | 8.3 | 380.2 | 141.8 | 92 | 359 |
| P-COM I | 5596 | 94.6 | 6.6 | 283.4 | 21240 | 3 | 17199 | 4041 | 25281 | 6.2 | 8.2 | 339.6 | 43.9 | 187 | 323 |
| P-COM II | 5713 | 93.1 | 6.4 | 279.2 | 21230 | 2.5 | 17413 | 3817 | 25047 | 6.2 | 7.5 | 334.3 | 27.8 | 99 | 216 |
| P-COM III | 5725 | 94.5 | 6.3 | 263.4 | 21309 | 2.1 | 17174 | 4135 | 25444 | 6.1 | 7 | 319.8 | 29.3 | 804 | 979 |
| P-COM IV | 5176 | 92.6 | 7.1 | 347.2 | 20050 | 5 | 16855 | 3195 | 23245 | 6.5 | 9.9 | 319.8 | 50 | 155 | 348 |
| **Relative values** | | | | | | | | | | | | | | | |
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| P-COM I | 103 | 100 | 97 | 84 | 103 | 61 | 103 | 104 | 103 | 97 | 99 | 89 | 31 | 203 | 90 |
| P-COM II | 105 | 99 | 94 | 83 | 103 | 51 | 104 | 99 | 102 | 97 | 90 | 88 | 20 | 108 | 60 |
| P-COM III | 105 | 100 | 93 | 78 | 103 | 43 | 102 | 107 | 104 | 95 | 84 | 84 | 21 | 874 | 273 |
| P-COM IV | 95 | 98 | 104 | 103 | 97 | 102 | 101 | 83 | 95 | 102 | 119 | 84 | 35 | 168 | 97 |

Figures 4.12 to 4.14 provide a comparison of all scenarios with regard to traffic operation, fuel consumption -and comfort-, and safety indicators, respectively. Figure 4.6 shows that the scenario P-COM III gives the most effective results in which capacity, throughput (in pcu), travel time, and congestion indicators are improved about 5%, 4%, 7%, and 57% , respectively, compared to the reference scenario (no platooning of trucks at on-ramps). The only difference between this scenario and the P-COM II scenario returns to the desired speed of platoons. Indeed, the P-COM III Scenario allows a higher speed of trucks in platoons. This is the main reason that why the P-COM III scenario leads to very high dangerous situations, compared to the P-COM II scenario (see TTC < 1.5 s values in figure 4.14).

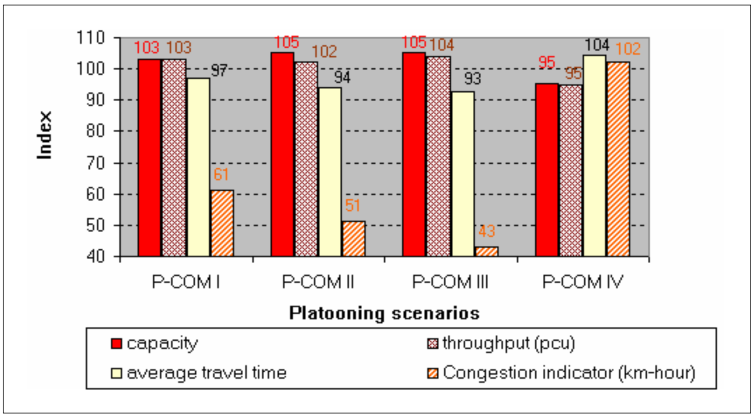



**Figure 4.12. Traffic operation indexes for the P-COM scenarios compared to the reference scenario**
**(index for the reference scenario = 100)**

The comfort indicator, represented by the average number of changes in acceleration/deceleration of vehicles, in the P-COM III scenario is also improved compared to the P-COM II scenario (see figure 4.13). It is due to a synchronized speed of platoons with crossing cars at the on-ramp in the P-COM III scenario (e.g. 85 km/h) compared to the P-COM II scenario.

Figure 4.13 clearly indicates that the improvement of the comfort indicator in the P-COM III scenario, compared to the P-COM II scenario, relies on reducing the number of acceleration/decelerations of cars, instead of trucks. Hence, taking into account all rates of changes of indicators and according to major role of the safety indicator, it can be concluded that the P-COM II scenario leads to optimal results.

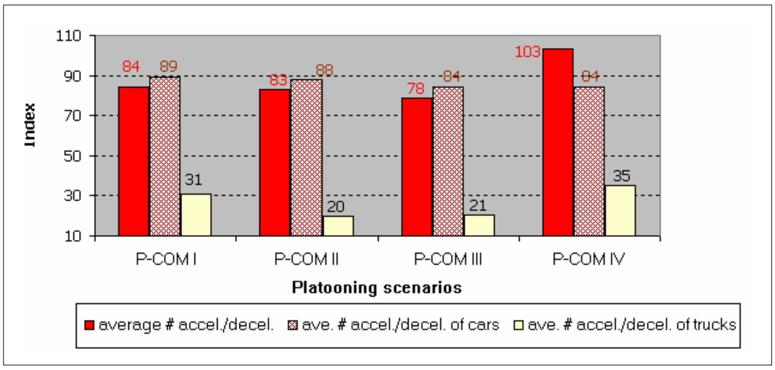



**Figure 4.13. Energy consumption and comfort indexes for the P-COM scenarios compared to the reference scenario**
**(index for the reference scenario = 100)**

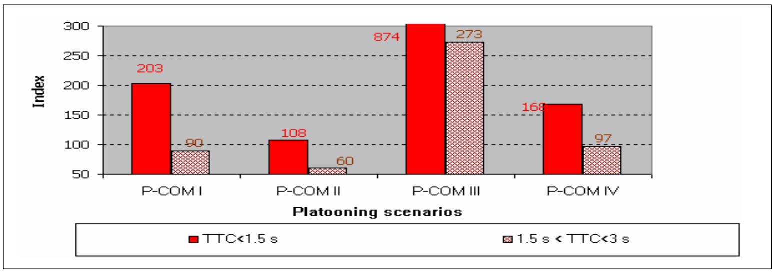



**Figure 4.14. Safety index for the P-COM scenarios compared to the reference scenario**
**(index for the reference scenario = 100)**

## 4.4 Evaluation of truck platooning at off-ramps

Similar to on-ramp areas, another set of simulations is conducted to assess the impact of truck platooning at off-ramp areas (figure 4.15). In an off-ramp area, ordinary vehicles which intend to exit from the mainline must cross the DFL, and consequently may hinder the flow of platooned trucks (or may be hindered by the flow of truck platoons). Indeed, such a hindrance would have negative impacts on both the platoon of trucks and the mainline flow of cars[4].

### 4.4.1 Simulation setup

*Input-output data*

[4] A similar set of simulations are performed and analyzed for a motorway segment including both on- and off-ramps, however, no major difference in results (compared to separate analysis of on- and off-ramps) is reported.

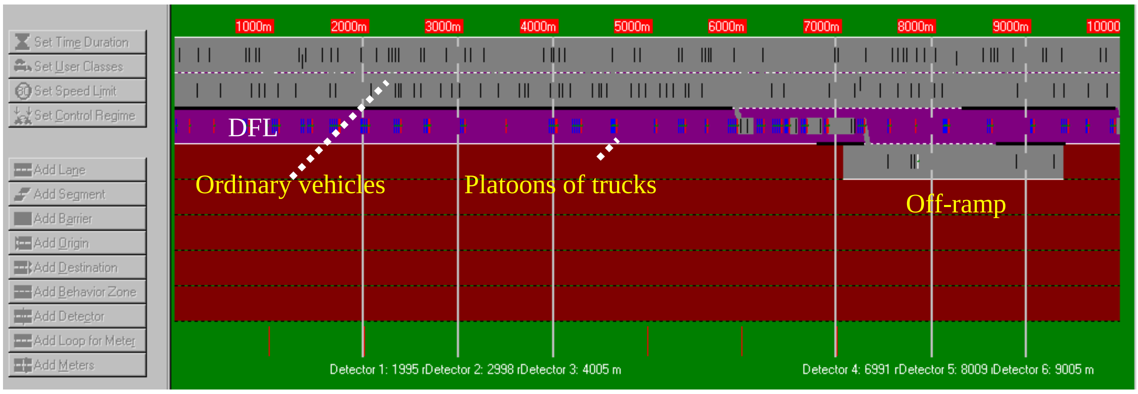



**Figure 4.15. The off-ramp layout with truck platooning**
**(screen picture from SiMoNe)**

All input data, including generated flow on all lanes of motorway, are assumed to be similar to simulation setting in on-ramp analysis (see section 4.3.1).

In order to assess a quantitative comparison among the platooning scenarios with the reference scenario, it is assumed that 20 % of the vehicles driving on the motorway (both cars and trucks) will leave the motorway at the off-ramp. Another simulation setup with a lower share of vehicles leaving the mainline (e.g. 10%) indicates that in this case the generated vehicles do not reach capacity at the off-ramp in the reference scenario. Thus the reduction of capacity while platooning of trucks can not be determined, compared to the reference scenario. In brief, the findings of this additional setup indicate that in case of a lower share of trucks leaving the mainline, the competitiveness of platooning scenarios with the reference scenario with regard to the safety indicator reduces considerably. Whereas, the traffic performance of platooning scenarios from other points of view (e.g. operation and comfort) is improved (see table D.8 in the Appendix D).

### 4.4.2 The scenarios

Like the on-ramp analysis, the simulation study is focused on two main options of scenarios, e.g. reference scenario and platooning scenarios. The analysis also aims to assess the impact of platooning characteristics (see section 4.3.2) on improving the performance of truck platooning, separately.  Like similar analysis for the on-ramp, it is assumed that the MDVs are allowed to merge through the automated lane. Although this is not the case in reality, however, the main aim is to explore the theoretical benefits of interference of ACTs and MDVs without applying additional control means. Such a case only would be permitted under the perfect state of communication among all road users and sophisticated flow control strategies..

All developed scenarios are named in the same manner as described in the on-ramp analysis, however, the initial letters ‘R’ or ‘P’ are doubled to simplify the recognition of an off-ramp scenario with its corresponding scenario in the on-ramp analysis.

### 4.4.3 Simulation results

The main findings of simulation concerning the proposed scenarios are described in this section. The default values for the initial and maximum number of trucks in platoons are the same as in the analysis of the on-ramp area, e.g. 2 and 8. However, in order to assess the impact of other characteristics of platoons like intra-distance of trucks in platoons, inter-distance of platoons, etc. higher values are finally selected for these two characteristics of platoons, e.g. 5 and 10 respectively. In such a case, a higher performance for platooning scenarios is expected, compared to the reference scenario.

*Analysis of 'PP-MAX' scenarios*

Figure 4.16 presents some major results of simulation concerning the impact of the maximum number of trucks in platoons of 4, 6, 8 and 10 trucks, respectively. It can be summarized as follows:

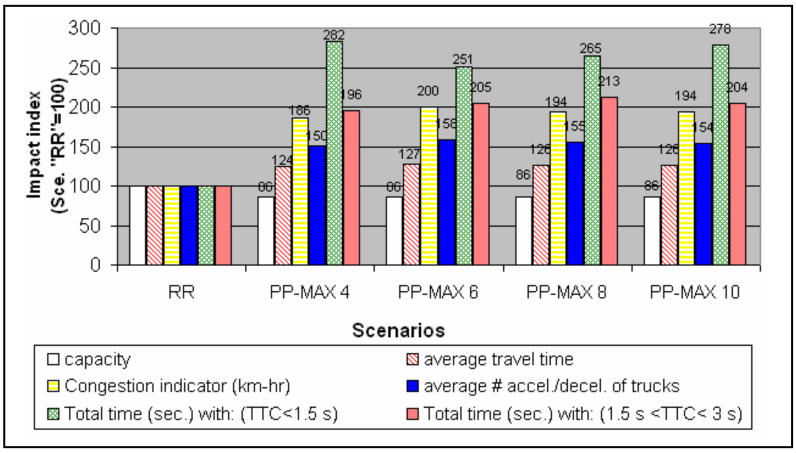



**Figure 4.16. Impact assessment of maximum number of trucks in platoons at off-ramps on some major indicators**

None of platooning scenarios presents better results, compared to the reference scenario. Indeed, all platooning scenarios clearly lead to a reduction in capacity, an increase in average travel time of vehicles, and an increase in level of congestion equal to 14%, 20%-30%, and 85%-100%, respectively. The platooning scenarios also do not show any improvement of the comfort and safety indicators, compared to the reference scenario. These indicators are worsened by about 50%-60% and 60%-180%, respectively. It means that in such a case, the platooning of trucks at off-ramps would heavily reduce the performance of motorways. Thus, platooning of trucks alone is not sufficient to improve the performance of motorways at off-ramps. It requires additional means like speed synchoronization of trucks and cars at off-ramps, traffic signals, or the construction of fly-overs to lead to a competitive scenario with the reference case. The impact of some of these additional means are investigated later. More detailed results of simulations can be found in the table D.9 of Appendix D.

*Analysis of 'PP-MIN' scenarios*

This analysis is achieved to identify the impact of change of the initial number of trucks in platoons on traffic performance at off-ramp areas (figure 4.17). The last two scenarios refer to two new scenarios in which the maximum possible number of trucks in platoons is changed from 8 to 10 in order to determine the impact of simultaneous change in initial and maximum number of trucks in platoons at off-ramp areas.

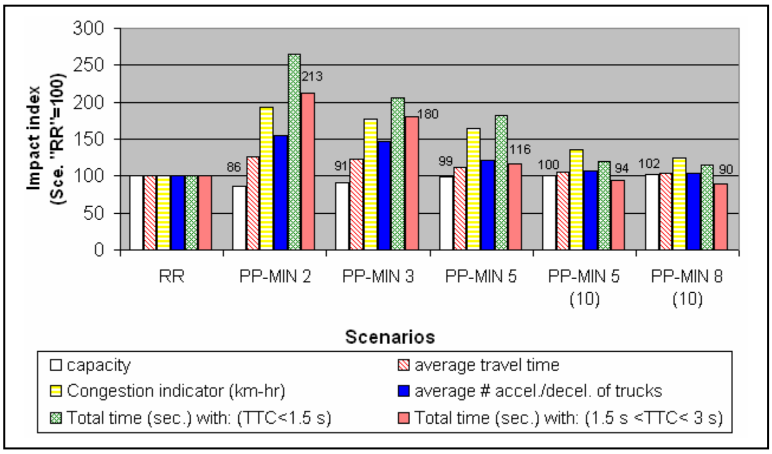



**Figure 4.17. Impact assessment of the initial number of trucks in platoons at off-ramps on some major indicators**

An overview of simulation results, given in table D.10 in the Appendix D, reveals that:

- by increasing the initial number of trucks in platoons, the effectiveness of platooning scenarios in general will improve. It indicates that 'initial number of trucks in platoons' has a great impact on increasing the capacity, as well as safety;

- Platooning scenarios with a minimum initial number of trucks, equal to 5, lead to (almost) similar capacity compared to the reference scenario, however they generate a slightly higher travel time (4%-11%), a higher number of accelerations and decelerations (3%-21%), a considerably higher level of congestion (25%-64%), and a lower level of safety (16%-82%), compared to the reference scenario;

- Platooning scenarios mostly lead to a reduction in number of accelerations and declerations of *trucks*, compared to the reference scenario (e.g. 33%-64%). In contrast, they result in an increase in the number of accelerations and decelerations of cars, considerably (14%-54%). It means that platooning provides more comfort for truck drivers. However, it is more difficult for cars to find a gap between the platoons of trucks to cross and leave the mainline at off-ramps in case of a high volume of truck traffic;

The results of the scenarios in which the maximum number of trucks in platoons is increased up to 10 trucks show the limited impact on improving the off-ramp capacity (e.g. 1%). However, it may lead to a meaningful improvement of other performance indicators like the average travel time (about 5%), the average number of accelerations and deceleration changes of vehicles (about 14%), and the traffic congestion indicator (reduction by about 28%) (see 'PP-MIN 5' and 'PP-MIN 5 (10)' scenarios in figure 4.17). In this case, the amount of dangerous TTC values is reduced considerably, but still remains higher than in the reference scenario.

*Analysis of 'PP-INTRA' scenarios*

The impact of the intra-distance of trucks in platoons on the traffic performance at off-ramps is shown in figure 4.18.

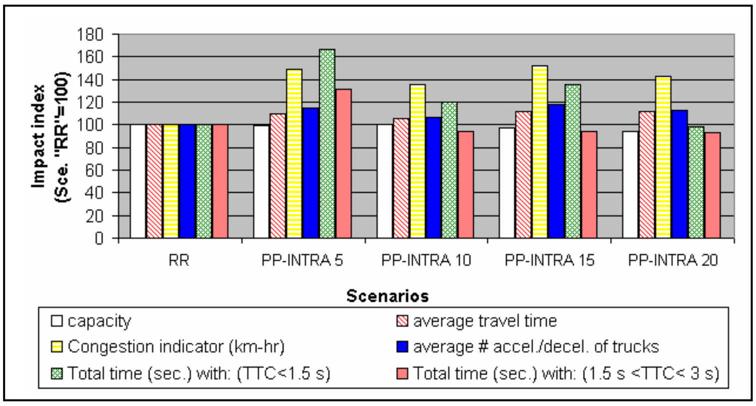



**Figure 4.18. Impact assessment of the intra-distance of trucks in platoons at off-ramps on some major indicators**

An overview of the results and its comparison with the on-ramp analysis (e.g. figure 4.7) indicates that the impact of intra-distance of trucks in platoons at off-ramp areas is rather different than its role at on-ramp areas. While at on-ramp areas a reduction in intra-distance of trucks (e.g. from 10 to 5 m) led to an improvement in almost all indicators, it causes no change in capacity at the off-ramp area. By increasing the intra-distance of trucks from 10 m to 20 m, capacity at off-ramp area decreases up to 6%. In general, the simulation findings indicate that none of the platooning scenarios leads to a higher performance of the off-ramp area, compared to the reference scenario. More detailed information about simulation results can be found in table D.11 of Appendix D.

*Analysis of 'PP-INTER' scenarios*

The impact of inter-distance of platoons on improving the performance of platooning scenarios at off-ramps is given in figure 4.19. Table D.12 in Appendix D gives an overview of results of simulations for all estimated indicators.

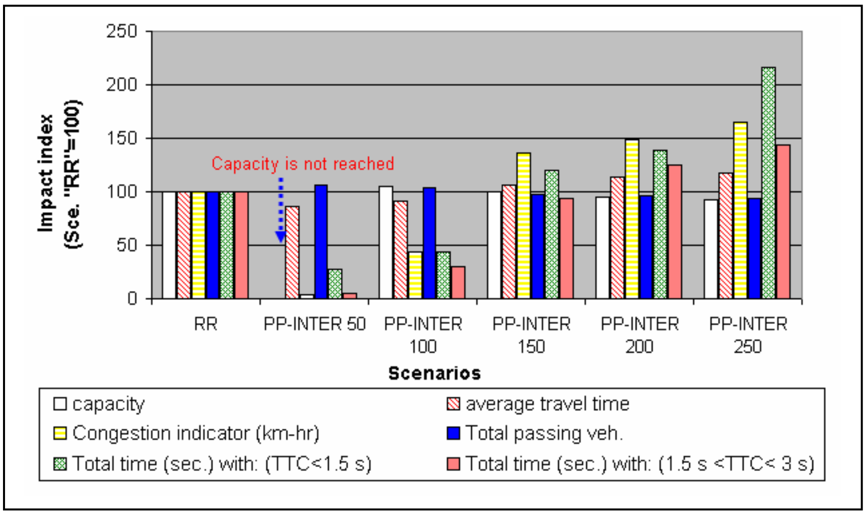



**Figure 4.19. Impact assessment of inter-distance between platoons at off-ramps on some major indicators**

The major findings of simulation can be summarized as follows:

- by decreasing the distance between platoons to 50 m, the performance improves considerably, compared to the reference scenario. For instance, in the PP-INTER 50 scenario the input traffic volume is not reached capacity, the average travel time of vehicles is decreased by about 14%, total throughput is increased about 6%, and the congestion indicator is decreased dramatically (e.g. 96%). Moreover, comfort indicators represented by the number of acceleration and deceleration changes of vehicles and TTC values between 1.5 and 3 s. are decreased about 50% and 94%, respectively, compared to the reference scenario. The safety indicator is also improved about 73%, compared to the reference scenario. These results emphasize the effective role of the inter-distance of platoons on increasing the efficiency of platooning scenarios at off-ramp areas, like on-ramp areas. An interesting point which is worth to be noted here is the decrease of travel time of cars, too. Thus, an optimal value for the inter-distance of platoons should be estimated in which both user groups, e.g. ordinary cars and automated trucks, can expect benefits;

- as it was expected, by increasing the inter-distance of platoons the competitiveness of platooning scenarios compared to the reference scenario reduces.

*Analysis of 'PP-S' scenarios*

The same findings which were found, concerning the impact assessment of desired speed of platoons at on-ramps, are valid here, too. The results of simulations indicate that increasing the desired speed of platoons from 55 to 85 km/h, leads to an increase of the capacity at the off-ramp by about 10%, to a reduction of the average travel time of vehicles by about 21%, and of the congestion indicator by more than 100%. Moreover, the average number of acceleration and deceleration changes of vehicles decreases by about 50% and the safety indicator improves considerably. However, none of these platooning scenarios lead to better results compared to the reference scenario. The only indicator that is improved while applying the platooning scenarios, is the number of acceleration and deceleration changes of trucks. This indicator is improved by about 65%, compared to the reference scenario (see table D.13 in the Appendix D).

*Analysis of 'PP-A' scenarios*

Like the results of simulation in the on-ramp analysis, the simulation findings for the off-ramp analysis shows no meaningful difference with regard to the impact of different rates of accelerations and decelerations (see table D.14 in the Appendix D).

*Analysis of 'PP-L' scenarios*

The aim of this analysis is to assess the impact of platooning strategy at upstream, downstream, or both upstream and downstream of off-ramp areas. The results of simulations are reported in table 4.3. In this table, the start and the end point of the platooning area on the DFL is shown within brackets. The off-ramp is located at a distance of 7 km from the starting point of the section. Therefore, in the second platooning scenario the trucks are platooned only downstream of the off-ramp, while in the third one, trucks are platooned only upstream of the off-ramp.

**Table 4.3. Results of simulation concerning impact assessment of Continuous or interrupted platooning of trucks at off-ramps**

| Absolute values | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 4718.8 | 98.8 | 7 | 314.8 | 17990 | 8.1 | 14123 | 3867 | 21857 | 6.5 | 8.7 | 348.8 | 190.6 | 51 | 254 |
| PP-L (0,10000) | 4714.1 | 99.3 | 7.4 | 336.9 | 17623 | 11 | 13904 | 3719 | 21342 | 6.9 | 9.5 | 409 | 67.2 | 61 | 239 |
| PP-L (9000,10000) | 5304 | 97.4 | 6.3 | 210.2 | 18666 | 2.6 | 14674 | 3992 | 22658 | 6.1 | 7.3 | 256.3 | 40.9 | 42 | 105 |
| PP-L (0,4000) | Not reached | Meaningless | 6.1 | 158.8 | 18800 | 0.4 | 14702 | 4098 | 22898 | 5.8 | 7.1 | 193.2 | 35.5 | 5 | 23 |
| Relative values | | | | | | | | | | | | | | | |
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| PP-L (0,10000) | 100 | 101 | 106 | 107 | 98 | 136 | 98 | 96 | 98 | 106 | 109 | 117 | 35 | 120 | 94 |
| PP-L (9000,10000) | 112 | 99 | 90 | 67 | 104 | 32 | 104 | 103 | 104 | 94 | 84 | 73 | 21 | 82 | 41 |
| PP-L (0,4000) | N.A. | N.A. | 87 | 50 | 105 | 5 | 104 | 106 | 105 | 89 | 82 | 55 | 19 | 10 | 9 |

The findings in table 4.3 reveal that an interrupted form of platooning of trucks at off-ramps leads to a higher performance, compared to the scenario in which platooning of trucks is kept within whole assumed length of the DFL. In case of platooning only up stream of the off-ramp (scenario PP-L (0,4000)), all indicators are improved meaningfully. The volume of traffic flow does not reach capacity and the average travel time decreases by about 13% and 20%, compared to the reference scenario and platooning scenario in which platooning strategy is applied over the whole length of the DFL, respectively. The findings also show that a reduction of 50% in average number of accelerations and decelerations, compared to the reference scenario can be expected when trucks platooning has been applied only upstream of off-ramps. This benefit would decrease if trucks are platooned downstream of the off-ramp, by about 17%.

The analysis also confirms the huge reduction of dangerous TTC values by 90% in case of platooning downstream of the off-ramp. However, an increase of the density of on/off-ramps of motorways, would need further decomposition and re-arrangement of platoons and lead to disutilities, particularly for trucks.

Taking into account all analyses together, in order to assess the impact of simultaneous change in characteristics of platoons, several combined scenarios (Scenarios PP-COM) are designed in which several characteristics of truck platooning are changed simultaneously. Table 4.4 provides the necessary information about the differences among all these platooning scenarios and table 4.5 shows simulation results of all these scenarios.

**Table 4.4. Scenarios with multiple changes of platoon characteristics at off-ramps**

| Platoon characteristics | Default value | Scenario PP-COM I | Scenario PP-COM II | Scenario PP-COM III | Scenario PP-COM IV |
|---|---|---|---|---|---|
| $N_{max}$ | 10 | 10 | 10 | 10 | 10 |
| $N_{initial}$ | 5 | 5 | 5 | 3 | 5 |
| $S_{initia}$ | 10 | 10 | 5 | 10 | 15 |
| $S_{inter}$ | 150 | 50 | 50 | 100 | 50 |
| $V_{plat}$ | 85 | 85 | 70 | 85 | 70 |
| $a_{plat}$ (+/-) | +/- 2 | +/- 2 | +/-1 | +/-2 | +/-1 |
| Platooning distance | [0,10000] | [0,4000] | [0,4000] | [0,5000] | [0,3000] |

**Table 4.5. Comparison of PP-COM scenarios with the reference scenario**

| Absolute values | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 4718.8 | 98.8 | 7 | 314.8 | 17990 | 8.1 | 14123 | 3867 | 21857 | 6.5 | 8.7 | 348.8 | 190.6 | 51 | 254 |
| PP-COM I | 5577 | 96.6 | 6.3 | 191.2 | 18811 | 1.3 | 14779 | 4032 | 22843 | 5.9 | 7.6 | 230.3 | 48 | 23 | 80 |
| PP-COM II | 5359.2 | 98.3 | 6.3 | 189.3 | 18744 | 1.6 | 14683 | 4061 | 22805 | 5.9 | 7.5 | 228.8 | 46.4 | 16 | 77 |
| PP-COM III | Not reached | Meaningless | 6.1 | 159.4 | 18655 | 0.4 | 14701 | 3954 | 22609 | 5.8 | 7.1 | 194.8 | 27.9 | 2 | 24 |
| PP-COM IV | Not reached | Meaningless | 6.3 | 186.6 | 18541 | 1.7 | 14585 | 3956 | 22497 | 5.9 | 7.6 | 226.8 | 38.5 | 25 | 79 |
| **Relative values** | | | | | | | | | | | | | | | |
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| PP-COM I | 118 | 98 | 90 | 61 | 105 | 16 | 105 | 104 | 105 | 91 | 87 | 66 | 25 | 45 | 31 |
| PP-COM II | 114 | 99 | 90 | 60 | 104 | 20 | 104 | 105 | 104 | 91 | 86 | 66 | 24 | 31 | 30 |
| PP-COM III | Meaningless | Meaningless | 87 | 51 | 104 | 5 | 104 | 102 | 103 | 89 | 82 | 56 | 15 | 4 | 9 |
| PP-COM IV | Meaningless | Meaningless | 90 | 59 | 103 | 21 | 103 | 102 | 103 | 91 | 87 | 65 | 20 | 49 | 31 |

It can be seen that the selection of appropriate values for platooning characteristics, like the initial and maximum number of trucks in platoons, the intra-distance of trucks within a platoon, the inter-distance between platoons of trucks driving on the DFL, and termination of platooning strategy at an adequate distance upstream of off-ramps would help to improve the traffic performance considerably, compared to the reference scenario. An increase of more than 18% in capacity of the off-ramp and a decrease of 13% in average travel time of all vehicles are among the results of applying the PP-COM scenarios, compared to the reference scenario. Moreover, in such platooning strategies a decrease of about 50% in the average number of accelerations and decelerations of vehicles can be expected (Scenario PP-COM III), compared to the reference scenario. Finally, a reduction by 96% of the dangerous TTC values is found (Scenario PP-COM III), which may indicate the improvement of the traffic safety by applying appropriate platooning strategies at off-ramps.

## 4.5 Necessity for applying traffic signals

It is indicated that platooning of trucks led to a more safe situation, compared to the reference scenario at both on- and off-ramps. For instance, scenarios P-S 85 and PP-COM III of the on- and off-ramp analysis, were lead to a higher degree of safety, represented by TTC< 1.5 s, compared to the reference scenarios (see tables 4.6 and 4.16). However, from a technical and legal point of view, it is not allowed to let manually driven vehicles merge into a flow of fully automated vehicles. A technical failure of a car would create a very dangerous situation in a mixed flow of automated trucks and manually driven vehicles.

It is obvious that the applied simulation model can not estimate the probability and impact of a technical failure of an ACT or of an error of a driver of a MDV crossing the path of an ACT at the wrong time, however, in reality this might happen. Therefore, it is required to apply additional traffic control measures, like traffic signals, to create safe gaps between the flow of the ACTs and MDVs at on-/off-ramps. Although traffic signals which completely stop the mainline flow on motorways currently are used only for closing individual lanes and not the total mainline flow, such a possibility will be investigated in order to estimate its theoretical impact on the overall performance of traffic.

In the on-ramp analysis traffic signals are applied on the DFL and the on-ramp, while in off-ramp analysis, traffic signals are assumed to be installed on the DFL and on the right lane of motorway for vehicles exiting the motorway.

Four different options of traffic signal control are applied in order to assess the impact of giving priority to different user classes, and also to indicate the influence of the total cycle time on the performance of the platooning scenarios. These options are described as follows:

- Option 1: an equal green time of 60 s for both the flow of ACTs on the DFL and the on-ramp flow (in on-ramp analysis) and the off-ramp flow (in off-ramp analysis), respectively;

- Option 2: an equal green time of 120 s for both the flow of ACTs on the DFL and the on-ramp flow (in on-ramp analysis) and the off-ramp flow (in off-ramp analysis) respectively;

- Option 3: priority is given to ACTs driving on the DFL with assigning a longer green time to this flow (e.g. 120 s) compared to the green time assigned to the on-ramp flow (e.g. 60 s) and the off-ramp flow (e.g. 60 s);

- Option 4: priority is given to the on-/off ramp flow of vehicles by assigning a longer green time to this flow (e.g. 120 s) compared to green time assigned to the flow of ACTs driving on the DFL (e.g. 60 s).

In order to evaluate the impact of applying traffic signal control on the traffic, ‘P-COM I’ and ‘PP-COM I’ scenarios are selected as representative scenarios of on- and off-ramp analysis and compared with one of the above four options of traffic signal control. The major results of simulations concerning on-/off-ramp analysis are illustrated in figures 4.20 and 4.21 separately (An overview of results of simulations can be found in tables D.15 and D.16 in Appendix D, respectively).

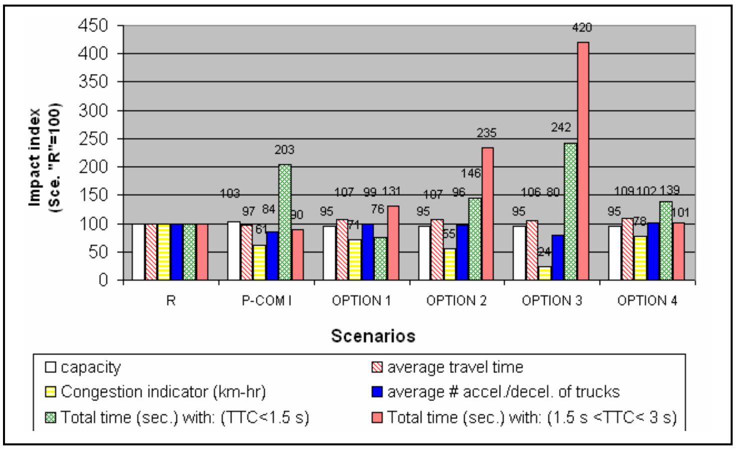



**Figure 4.20. Impact assessment of traffic signal control on the performance of platooning strategies at on-ramps**

In all options of traffic signal control the capacity of *the on-ramp* has decreased by about 8% compared to the scenario P-COM I. Application of traffic signal even leads to a lower capacity of the on-ramp (about 5%) in case of the platooning scenarios, compared to the reference. Not any difference is reported concerning the impact of the length of the green time on the estimated overall capacity at on-ramps.

The findings of simulations also indicate that the change in number of accelerations and decelerations of vehicles is very sensitive to the assigned green time to different user groups. For instance, if platoons of trucks on the DFL receive priority, by doubling the assigned green time, this leads to a 20% decrease of the number of accelerations and decelerations of vehicles compared to the reference scenario. Moreover, the selection of an equal green time for both flows on the mainline and the on-ramp does not improve the traffic condition, compared to the platooning scenario without any signal (see OPTION 1 and OPTION 2 in figure 4.20).

Indeed, the application of a traffic signal control on both the DFL and the on-ramp eliminates possible direct hindrance between both flows of MDVs and ACTs at on-ramps by enforcing a stop of one of the flows in conflict. The selection of an appropriate time for traffic signals on the DFL and on-ramp might create a smooth flow of ACTs and MDVs with a minimum possible number of stop and go conditions by an appropriate dynamic traffic signal control according to the actual density of both flows.

The results of simulations also support the important role of traffic signal control on the change of the level of congestion at on-ramps in case of platooning of trucks.

It can be seen that the selection of an appropriate time for traffic signal control (as in OPTION 3 in figure 4.20) creates a lower level of congestion, compared to the reference scenario, and also compared to platooning scenarios without traffic signal control.

Figure 4.20 shows clearly the benefits of applying traffic signals at on-ramps from safety point of view. The selection of a suitable green time for traffic signal control decreases the number of dangerous TTC values compared to the reference scenario by about 34%. However, the assignment of a longer green time to trucks in platoons (e.g. 120 s compared to 60 s for the on-ramp flow) creates more dangerous TTC values, even compared to platooning scenarios without signals (about 40%).

Considering all indicators together, it can be concluded that the application of traffic signal control with an appropriate signal time, does not decrease the performance of on-ramp areas in case of platooning of trucks on the DFL, considerably.

The interruption of platooning upstream of on-ramps might be a competitive control strategy in case of no traffic signals are applied at on-ramps. In such a case, trucks would approach to the on-ramp areas in forms of platoons, however they need to be manually controlled at a certain distance before on-ramp areas to ensure traffic safety, but this, of course, is impractical at motorways with frequent on-/off-ramps.

The major results of simulations concerning the impact assessment of traffic control signals on the performance of platooning strategies *at off-ramps* are summarized in figure 4.21. Contrary to the results of the similar analysis for on-ramp areas, the findings indicate clear disadvantages of using traffic control measures for ensuring the safety aspects of trucks platooning at off-ramps. For instance, in all platooning scenarios in which a traffic signal control is applied, the capacity of the off-ramp area is decreased by about 13%, even compared to the reference scenario. It clearly indicates the adverse influence of applying traffic signal control on the efficiency of platooning scenarios (a reduction of 30% in the capacity compared to the PP-COM I scenario).

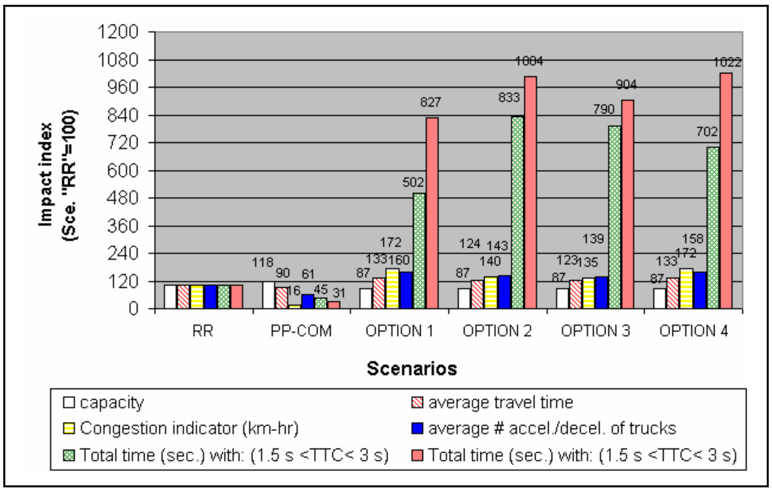



**Figure 4.21. Impact assessment of traffic signal control on the performance of platooning strategies at off-ramps**

The average travel time of the vehicles in all platooning scenarios including traffic signal control is increased by about 23%-33%, compared to the reference scenario. The congestion indicator shows an increase of 35%-72%, and the total throughput of vehicles decreases by about 11% (see table D.16 in Appendix D), compared to the reference scenario. Therefore, a quite negative impact on the traffic performance in case of the platooning scenarios can be expected when the traffic signal control is applied at off-ramps.

The findings of figure 4.21 further show an increase of 40%-60% in the average number of accelerations and decelerations of vehicles, compared to the reference scenario at off-ramps. This is due to cars driving on the mainline confronted with the queue of cars standing upstream of the traffic signal in order to leave the motorway.

The results of analysis also show that the application of a traffic signal control has led to much more dangerous TTC values in case of platooning scenarios, independently from the green time of the signals. The same reason described for increasing the number of accelerations and decelerations of vehicles at above are valid here, too. In brief, it can be concluded that the application of traffic signal control at off-ramps leads to a dramatic decrease in the performance of the platooning strategies.

Thus, on the one hand, it was described that the existing of traffic signals at off-ramps is necessary to ensure a safe crossing for MDVs at conflict areas with ACTs passing off-ramps[5]. On the other hand, the simulation findings indicate that the application of traffic signals on the mainline leads to more dangerous situations.

Two possibilities can be considered in order to reduce the negative impact of the application of the traffic signal control at off-ramp areas of motorways:

- to create an extra lane for cars leaving the mainline (standing upstream of the traffic signal control);
- to implement an Intelligent Speed Adaptation (ISA) system for controlling the speed of cars approaching to the off-ramp area (location of the traffic signal control), externally.

The impact of creation of an extra lane with a sufficient length (about 2 km) for leaving cars at off-ramps is evaluated (Figure 4.22).

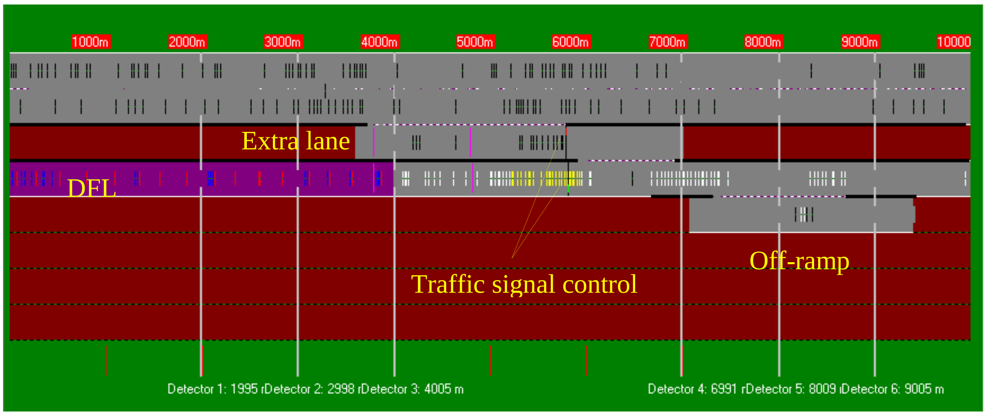



**Figure 4.22. An extra lane created for cars leaving the mainline**
**(screen picture from SiMoNe)**

Figure 4.23 shows the impact of the creation of an extra lane at off-ramps on the performance of platooning scenarios (see table D.17 in Appendix D for more detailed information). By creating such a lane, the off-ramp capacity in platooning scenarios would increase by about 18 %, compared to the case in which no extra exit lane is applied (for instance compare the OPTION 2 cases in tables 4.21 and 4.23). However, other performance indicators like the average travel time of vehicles, the average number of accelerations and decelerations of vehicles, and the total number of dangerous TTC values are not improved, compared to the reference scenario.

platooning strategies at off-ramps with traffic signal controls, two different strategies are evaluated:

[5] Because, we have assumed that the change in control mode of ACTs from automatic to manual mode (and vice versa) only can take place in buffer areas and can not directly be achieved along the road.

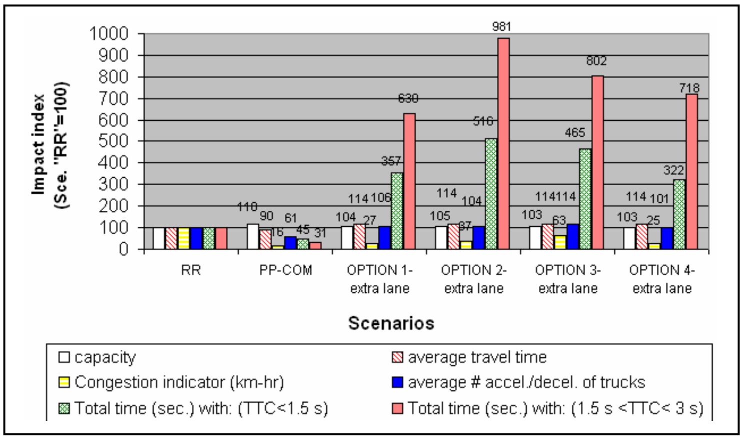



**Figure 4.23. The impact of the creation of an extra lane on the performance of The platooning strategies at off-ramps with traffic signal control**

- In the first strategy, an incremental reduction of speed of ISA cars from 120 km/h at origins to 50 km/h at the traffic signal control section is assumed. This external reduction in speed of ISA cars is implemented at 3 sections with a distance of 1.5, 3, and 4.5 km from the origins. The design speed (maximum allowable speed of ISA cars) in these three sections is assumed to be equal to 100, 80 and 50 km/h respectively.

- In the second strategy, a uniform speed of 80 km/h is assumed for ISA cars along the whole length of the mainline.

These two strategies are simulated for three penetration rates[6] of cars controlled by the ISA system among the whole generated cars, e.g. 20%, 50% and 100%. In the simulation tool, vehicles equipped with ISA will obey the speed limits received from the road-side controller. This speed limit of such vehicles can not be exceeded by themselves.

Figures 4.24, 4.25 and 4.26 illustrate the comparative results of simulations for each of the above ISA strategies, compared to the case in which no ISA strategy is applied (OPTION 1 in the figure 4.21).

Figure 4.24 indicates that the implementation of the first strategy for controlling the speed of cars controlled by ISA systems does not improve the traffic operation indicators (represented by a comparative index in the figure 4.24). Only a slight improvement is seen when a penetration of 100% for cars controlled by ISA systems (driving on the mainline) is analysed. The adverse impact of this ISA strategy is due to a sudden reduction of speed of cars controlled by ISA systems at threshold of sections in which the change in design speed of these cars occurs. Such a rapid reduction in the speed of cars controlled by ISA systems (for instance from 100 km/h to 80 km/h at the

[6] A penetration rate refers to the share of cars which are controlled by the ISA system, compared to all generated cars in a simulation run.

section of 3 km from the origin) creates more severe shock waves in the traffic flow of cars driving on the mainline. The simulation findings indicate that such a negative impact decreases by increasing the share of cars controlled by the ISA system (e.g. from 20% to 100%).

Conversely, the second ISA strategy leads to major improvements in the traffic operation indicators, compared to the case in which no cars are instrumented by the ISA system. For instance, in case of a penetration rate of 20% for driving cars instrumented by the ISA system, an increase of capacity about 15%, an increase of throughput about 10%, a reduction of average travel time by about 10%, and a reduction of congestion indicator about 17% is expected. By increasing the penetration rate of cars controlled by ISA systems by about 100%, the above indicators improve by about 19%, 13%, 8%, and 9% respectively. The marginal increase of average travel time of vehicles by increasing the penetration rate of cars controlled by the ISA system might be due to a lower design speed of these cars (e.g. 80 km/h) compared to ordinary cars in which no ISA system is applied (e.g. 120 km/h).

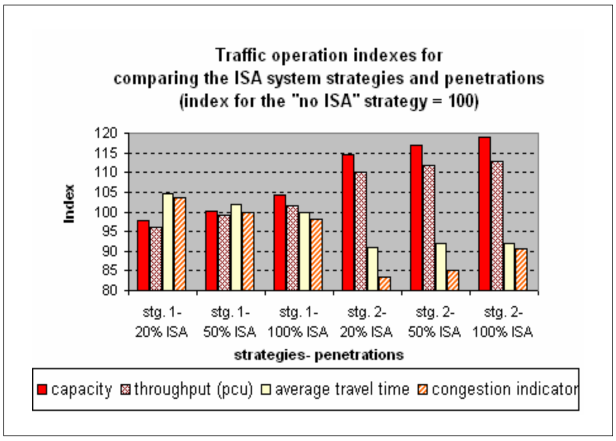



**Figure 4.24. The impact of the implementation of the ISA system on the traffic operation performance of platooning scenarios at off-ramps**

Figure 4.25 presents the simulation results concerning the number of acceleration and deceleration changes of vehicles, integrally and separately. It indicates that in case of the implementation of the first ISA strategy, the major reductions in the number of acceleration/deceleration changes is related to the case in which all generated cars are ISA cars (e.g. Strategy 1- 100% ISA). In such a case, a reduction of 12% in the total changes of accelerations and decelerations of vehicles would be expected, compared to the case in which all generated cars are ordinary cars. Since the ISA strategy is applied to cars, these vehicles (e.g. cars) gain whereas the trucks might be enforced by a higher number of acceleration and deceleration changes, compared to the “no ISA” case. For instance, the average number of acceleration/deceleration changes of trucks increases by about 11%, compared to the case in which no ISA strategy is applied to cars.

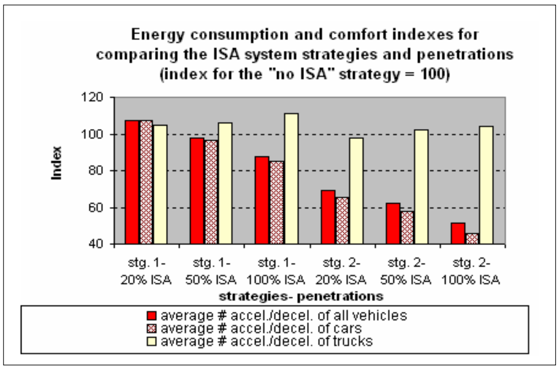



**Figure 4.25. The impact of the implementation of the ISA system on the comfort performance of platooning scenarios at off-ramps**

Compared to the first ISA strategy, figure 4.25 indicates that the implementation of the second ISA strategy causes much more benefits with regard to the number of acceleration/deceleration changes of vehicles. In such a case, even a penetration rate of 20% for cars driving with the system of ISA leads to a reduction of the total number of acceleration/deceleration changes of vehicles by about 30%, compared to the “no ISA” scenario. This indicator ( # acceleration/deceleration changes of vehicles) night improve by about 50%, compared to the “no ISA” scenario when a penetration rate of 100% is implemented. Similar to the findings of the first ISA strategy, this improvement mostly is related to cars, rather than trucks. The optimal result of the number of acceleration/deceleration changes of trucks in this second strategy is related to the case in which a penetration rate of 20% for cars driving with the ISA system is assumed; however, the differences among various penetration rates are marginal (e.g. 7%).

The most important advantage of the implementation of an appropriate ISA strategy is related to the safety indicators. As it is shown in the figure 4.26, the implementation of the second ISA strategy might cause a major reduction of the dangerous TTC values, compared to the “no ISA” case (e.g. about 35%). However, the implementation of the first ISA strategy does not lead to a better safety situation, compared to the “no ISA” case. The main reason underlying such a result is the sudden reduction of speed of cars, controlled by the ISA system, at sections in which a new upper limit of the speed is defined. Indeed, a sudden reduction of the speed of cars driving with the ISA system causes more severe shock waves for the following cars on the mainline. Since cars with the ISA system is controlled externally, actually it is very difficult to decrease the desired speed of these cars continuously along a limited length of the road to ensure a safe reduction of the speed of cars from 120 km/h to 50 km/h at the off-ramp area.

A similar analysis is conducted in which the impact of the implementation of the ISA strategy in case of an extra lane is evaluated. In this analysis, a penetration rate of 20% for cars controlled by the ISA system is assumed. The two above ISA strategies are evaluated, separately. The results of the simulation indicate that in such a case for minimizing the hindrance of flow of approaching cars on the mainline by vehicles stopping at the back of signal (for leaving the mainline), only the second ISA strategy

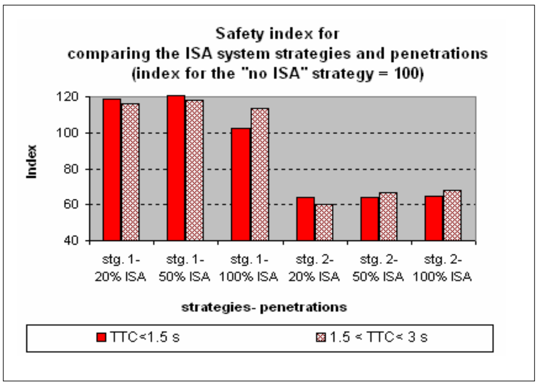



**Figure 4.26. The impact of the implementation of the ISA system on the safety of platooning scenarios at off-ramps**

has a slight influence on improving the performance of the motorway at off-ramps, compared to the case where only an extra lane is created. Figures D.1 to D.3 in the Appendix D present the relative traffic performance indexes (e.g. for the traffic operation, traffic comfort, and safety aspects, respectively) compared to the case in which only an extra lane is implemented.

The construction of a fly-over for one of the crossing traffic flows (either leaving cars or passing trucks on the DFL) at off-ramps can be considered as the ultimate possibility to improve the capacity and level of safety of flow of ACTs and MDVs at off-ramp areas. This option is not investigated in this study.

## 4.6 Summary

This chapter described the concept of truck platooning as one of the main control strategies when automatically controlled trucks are operating on motorways. In order to assess the required platoon characteristics which might improve the performance of operation of ACTs, a simulation study was conducted.

The results of simulations indicate that at on-/off-ramps, due to the hindrance of flow of platoons of trucks by crossing cars, a platooning scenario does not lead to a higher traffic performance, necessarily. However, it emphasizes the major role of the variables ‘number of trucks in platoons’ and ‘inter-distance of platoons’ on improving the performance of the platooning strategy at on-/off-ramps.

The application of additional traffic control measures, like traffic signals control, is defined essential while applying a continuous platooning strategy to ensure safety specially at on-ramps. However, at off-ramps the application of traffic signals control alone is not sufficient. It still might create a very dangerous situation on the mainline, due to stopping vehicles at the back of the traffic signal control at the off-ramp. Therefore, in order to create a safe situation at off-ramp areas, it is recommended to apply an extra lane for cars leaving the mainline flow (in case of existence of the required space) or to implement an appropriate ISA strategy for cars on the mainline.

Although applying a platooning strategy in a continuous form at on-ramp areas would not increase the capacity of motorways at on-ramps, it would result in a lower number of accelerations and decelerations of vehicles, by about 20%. This reduction in the number of accelerations and decelerations mostly is related to trucks driving within platoons. Selection of an appropriate green time for both platoons of trucks on the DFL and the on-ramp flow, also would lead to an improvement in safety (by about 24%). Therefore, the application of a platooning strategy at on-ramps would improve the performance of the traffic flow with regard to comfort, energy consumption and safety, rather than capacity.

The discontinuation of platooning of trucks upstream of an on-ramp area results in an increase in capacity, equal to 7 % and 15% compared to the case in which no platooning is applied and the continuous platooning scenario, respectively. It leads to better results with regard to almost all indicators. Thus, it can be assumed as a competitive option for applying platooning at all length of the DFL. A decision about the location and the optimal length for applying the platooning control strategy depends on the density of on- and off-ramp areas. The closer the distance between on-/off-ramp, the lower the performance of the discontinuous platooning case (without traffic signal control) compared to the case in which continuous platooning scenario is applied (with traffic signal control).

At off-ramp areas, the application of traffic signal control reduces the traffic performance compared to the case in which no traffic signal is applied. A reduction of 30% in the capacity of the off-ramp area and an increase of 43% of the average travel time of vehicles are expected. Even, a decrease of the comfort and the safety indicators are expected, due to the creation of queues of vehicles stopping upstream of the off-ramp area. In order to recover a part of this disutility it is recommended to apply an extra lane for vehicles leaving the mainline (in case of the existence of an adequate space for creating this extra lane) or to apply VMS systems which inform the cars driving at upstream of the off-ramp about the need for reducing their speed. This synchronization of the speed can be applied more effectively by changing the control mode of a part of ordinary cars by the ISA system and the implementation of an appropriate ISA strategy at upstream of off-ramps.

By creating an extra lane at off-ramps, the capacity in platooning scenarios increases by about 18 %, compared to the case in which no extra exit lane is applied. However, other performance indicators like the average travel time of vehicles, the average number of accelerations and decelerations of vehicles, and the total number of dangerous TTC values are not improved.

The implementation of an appropriate ISA strategy at upstream of off-ramp areas (e.g. the selection of a constant desired speed of 80 km/h for cars driving on the mainline and controlled by the ISA system) also leads to benefits for the performance of platooning scenarios at off-ramps. In case of a penetration rate of 20% for cars controlled by the ISA system, the capacity improves about 15%, the average travel time decreases by about 9%, the average number of acceleration/deceleration changes of vehicles decreases by about 50%, and specially the dangerous TTC values decreases by about 35%, compared to the case in which no ISA strategy is applied. Thus, the application of an extra lane or the implementation of an appropriate ISA strategy for cars at off-ramp areas might compensate a part of the disutility caused by the application of the traffic signal control at off-ramp areas.

Termination of the platooning strategy upstream of an off-ramp area is proposed as another solution for increasing the performance of the platooning strategies at off-ramps. In such a case, the control mode of platooned trucks on the DFL would be changed from the platooning mode (and consequently automatic mode) to the manual mode at an adequate distance upstream of an off-ramp (about 2 km). Such a change in the control mode of trucks, would avoid the necessity for applying traffic signals at off-ramps and may create a continuous (uninterrupted) flow of trucks and cars at off-ramp areas. By applying such a platooning strategy, an increase of 18% in capacity of off-ramps could be expected. The simulation findings also indicate that in case of platoons terminating upstream of off-ramps, a decrease of 10% in the average travel time of vehicles, a reduction of 40% in the average number of accelerations and decelerations of vehicles, and an improvement of the dangerous TTC values by about 55% are expected, compared to the case in which no platooning strategy is applied.

A summary overview of results of simulations, presented in all previous chapters, indicates the capability of truck automation for improving the performance of existing motorways. However, the benefits mostly are related to comfort and safety, rather than capacity and throughput. This finding would be plausible because the high potential of traffic performance of ACTs, alone, on uninterrupted road sections would be hampered by traffic flow of MDVs (crossing the DFL) at on-/off-ramps. It means that the resultant capacity gain of the operation of fully automated vehicles (ACTs), while operating in a fully automated environment, heavily would be affected by traffic flow of ordinary vehicles (MDVs) when two user groups (e.g. ACTs and MDVs) will reach each other at on-/off-ramps.

In order to avoid possible collisions of ACTs and MDVs, additional traffic control measures at *on-ramps* are considered necessary to create a safe situation for the operation of automatic vehicles, while the safety at *off-ramps* can be ensured only by adding extra lanes, implementing appropriate ISA strategies for cars driving on the mainline, or building fly-overs on the DFL for platoons of trucks.

Another specific benefit of the operation of ACTs, compared to the traffic flow of manually controlled trucks, is the quasi deterministic state of flow of ACTs. This capability could provide additional advantages for automated vehicles by minimizing the hindrance of flow of them by MDVs at on-/off-ramps based on the estimated flow of merging/diverging cars at on-/off-ramps, and the regulation of flow of ACTs approaching to the on-/off-ramps. This reduction in the degree of hindrance may provide a higher performance of traffic flow at on-/off-ramps.

The next chapter describes the flow dynamics equations of vehicles at on-/off-ramps, more in detail. Then, the structure of equations will be developed in such a way that it describes the behavior of automated vehicles, rather than manually controlled vehicles. Finally, the equations will be included within an optimization model which is aimed to improve the performance of the traffic on motorways at on-/off-ramps.

# 5
# Flow Control Optimization at Motorway Ramps

## 5.1 Introduction

In chapter 2 it was described that traffic control and drivers' behavior are two mutually dependent processes in the ordinary state of traffic flow with different objectives. Traffic control measures influence the drivers' possibilities in choosing their preferred option of flow. Conversely, the choices made by drivers influence the strategy of control based on the existing tools. This makes the optimization process very complicated. The application of optimization methods, so far, has been mostly neglected in the literature of traffic flow (Papageorgiou (1997), Van Zuylen and Taale (2000)).

By contrast, when vehicles are fully automated, the gap distance a vehicle maintains from the vehicle in front, its speed and its route from entry to exit of the motorway, are all determined by the vehicle's feedback control laws. This may encourage applying optimization techniques for traffic flow control on roads.

Thus, automation at least offers two major benefits for the operation of ACTs:

- promotion of the capabilities of ACTs compared to ordinary trucks including the decrease of the reaction time for ACTs which may improve the volume of ACTs on DFL s due to smaller headway times;

- development of methods for controlling the motion of ACTs by the operator of the system via optimal control strategies.

The road operator may generate much benefit if the flow of automatically controlled trucks and manually driven vehicles could be mixed. In order to reach such a state, it is required to develop a model in which all components of traffic control are taken into account.

In the previous chapters, the higher capabilities of operation of platoons of ACTs compared to ordinary trucks were evaluated by using a simulation tool. In fact, the previous analysis did not consider the whole range of automation of ACTs. A more advanced capability of ACTs might include the possibility that the flow of ACTs could be harmonized with the flow of MDVs in order to increase capacity at bottlenecks, like on/off-ramps.

Thus, the fully controlable flow of ACTs leads to a flow optimization model in which the objective function is defined by the system operator, like the average travel time, or average fuel consumption of vehicles. The model is subject to constraints which describe the flow dynamics of the user groups (e.g. ACTs and MDVs) nearby on/off-ramps, the upper and lower bounds of flow components (e.g. speed and density) for each of the user groups, the interaction of flow between ACTs and MDVs at on/off-ramps, the impact of traffic control devices, and the definition of buffer area characteristics etc. Figure 5.1 describes the structure of the proposed optimization model.

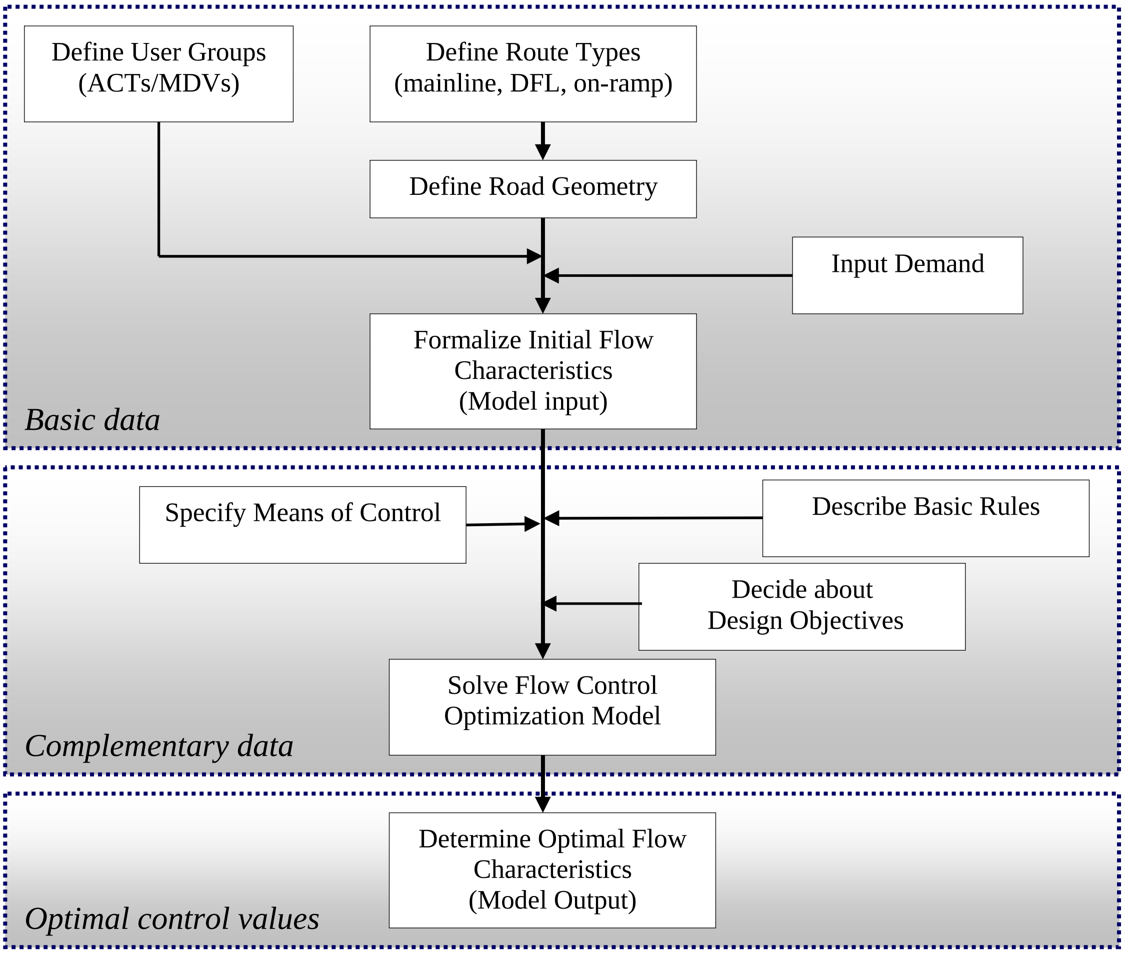



**Figure 5.1. Design of the traffic flow control optimization model**

As it is shown in the above flowchart, the optimization process includes three steps: in the first step the basic data will be defined. This data includes information concerning the types of user groups, route types, and traffic demand. For instance, we can divide the user groups in two different groups, namely ACTs and MDVs. While the ACTs can be fully controlled by the Traffic Control Center (TCC), the MDVs are controlled only by the drivers, who might not fully respect the messages sent via Dynamic Route Information Panels (DRIPs) or Variable Message Signs (VMS). It would be necessary to specify which user group is permitted to drive at which time period on which part of the road. It is clear that only ACTs are permitted to drive on DFLs. It would be necessary to specify the road geometry, like the number of lanes of each part of the road (DFL, mainline, on/off-ramp), the length of road segments, the capacity of each segment, etc. Another important data in this step is to assume or estimate the input flow of each of the user groups approaching to the merging or diverging area, including DFL, mainline, and on-/off-ramps, for the certain time period of analysis. Based on results of analysis in chapter 3, a minimum share of 20% for trucks in the mainline flow should be taken into account to justify the existence of a separate DFL for trucks. This input flow, in addition to the road geometry design forms the basic input of the optimization model.

When the basic data is defined, it is necessary to describe the complementary data. The complementary data includes the rules, control strategies, and design objectives. The rules mean constraints which are to be followed in order to lead to optimal values. For instance, the flow conservation rule within the total time period of analysis must be assured. Other possible issues are the upper and lower limits for some design variables of the optimization model, such as the speed and the density of user groups in each road segment. Further, the impact of traffic signals, buffer areas, and other means of traffic control, like applying ISA are to be defined here.

The third important element in this model is to specify which criteria are to be optimized. For instance, it must be described whether the main aim of the flow control optimization is to minimize the average travel time of ACTs or MDVs, or of both of these user groups. The structure of the proposed flow control optimization model, indicating the objective function, design variables and constraints of the model can be found in Appendix E[1].

When the model formulation is achieved, it is necessary to apply a tool which can solve the optimization model. The selection of an appropriate tool for solving the optimization model depends on factors like the type of model formulation (e.g. linear, non linear), the dimensions of the model, etc. The findings for different control strategies of the optimization models may be compared to determine which control strategy is most beneficial.

The next sections give more information concerning the model formulation and the selected tool for solving the proposed flow optimization models. The indicators, which will be used as a basis for the comparison of different scenarios for control and design, will be described, too.

[1] The next sections of this chapter give more information about the basic structure of the model elements, including design and control variables, constraints and objective functions.

## 5.2 Model formulation

This section gives an overview about the structure of the proposed optimization model which may be applied to control the traffic flow components of each of the user groups of the system. Since MDVS are manually driven, extra control devices, like traffic signals or buffer areas at on-/off-ramps are assumed to control the flow of MDVs while entering to the mainline (at on-ramp areas) or exiting the mainline flow (at off-ramp areas).

The proposed optimization model takes into account the required constraints for simulating the traffic flow of ACTs and MDVs on a macroscopic level. The macroscopic traffic flow model helps to assess the impact of different control strategies, like the syncronization of speed of user groups, or the application of buffer areas with different geometry designs. Due to a lower number of flow components in a macroscopic model (e.g. speed and density), it also might help to reduce the complexity of the optimization model. An analysis of the traffic control solution on a microscopic level is out of the scope of this dissertation.

For the purpose of model formulation, the following categories of rules are taken into account:

- Definition of the flow dynamics of ACTs and MDVs on all parts of the road (DFL, mainline, on/off-ramp);
- Definition of the upper and lower bounds for all decision variables;
- Determination of the merging/diverging capacity at on/off-ramps;
- Development of the constraints related to buffer areas;
- Definition of the objective function(s).

In order to determine the dynamics of traffic flow for each of the above categories, the parts of roads are divided to different segments (cells). Figure 5.2 indicates a schematic layout of the motorway that is divided in segments. For each cell, the equations with respect to each of the above categories are developed. In the following subsections more detailed information about each of categories of constraints is given.

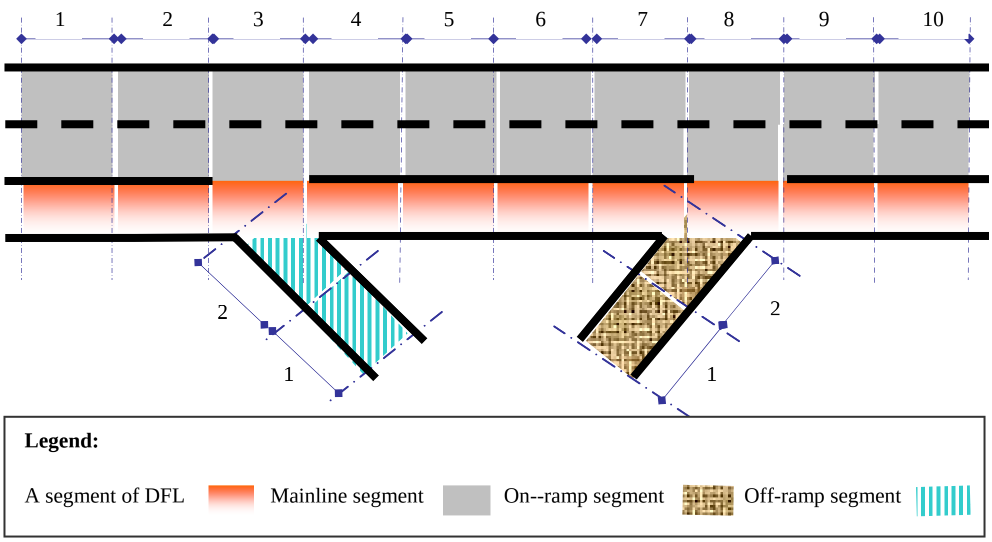



**Figure 5.2 Definition of segments of the motorway and on-/off-ramps**

### 5.2.1 Dynamics of flow of user groups

Three main types of continuum macroscopic models have been addressed in the literature (Hoogendoorn and Bovy (2001)):

(a) Lighthill-Whitham-Richards models (dynamic equation of density);
(b) Payne-type models (dynamic equations of density and speed);
(c) Helbing type models (dynamic equations of density, speed, and speed variance).

The first category of models only considers the dynamic equations of density. The second group adds the dynamic equation of the speed to the initial set of dynamic equations. The Helbing-type models consider the dynamic of the speed variance, too. Based on the required parameters for modeling and according to the pursued objective of this research study, the second type of modeling (namely Payne-type) is selected for the description of dynamics of flow of ACTs. Therefore, this category of equations includes the equations related to conservation of flow of ACTs, the (equilibrium) speed-density relationship of ACTs, the dynamic equation of speed of ACTs, and the derivation of the flow from speed and density. It is emphasized here that the selection of other types of flow dynamics equations also is possible.

- *Flow Conservation*

The conservation equation mainly assures that the traffic flow of vehicles between each segment remains consistent with the change of speed and density (Papageorgiou (2001)). Figure 5.3 illustrates this constraint:

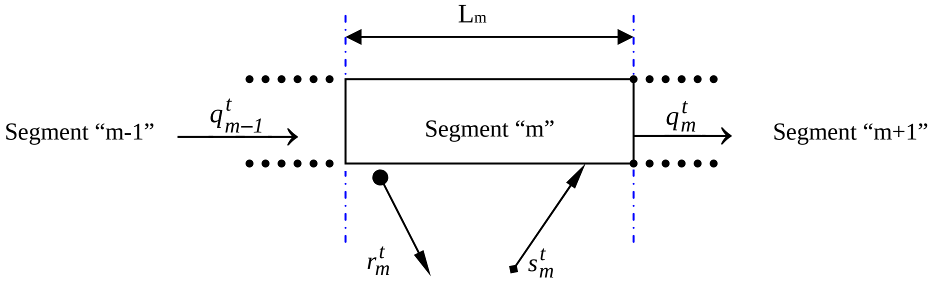



**Figure 5.3. Simple diagram indicating the constraint of flow conservation**

In this figure:

$q^t_m$ : Output flow of segment "m" of the road at time "t" (veh/h);

$q^t_{m-1}$ : Output flow of segment "m-1" of the road (the input flow of segment "m" of the road) at time "t" (veh/h);

$r^t_m$ : Exit flow from segment "m" of the road at time "t" (directed to the off-ramp) (veh/h);

$s^t_m$ : Entrance flow to the segment "m" of the road at time "t" (directed via the on-ramp) (veh/h);

Normally, the conservation of flow is represented by the equation (5.1):

$$k_m^{t+\Delta t} = k_m^t + \left(\frac{\Delta t}{3600 L_m}\right)\left(q_{m-1}^t - q_m^t - r_m^t + s_m^t\right) \tag{5.1}$$

where:

$\Delta t$ : Assumed time interval (sec);

$k_m^{t+\Delta t}$ : Flow density on segment “m” of the road at time “$t+\Delta t$” (veh/km);

$k_m^t$ : Flow density on segment “m” of the road at time “$t$” (veh/km);

$L_m$ : Length of segment “m” of the road (km).

However, we need to make some improvements of this equation in order to:

(1) describe the impact of a buffer area as an additional mean in specific road segments;
(2) indicate the flow connection between the DFL, the mainline, and the on/off-ramp (flow conservation at on-/off-ramps).

To reach the first aim, we add two terms to the equation 5.1 in order to define the existence of a buffer area in a specific road segment of routes (DFL, mainline, on/off-ramps). In such a case, the equation 5.1 will be reformulated as:

$$k_m^{t+\Delta t} = k_m^t + \left(\frac{\Delta t}{3600 L_m}\right)\left(q_{m-1}^t - q_m^t - r_m^t + s_m^t - Iin_{bm}^t + Iout_{bm}^t\right) \qquad (5.1\text{-a})$$

Where:

$Iin_{bm}^t$ : Flow directed from the road segment “m” to the buffer area “b” at time “t” (veh/h);

$Iout_{bm}^t$ : Flow directed from the buffer area “b” to the road segment “m” at time “t” (veh/h).

And to describe the connection between two different routes which intersect each other, in the segment of the DFL (and similarly the mainline) which is intersected by the last segment of the on-/off-ramp, the terms $r_m^t$ and $s_m^t$ are to be replaced by the flow components resulting from the modelling of the last segment of the on-/off-ramp. For instance, in figure 5.4 the segment 2 of the on-ramp has an intersection with segment 8 of the DFL (or mainline).

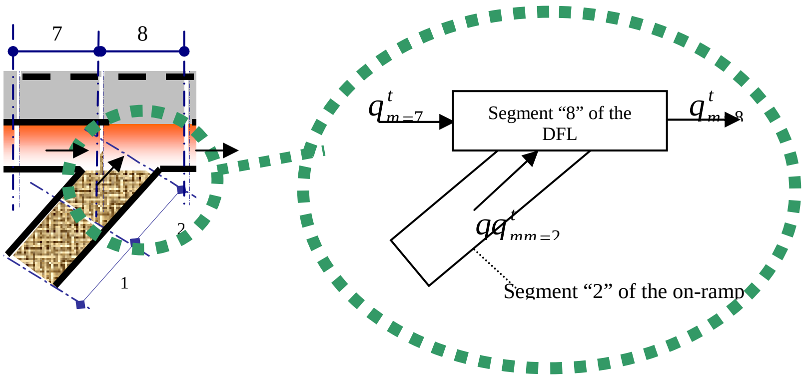



**Figure 5.4. Description of flow connection between the DFL and on-ramp**

Thus, to take into account this connection between flow components on both DFL (or mainline) and on-ramp, it is necessary to describe the term $s^t_{m=8}$ by the following equation:

$$s^t_{m=8} = qq^t_{mm=2} \qquad (5.1\text{-b})$$

In which:

$qq^t_{mm=2}$ = Output flow of vehicles from segment 2 of the on-ramp (veh/h).

The definition of such a connection provides the possibility for speed or density synchronization near on/off-ramp areas.

The input flow for the first segments of each route (DFL, mainline, and on-ramp), is the assumed volume of vehicles as input for the model.

- *Speed-density relationship*

A lot of speed-density models have been reported in the literature of traffic flow theory (Georlough and Huber (1975), Gartner et al. (1992)). For the purpose of this study, an exponential relation as described in equation (5.2) has been chosen to model the change of equilibrium speed of vehicles due to the change of flow density in each segment of the assumed route. The results of simulation, carried out in previous chapters, also indicate that using such a formulation for indicating the speed-density relation can interpret the speed-density relationship for the assumed layout of the motorway properly. However, it is emphasized that the selection of other continuous forms of speed-density formulations is possible to be included in the structure of the proposed optimization model.

$$v^t_{e,m} = v^t_{f,m} \cdot e^{-\frac{1}{2}\left(\frac{k^t_m}{k_{cr,m}}\right)^2} \qquad (5.2)$$

Where:

$v^t_{e,m}$ : Equilibrium speed of segment “m” of the road at time “t”;

$v^t_{f,m}$ : Free flow speed of the assumed user group on segment “m” of the road at time “t”;

$k_{cr,m}$ : Critical density of the assumed user group on segment “m” of the road.

The results of simulation (see Appendix F) indicate a good fit of the values given in table 5.1 for each of the assumed user groups in this equation.

**Table 5.1. Selected values describing the speed-density relation for user groups**

| Parameter | User group | |
|---|---|---|
| | ACT | MDV |
| $v_f$ (km/h) | 88 | 120 |
| $k_{cr}$ (veh/km/lane) | 18 | 30 |
| $k_j$ (veh/km/lane) | 60 | 125 |

Figure 5.5 indicates the speed-density relation for ACTs and MDVs applied here.

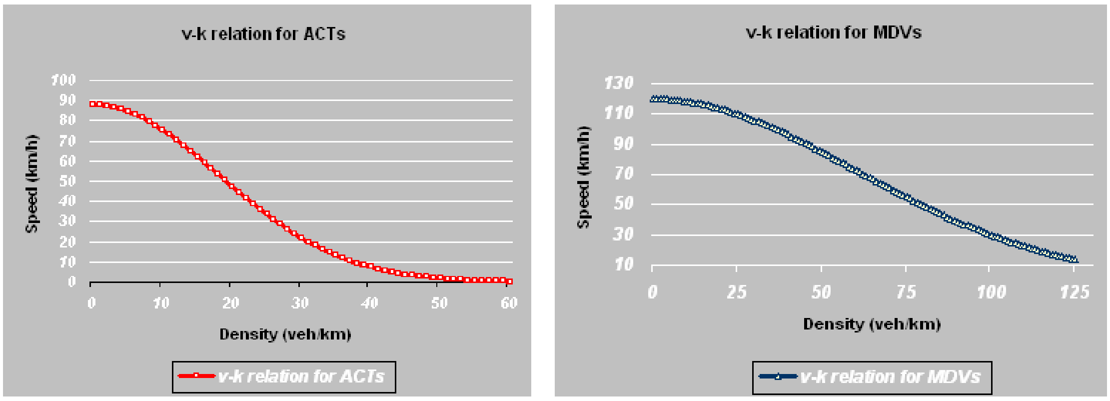



**Figure 5.5. Applied speed-density relation for ACTs and MDVs**

- *Variation of the speed*

The variation of speed of vehicles on each segment of the road during each time interval is derived from the following equation (Kotsialos et al. (1998), Kotsialos et al. (1999), Hoogendoorn and Bovy (2001)):

$$v_m^{t+\Delta t} = v_m^t + \left(\frac{\Delta t}{\tau}\right)\cdot\left(v_{e,m}^t - v_m^t\right) + \left(\frac{\Delta t}{3600 L_m}\right)v_m^t\left(v_{m-1}^t - v_m^t\right) - \frac{\nu \Delta t (k_{m+1}^t - k_m^t)}{\tau L_m (k_m^t + \kappa)} \qquad (5.3)$$

where:

$v_m^{t+\Delta t}$ : Speed of vehicles on segment "m" of the road at time "$t+\Delta t$";

$v_m^t$ : Speed of vehicles on segment "m" of the road at time "t";

$\tau$ : Relaxation factor, describing the convergence of the mean speed of a segment to its equilibrium value;

$\nu, \kappa$ : Anticipation constants, representing the impact of the change in density of vehicles in the next segment on the speed of vehicles in the previous segment;

In the literature (Kotsialos et al. (1998), Kotsialos et al. (1999)), the calibration of the above equation is given for segments of motorways on which the influence of lane-closure and on-/off-ramps is neglected. A similar approach can be selected to verify the influence of lane changing of vehicles at on-/off-ramp areas on speed changes of vehicles at merging/diverging areas. With regard to this issue, the comments of Ngoduy and Hoogendoorn are worth noting (Ngoduy and Hoogendoorn (2003)).

Moreover, due to the special characteristics of the operation of ACTs where the driving is controlled by the TCC (and not the driver), the anticipation term in equation (5.3) can be neglected for ACTs. Since ACTs on different segments communicate with each other continuously, the impact of this term on the change in speed of ACTs is neglected. However, even if this term were included, the only additional requirement is to estimate the anticipation constants ($\nu,\kappa$) for ACTs.

- *Computing the flow*

Evidently, the flow rate of a certain user group on each segment "m" of the road during each time interval "t" is the product of speed and density:

$$q_m^t = k_m^t . v_m^t \tag{5.4}$$

Figure 5.6 indicates a schematic diagram of the flow-density relation, based on equation (5.2) to estimate the speed of the vehicles in equation (5.4).

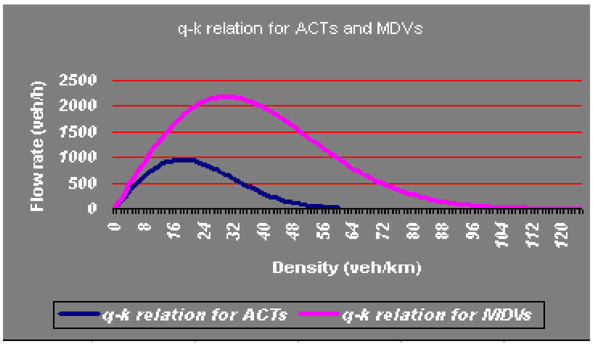



**Figure 5.6. Applied flow-density relation for ACTs and MDVs**

### 5.2.2 Upper and lower bounds

Density, speed and flow of vehicles in each segment of roads are limited by the jam density, free flow speed, and capacity of each segment, respectively. Moreover, each of these variables should have a positive value. Therefore, it is only permitted to assign values to these variables, e.g. density, speed and flow of ACTs and MDVs, within the upper and lower bounds. This can be formulated as:

$$0 \le k_m^t \le k_{j,m}^t \; ; \quad 0 \le v_m^t \le v_{f,m}^t \; ; \quad 0 \le q_m^t \le cap_m^t \tag{5.5}$$

In which:

$k_{j,m}^t$ : Jam density on segment "m" at time "t" for the user group in the segment;

$v_{f,m}^t$ : Free flow speed on segment "m" at time "t" for the user group in the segment;

$cap_m^t$ : Capacity of segment "m" at time "t".

Based on the dependence of flow from speed and density, the capacity can be calculated from the following equation:

$$cap_m^t = k_{cr,m}^t v_{f,m}^t e^{-0.5} \tag{5.5-a}$$

### 5.2.3 Estimation of on/off-ramp capacity

The impact of merging (or diverging) vehicles on passing vehicles at on-ramps (or off-ramps) must necessarily be taken into account in the structure of the model. Therefore, at segments which are located at the intersection of on/off-ramp areas this restriction must be considered.

In order to formulate the capacity at on/off-ramp areas, we need to specify the way of control at these areas. Two different kinds of flow control are distinguished: without or with signals.

If there are no traffic signals at on/off-ramps then gap acceptance rules are to be applied. Lertworawanich and Elefteriadou (2000, 2001) in their estimation use a rather simple gap acceptance rule to calculate the capacity at weaving areas. A similar model structure may be used here to calculate the maximum possible lane changing at merging areas (or similarly at diverging areas):

$$SD(t) = \frac{L_{ACT} + L_{MDV}}{v^t_{m=ii}} + 2RT - \frac{1}{2}\frac{[v^t_{m=ii} - vv_{mm=jj}]^2}{2vv^t_{mm=jj}\,fg} - 0.2 \qquad (5.6\text{-a})$$

where:

$SD(t)$ : Ideal (required) lag distance for crossing of MDVs by ACTs at merging areas at time "t";

$L_{ACT}$ : Average length of ACTs approaching to merging areas on the DFL;

$L_{MDV}$ : Average length of MDVs approaching to merging areas from the on-ramp;

$v^t_{m=ii}$ : Speed of ACTs at time "t" on a segment "ii" of the DFL which intersects the on-ramp;

$vv^t_{mm=jj}$ : Speed of MDVs at time "t" on a segment "jj" of the on-ramp which intersects the DFL;

$RT$ : Average assumed respond time for detection and reaction to objects by ACTs;

$f$ : Coefficient of friction;

$g$ : Gravitational acceleration.

Then, according to Lertworawanich and Elefteriadou equation (5.6-b) can be used to assess the maximum possible flow of ACTs which may cross the flow of MDVs safely:

$$q^t_{m=ii} \le \frac{qq^t_{mm=jj}\,\alpha e^{-\lambda(\frac{SD(t)}{2} - t_m)}}{\lambda^2(\frac{\alpha}{\lambda} + t_m)SD(t)} \qquad (5.6\text{-b})$$

Where:

$$\lambda = \frac{\alpha D^t_{MDV-R}}{1 - t_m D^t_{MDV-R}} \qquad (5.6\text{-c})$$

and:

$q^t_{m=ii}$ : Output flow of ACTs from segment "ii"[2] of the DFL;

[2] A segment of the DFL which intersects the on-ramp.

$qq^t_{mm=jj}$ : Output flow of MDVs from segment "jj"[3] of the on-ramp (crossing the flow of ACTs on the DFL);

$\alpha$ : Percentage of non-clustered MDVs;

$t_m$ : Clustered vehicles' time headway in seconds.

The complicated structure of the above equations for assessing the capacity at merging (or similarly diverging) area, of course, increases the complexity of the proposed optimization model.

Another possibility to include the capacity of merging (or diverging) areas in the set of constraints is to use the results of micro-simulation. In this case, the capacity at the merging (or diverging) area may be estimated for different values of input flow of ACTs and MDVs on different routes (e.g. DFL and on (or off-)-ramp). Based on this information, a regression model may be built in which the capacity at the merging area (or diverging area) is calculated as a function of the input flow of ACTs on the DFL and the input flow of MDVs at the merging area (or diverging area). Equation (5.7) represents such a formulation:

$$q^t_{m=ii} + qq^t_{mm=jj} \leq \beta_1 \cdot D^t_{ACT} + \beta_2 \cdot D^t_{MDV} \qquad (5.7)$$

Where:

$D^t_{ACT}$ : The generated volume of ACTs on the DFL at time "t";

$D^t_{MDV}$ : The generated volume of MDVs on the on-ramp at time "t";

$\beta_1$ and $\beta_2$ : Reduction factors to translate the volume of ACTs and MDVs to the capacity at merging (diverging) areas;

However, as it was described in chapter 4, for safety reasons it is considered necessary to apply traffic signals at on/off-ramps, on both DFL and the on-ramp (or off-ramp) to segregate the conflicting flows of ACTs and MDVs at the junctions. In this case, the following equation can be used to avoid any simultaneous flow of ACTs and MDVs at merging (or diverging) areas:

$$q^t_{m=ii} qq^t_{mm=jj} = 0 \qquad (5.8)$$

### 5.2.4 Buffer area constraints

It is assumed that buffer areas are located on both the DFL (only for ACTs), and on the on-ramp (for both ACTs and MDVs) separately. The mainline buffer controls the flow of ACTs on the DFL approaching to on-ramp areas, and the on-ramp buffers would act

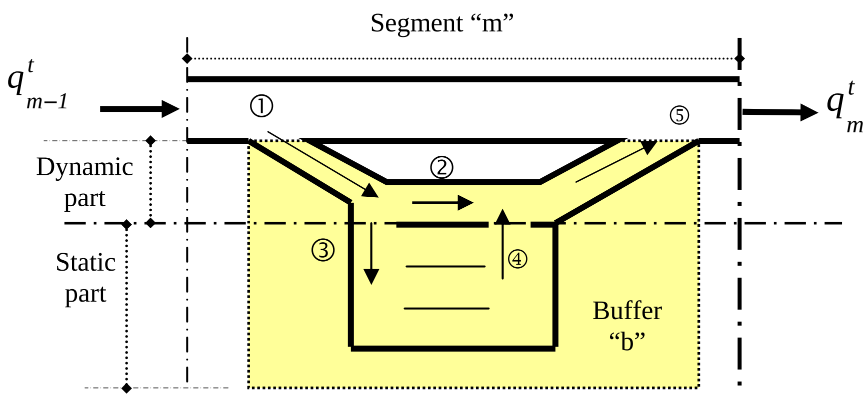
[3] The last segment of the on-ramp which intersects the DFL (or the mainline).

as controllers of on-ramp flow of ACTs and MDVs. For off-ramp areas a similar approach can be applied.

Each buffer area is divided in two parts: *the dynamic part*, and *the static part*. In the dynamic part, vehicles are driving just like a normal segment of the road. Therefore, this part of the buffer acts as an additional lane that may decrease the queue length when over-saturated flow occurs. All the vehicles which are directed to the buffer area pass the dynamic part in order to proceed to the main roadway when here is no risk of congestion. The static part of a buffer area acts as a parking area for vehicles (ACTs or MDVs depending on the buffer type). During peak periods, depending on the capacity of this area, a part of the extra flow will be directed to this area in order to wait until the traffic control center give spermission to proceed. It also allows the road operator to form platoons of ACTs nearby on/off-ramp areas.

Figure 5.7 indicates schematically the two parts of a buffer area and the flow distribution within a buffer area. Based on this figure, the following aspects for each buffer area should be taken into account:

- The existence of a buffer area in a specific segment of the roadway
- Flow conservation in the buffer area (dynamic part)
- Upper bounds for input flow to the buffer area
- Determination of capacity of the buffer area (for both dynamic and static parts)
- Discharge of the buffer area within the total time period of analysis
- Flow distribution between the dynamic and static part of buffers.




**Legend:**
① Input flow to the buffer area
② Directed flow to the dynamic part of the buffer area
③ Input flow to the static part of the buffer area (parking area)
④ Output flow from parking area to the dynamic part of the buffer area
⑤ Output flow from buffer area

**Figure 5.7. Flow distribution between the dynamic and static part of a buffer area**

*- The existence of a buffer area*

Initially, it is required to indicate whether a buffer is designed or not on a specific segment (DFL, or on-ramp). In addition to the creation of a buffer area, the location of the buffer area (distance from the on/of-ramp areas) plays a major role for the efficiency of the buffer area on flow control. A very close distance of a buffer area to the merging (or diverging) area may result in an over saturated buffer area due to congestion. Conversely, a buffer area which is located too far from merging (or diverging) areas, does not function well because changes in the traffic conditions may happen within the time that the regulated flow arrives the merging/diverging area. Furthermore, the location of the buffer depends on the alignment of the roadway and the available space.

In this dissertation, we assume a fixed location for the buffer areas for reasons of simplicity. Thus, the location of the buffer areas here is applied as input of the model. In the next chapter, the impact of a change of the location of mainline buffers on function of buffers is evaluated based on a numerical example.

- *Flow dynamics in the buffer area (dynamic part)*
Since the dynamic part of a buffer area acts similar to a normal segment of the road, similar equations like (5.1-b), (5.2), and (5.4) for the definition of density, speed and flow of vehicles can be applied. In this case equation (5.1-b) for the dynamic part of the buffer area can be reformulated as:

$$k_b^{t+\Delta t} = k_b^t + \left(\frac{\Delta t}{3600 L_b}\right)\left(\alpha_{bm}^t Iin_{bm}^t - Iout_{bm}^t + IoutP_{bm}^t\right) \qquad (5.9)$$

Where:

$k_b^{t+\Delta t}$ : Density of vehicles in buffer area “b” at time “$t+\Delta t$”;

$k_b^t$ : Density of vehicles in buffer area “b” at time “$t$”;

$L_b$ : Length of buffer area “b”;

$\alpha_{bm}^t$ : Share of input flow to the buffer area “b” located on segment “m” which remains in the dynamic part at time “t”;

$IoutP_{bm}^t$ : Output flow from static part (parking area) of the buffer area “b” located on segment “m” at time “t”.

The other equations are analogue to (5.2) and (5.4).

- *Upper bound value for input flow to the buffer area*
The input flow to each buffer area located on a certain segment of the road is limited by the input flow of the vehicles to that segment. This can be modeled as:

$$Iin_{bm}^t \le q_{m-1}^t \qquad (5.10)$$

Moreover, in the static part of the buffer area the output flow from the parking area (static part of the buffer area) is limited by the stored number of vehicles within the parking area in all previous time periods. This can be modeled as:

$$IoutP_{bm}^{t+\Delta t} \le \sum_{t'=0}^{t} (IinP_{bm}^{t'} - IoutP_{bm}^{t'}) \qquad (5.11)$$

Where:

$IinP_{bm}^{t'}$ : Input flow to the static part of the buffer area "b" located on segment "m" at time "$t'$"; and:

$$IinP_{bm}^{t'} = (1-\alpha_{bm}^{t'})Iin_{bm}^{t'} \quad (5.12)$$

- *Capacity of the buffer area*

It is clear that each part of the buffer area (either dynamic or static part) has a certain capacity which limits the flow of passing or stored vehicles on that specific part. The capacity of the dynamic part of a buffer area, similar to that of segments of roads, can be modeled as follows:

$$Iout_{bm}^{t} \le k_{cr,bm}^{t} v_{f,bm}^{t} e^{-0.5} \quad (5.13)$$

Where:

$k_{cr,bm}^{t}$ : Critical density of vehicles within buffer area "b" located on segment "m" at time "t";

$v_{f,bm}^{t}$ : Free flow speed of vehicles within buffer area "b" located on segment "m" at time "t".

The capacity of the static part (parking area) of the buffer area can be described by the following equation:

$$\sum_{t'=0}^{t}(IinP_{bm}^{t'} - IoutP_{bm}^{t'}) \le \frac{1000(L_{bm})(NL_{bm}^{t})}{L_{veh}} \cdot \frac{\Delta t}{3600}\gamma \quad (5.14)$$

Where:

$NL_{bm}^{t}$ : Number of lanes available in the parking area of the buffer "b" located on segment "m" at time "t";

$L_{veh}$ : Average length of vehicles directed to the parking area (static part) of the buffer area;

$\gamma$ : Reduction factor for translating the total existing space of a parking area to usable space for parking of vehicles in the static part of the buffer area.

- *Discharge of buffer area*

It is required to discharge all buffer areas (on both static and dynamic parts) within the total time period of analysis. Equations (5.15) and (5.16) ensure this aspect for static and dynamic parts of buffer areas, respectively:

$$\sum_{t=0}^{T} IinP_{bm}^{t} = \sum_{t=0}^{T} IoutP_{bm}^{t} \quad (5.15)$$

$$\sum_{t=0}^{T} Iin_{bm}^{t} = \sum_{t=0}^{T} Iout_{bm}^{t} \quad (5.16)$$

Where:

$T$ : Total time period of analysis.

*- Definition of flow distribution factor*

The last category of equations with regard to buffer areas is related to the determination of the flow distribution factor. This factor is a variable indicating the share of input flow of vehicles to the buffer area which is not be directed to the parking area in each time period of analysis. In fact, this share of flow continues driving through the dynamic part of the buffer area and returns to the main flow (on DFL or on-ramp) directly. Equation (5.17) ensures that this share may get a value between 0 and 1:

$$0 \leq \alpha_{bm}^{t} \leq 1 \qquad (5.17)$$

### 5.2.5 Definition of objective function(s)

The definition of the objective function depends on the policy of the designer of the system. We have distinguished five categories of objective functions and the role of each of the buffer areas (e.g. mainline and on/off-ramp buffers) to reach these optimization objectives are evaluated, separately. These functions are as follows:

- Minimization of average travel time of vehicles
- Minimization of total travel time of vehicles
- Maximizatiuon of throughput at the merging (or diverging) area
- Minimization of fuel consumption
- Maximization of safety.

Each of these categories of objective functions can be analyzed for a specific user group of the road. For instance, it would be possible to give priority to ACTs and to minimize the average travel time of ACTs, independently from MDVs. In such a case, the multiplier factors of the terms in the equations below may change, based on the chosen priority of the system designer. Chapter 7 will focus on this issue more in detail and presents the results of the analysis for different priority scenarios.

<u>(1) - Minimization of average travel time of vehicles</u>

This function most commonly is considered as the main objective in optimization models for control of traffic. The travel time for each vehicle, either on the DFL or on the on/off-ramps consists of two parts: *running time* and *waiting time*. This function optimizes the flow of all vehicles generated on all routes during the total time period of analysis. Equation (5.18) indicates the formulation of this objective function.
In this equation the indexes “$M$” and “$R$” represent the type of user groups (ACTs and MDVs) and route types (DFL, mainline, and on/off-ramps), respectively.

The first term in equation (5.18) represents the running time of all user groups over the road segments of the assumed layout and the second term indicates the running time for all user groups over the dynamic part of the buffer areas. The third part in this equation specifies the waiting time of all user groups in the parking areas of all buffers, and finally, the last term refers to total number of generated vehicles.

$$ATT = \{\{\sum_M \sum_R \left( \frac{\sum_m \sum_t (k_m^{M,R,t} L_m^{M,R})}{\dfrac{1000 \sum_m L_m^{M,R}}{\dfrac{\sum_m \sum_t v_m^{M,R,t}}{NS^{M,R} \cdot NT}} \cdot \dfrac{1000 \Delta t}{3600}} \right) \cdot \frac{3600 \sum_m L_m^{M,R}}{\dfrac{\sum_m \sum_t v_m^{M,R,t}}{NS^{M,R} \cdot NT}} \cdot \omega^{M,R}\} +$$

$$\{\sum_M \sum_R \left( \frac{\sum_b \sum_t (k_b^{M,R,t} L_b^{M,R})}{\dfrac{1000 \sum_b L_b^{M,R}}{\dfrac{\sum_b \sum_t v_b^{M,R,t}}{NT}} \cdot \dfrac{1000 \Delta t}{3600}} \right) \cdot \frac{3600 \sum_b L_b^{M,R}}{\dfrac{\sum_b \sum_t v_b^{M,R,t}}{NT}} \cdot \delta^{M,R}\} +$$

$$\{\sum_M \sum_R \left( \sum_b \sum_t \sum_{t'=0}^{t} (IinP_b^{M,R,t'} - IoutP_b^{M,R,t'}) \right) \cdot \frac{\Delta t}{3600} \cdot \Delta t \cdot \theta^{M,R}\}\} /$$

$$\{\sum_M \sum_R \left( \frac{\sum_m \sum_t (k_m^{M,R,t} L_m^{M,R})}{\dfrac{1000 \sum_m L_m^{M,R}}{\dfrac{\sum_m \sum_t v_m^{M,R,t}}{NS^{M,R} \cdot NT}} \cdot \dfrac{1000 \Delta t}{3600}} \right)\} \tag{5.18}$$

Where:

$ATT$ : Average travel time of a vehicle passing the assumed layout;

$NS^{M,R}$ : The number of road segments for user group “M” on road type “R”;

$NT$ : The number of time intervals during the total time period of analysis;

$\omega^{M,Rt}$ : Assumed weight for running time of user group type “M” on road type “R”;

$\delta^{M,R}$ : Assumed weight for running time of user group type “M” in buffer areas on road type “R”;

$\theta^{M,R}$ : Assumed weight for waiting time of user group type “M” on road type “R”;

(2) - Minimization of total travel time of vehicles

This function has a close relation with the first objective function. The only difference is that the denominator of the equation (5.18)[4] will be deleted. Due to such a deletion, it may lead to different results, rather than the first proposed objective function. Similar to the previous function, this objective also can be analyzed with different weight factors for each of the components of the formula. For instance, it may provide the possibility to minimize the total travel time of ACTs on the DFL, only. Chapter 7 discusses the impact of giving such priorities on the function of buffer areas.

(3) - Maximizatiuon of throughput at the merging area

This objective tries to maximize the flow of vehicles at the merging area. This function has an indirect relation with the previous functions. Because minimization of the travel time results indirectly into a maximization of flow. Anyway, the equation (5.19) specifies the formulation of this objective.

$$Max \quad \sum_{M} \sum_{R} \sum_{t} q_{m=ii}^{M,R,t} \varphi^{M,R} \tag{5.19}$$

Where:

$q_{m=ii}^{M,R,t}$ : Traffic flow of the user group type "M" on road type "R" at time "t" for segment of the road which is located at the on-ramp (or off-ramp) area;

$\varphi^{M,R}$ : Assumed weight factor for the user group type "M" on road type "R".

(4) - Minimization of fuel consumption

The main aim of this objective is to minimize the fuel consumption of a user group on the roadway section. As the consumption of fuel heavily depends on the average speed and its variation, this function tries to minimize the speed changes on all successive segments of the assumed road type. Of course, fuel consumption is not only due to speed changes, however, the variation of speed along a road can represent a relative sense about the change in fuel consumption. Thus, this objective can be formulated as follows:

$$Min \quad \sum_{M} \sum_{R} \sum_{m} \sum_{t} (v_m^{M,R,t} - \bar{v}^{M,R})^2 \sigma^{M,R} \tag{5.20}$$

where:

$\bar{v}^{M,R}$ : Average speed of the user group "M" on all segments of route "R";

$\sigma^{M,R}$ : Assumed weight for minimizing the speed changes for user group "M" on route "R".

(5) - Maximization of safety

Safety at on/off-ramp areas without signals heavily depends on number of intersection points (e.g. crossing, merging, and diverging points) and also the speed difference of all

[4] The last term (line) in equation (5.18)

user groups approaching to the on/off-ramp area from different directions. Therefore, one of the ways to maximize the safety at unsignalized on/off-ramp areas is to achieve a speed synchronization between different user groups approaching to the on/off-ramps from different directions. Figure 5.8 indicates the possible intersection points in case of an on-ramp with two different user groups, e.g. ACTs and DFLs approaching to the on-ramp area on three different routes, e.g. mainline, DFL, and on-ramp. A similar configuration can be imagined for the case of an off-ramp area.

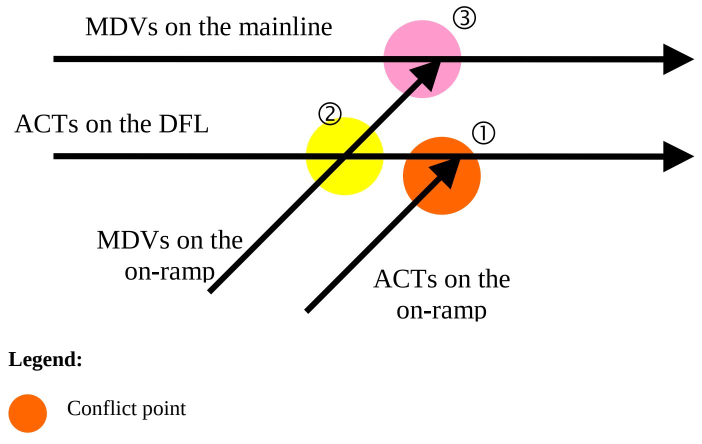



**Figure 5.8. Intersection points of routes at the on-ramp area**

Thus, in order to synchronize the speed of all approaching user groups, it is required to minimize the speed differences between all intersecting flows. The equation (5.21) represents the formulation to minimize the speed difference between all approaching user groups. It is emphasized here that due to the automatic control of ACTs, the synchronization of speed between the ACT flows (point 1 in figure 5.8), and even ACT-MDV flows (point 2 in figure 5.7) can be ensured more easily than the synchronization of speed for the MDV flows (point 3 in figure 5.7). The synchronization of speed between the approaching flow of MDVs to the on-ramp area, from two different directions (mainline and on-ramp) may be achieved by using VMS messages in the respected routes to inform MDV drivers about the optimal speed in the approaches. In equation (5.21) the indexes “ii”, “jj”, “kk”, “ll” represent the segment of an assumed route which is located at the on-ramp area, respectively for ACTs on the DFL, ACTs on the on-ramp, MDVs on the on-ramp, and finally MDVs on the mainline.

$$\begin{aligned} Min \quad & \sum_t (v_{m=ii}^{M=ACT,R=DFL,t} - v_{m=jj}^{M=ACT,R=RAMP,t})^2 . \sigma^{ACT/ACT} + \\ & \sum_t (v_{m=ii}^{M=ACT,R=DFL,t} - v_{m=kk}^{M=MDV,R=RAMP,t})^2 . \sigma^{ACT/MDV} + \\ & \sum_t (v_{m=kk}^{M=MDV,R=RAMP,t} - v_{m=ll}^{M=MDV,R=Mainline,t})^2 . \sigma^{MDV/MDV} \end{aligned} \qquad (5.21)$$

Moreover:

$\sigma^{ACT/ACT}$ : Assumed weight for speed synchronization in point "1" of figure (5.8);
$\sigma^{ACT/MDV}$ : Assumed weight for speed synchronization in point "2" of figure (5.8);
$\sigma^{MDV/MDV}$ : Assumed weight for speed synchronization in point "3" of figure (5.8);

In cases which there are signals at on-/off-ramp areas, as it was described in the previous chapter, in order to avoid the dangerous TTC values it is required to apply the speed synchronization along the roadway section (particularly for MDVs on the mainline). Hence, a similar structure of the objective function, like what was described in the forth model, can be applied. The only difference, here, is the replacement of the equation (5.7) with (5.8) in the set of constraints.

## 5.3 Model Solving

Taking into account all sets of equations (constraints) and objective functions, described in the previous section, it can be concluded that the proposed optimization models would have a very large dimension. The complicated structure of constraints and objectives would require a powerful tool to be able to solve such an optimization model with a Non-Linear structure (NLP). Table 5.2 indicates the number of variables and constraints of the proposed optimization model with respect to the assumed values for the number of time steps of analysis, number of road segments on the mainline and the on-ramp. It is assumed that a minimum type step of 10 seconds would be required to develop the equations that describe the flow dynamics. Moreover, it is assumed that only one buffer area for each type of user groups is available. As it is shown in the table, for a time period of 60 min of analysis approximately 94000 variables and 244000 constraints are included into the model.

This emphasizes the need of a powerful optimization tool, like GAMS[5] software (Brooke et al. (1998)) to solve such a model. Due to the dynamic structure of the proposed model, increasing the total time period of analysis will increase the dimension of the model, rapidly. It creates complexity for solving the model and might lead to problems for solving the model. However, due to uncertainties in predicting the traffic demand for rather long periods (e.g. half hour), the selection of a rolling horizon for solving the optimization model needs to be updated continuously within specific time intervals of analysis. Taking into consideration the total time period of 10 min for analysis, the local optimal solutions for the different objectives have been found within an execution time of 1 CPU-second[6]. If it is necessary to increase the total time period of analysis to one hour, then the heuristic methods can be applied to decompose the model to the sub-models in order to be solved by other techniques like Genetic Algorithm (GA), etc.

[5] General Algebraic Modelling System
[6] on a PC with these characteristics: Pentium 4- CPU 1.7 GHz- 512 MB of RAM.

**Table 5.2. Number of model variables and constraints for the considered roadway design and traffic flow control**

| Total time period of analysis (min.) | Required time intervals (#) | Number of segments on the DFL (and mainline) (#) | Number of segments on the on-ramp (#) | Number of model variables ($N_{var}$) | Number of model constraints ($N_{equ}$) |
|---|---|---|---|---|---|
| 10 | 60 | 5 | 3 | 5100 | 12427 |
| 30 | 180 | 10 | 6 | 26820 | 68047 |
| 60 | 360 | 20 | 10 | 93960 | 243367 |

In order to evaluate the impact of the buffer area quantitatively, a numerical example is given in chapter 6 for which optimum traffic flow control conditions are investigated. In that chapter, a sensitivity analysis is also made to quantify the impact of different parameters on the optimal plans of flow control at merging areas (or similarly in off-ramp areas).

According to the major role of the objective functions in developing the traffic control system of the different user groups at on/off-ramp areas, the results of optimization of the objectives are discussed more in detail in chapter 7. This chapter also comments on the impact of various weight factors which represent different priorities for flow control which could be implemented in TCCs in future.

## 5.4 Summary

This chapter proposed an optimization-based approach which can be applied to minimize the travel and fuel consumption by means of e.g. synchronizing the speed and density of ACTs and MDVs at on/off-ramps. It described suitable flow dynamics equations for applying buffer areas and also operation of mixed traffic of ACTs and MDVs.

The main reason underlying the development of an optimization-based approach for flow control at on/off-ramps is the possibility to fully control the flow of ACTs and to achieve an optimal control for these vehicles aimed at a higher degree of reliability and efficiency of ACTs, compared to ordinary vehicles which are driven by individual drivers.

The proposed model has taken into account four categories of rules (as constraints of the model) including:

- definition of flow dynamics of ACTs and MDVs on different kinds of road segments (DFL, mainline, on/off-ramp);
- definition of upper and lower bounds for the decision variables (like density, speed, flow, etc.);
- description of merging (diverging) capacity at on/off-ramps; and
- required rules with regard to applying buffer areas.

Each buffer area was divided in two parts: *dynamic* and *static* part. The dynamic part acts as a normal segment of the road. Hence, this part plays the role of an additional lane that may decrease the queue length when an over-saturated flow occurs. All vehicles which are directed to the buffer area must pass at this part in order to proceed to the main road (DFL or on-ramp). However, the static part of a buffer acts as a parking area where the vehicles (ACTs or MDVs depending on the buffer type) can be stored. During peak periods, depending on the capacity of this area, a part of the extra flow may be directed to this area to wait for a specific time period. This part also allows the road operator to make platoons of ACTs near on/off-ramp areas.

In order to verify the impact of different strategies of system design and control, five categories of objectives were addressed as follows: Minimization of average travel time of vehicles, minimization of total travel time of vehicles, maximization of throughput at merging (or diverging) area, minimization of fuel consumption, and maximization of safety. Then, the required equations were developed.

Finally, this chapter addressed a tool for solving the developed models (e.g. GAMS) and referred to the dependency of the dimension of the model on the total time period of analysis. By increasing the total time period of analysis (to one hour), and consequently the dimension of the proposed dynamic model, the application of other techniques like decomposition methods, Genetic Algorithms, and other heuristic approaches are proposed. However, due to uncertainties in predicting the traffic flow input for rather long time periods (e.g. half hour), the selection of a rolling horizon for solving the optimization model is recommended.

In order to assess the impact of the buffer area quantitatively, in the next chapter, the proposed flow control model[7] will be applied for a specific set of data. Then, the results of analysis will be compared with the scenario in which no buffer area exists. We also address the impact of some major model parameters and design objectives on the effectiveness of buffer areas in the remaining chapters.

[7] The proposed optimization model in the present chapter

# 6
# Sensitivity Analysis of the Optimization Model And Impact Assessment of the Buffer Area

## 6.1 Introduction

In the previous chapter we developed the structure of the optimization model which can be used to control the flow of ACTs and MDVs at merging areas to lead to minimum possible hindrance of flow. The application of this model would help the operator of the traffic control center how to synchronize the speed and density of ACTs and MDVs near on-ramp areas. The synchronization would lead to a minimal congestion at on-ramp areas of motorways, when a mixed flow of ACTs and MDVs is expected in future. A similar approach can be implemented at off-ramp areas.

The input of the model can be divided into three groups: first, the "*design elements*" of routes. This input describes the geometric characteristics of the road that the assumed user groups (ACTs and MDVs) will follow. The second are "*flow characteristics*" which describe the flow dynamics coefficients and traffic demand of the user groups. The last is the "*time period of analysis*" which defines the total time period of analysis and also the time steps, which are selected to describe the flow dynamics of user groups. It is clear that by changing any of these inputs the optimal situation may change, too.

The results of flow control optimization model and also the impact of the change of some inputs of the model will be discussed in this chapter.

The required design elements which initially must be implemented in the model are:

(a) Length of each of the roadways (either mainline or on-ramp);
(b) The connection point (segment) of the two crossing roadways (mainline and on-ramp);
(c) Length of each segment of the roadway;
(d) The location of the buffer area (on the assumed roadway for the specific user group);
(e) The length of the buffer area(s);
(f) Number of parking lanes in the buffer area(s).

The required flow characteristics are as follows:

(a) Input flow (demand) of each of the user groups (ACTs and MDVs) during the total time period of analysis;
(b) Free flow speed of each user group per segment of roadway;
(c) Jam and critical density of each user group per segment of roadway;
(d) Coefficient of the speed and density dynamics equations, like the relaxation term $(\tau)$;
(e) Reduction factors applied for the prediction of the capacity at merging areas (indicated by $\beta_1, \beta_2$ in equation (5.7);
(f) Average length of user group vehicle (ACTs and MDVs);
(g) Initial flow conditions on each of the segments.

The last group of the required inputs of the model includes time-related constants which consist of:

(a) Total time period of analysis;
(b) Each time step for recalculating the equations.

In order to assess the impact of the buffer area quantitatively, the proposed optimization model has been applied for a specific set of data. The analysis has been made for a total period of 15 minutes, which is divided into 10 seconds time intervals. It is assumed that the DFL is constituted by 5 segments with each a length of 500 meters. The on-ramp includes three segments with a total length of 1500 meters where the third segment is connected to the DFL. Appendix E indicates how the above inputs can be translated into the GAMS model optimisation structure.

The first part of analysis is designed to assess the impact of the creation of a buffer area, compared to the situation in which no buffer area exists. This part of the analysis allows to determine the beneficial conditions for the application of a buffer area.

The second part of the analysis aims to verify the impact of the change of some of the above mentioned parameters on the functioning of the buffer area. For instance, it can be shown how efficiently a buffer area works if the length of the buffer area is increased or conversely is decreased); furthermore the impact of the location of a buffer area on the improvement of capacity of the buffer area can be estimated.

In these two parts of the analysis, the minimization of the average travel time of all vehicles driving on the assumed layout during the total time period of analysis is selected as the objective function of the model. The impact of the selection of other objective functions like the minimization of fuel consumption or maximization of throughput will be discussed in the next chapter.

## 6.2 Impact assessment of the creation of a buffer area

In order to assess the impact of the creation of a buffer area, three different scenarios of traffic flow of user groups are analyzed (see table 6.1). Since, a buffer area acts like a reservoir in the system, the creation of a buffer area may advantagous if a fluctuation in the traffic flow is expected. For this reason, it is assumed that a reduction of 20% of the input flow of all user groups (e.g. ACTs on the DFL, MDVs on the mainline, ACTs on the on-ramp, and MDVs on the on-ramp) happens in the second half of the total time period of analysis. For the following two reasons, such a major change of traffic flow (e.g. 20%) during a short time period (e.g. 15 min.) is assumed:

- the total time period of analysis should be limited to decrease the dimension, and consequently the complexity of the model for solving;
- the buffer area should be discharged during the total time period of analysis.

**Table 6.1. Flow Characteristics in the assumed scenarios**

| Scenario | ACTs | | | | MDVs | | | | Main characteristic of the assumed scenario | |
|---|---|---|---|---|---|---|---|---|---|---|
| | DFL | | Ramp | | DFL | | Ramp | | (Demand*/Capacity**) ratio for road users | |
| | First half | Second half | First half | Second half | First half | Second half | First half | Second half | for ACTs | for MDVs |
| 1 | 870 | 700 | 130 | 100 | 1740 | 1400 | 520 | 420 | > 1 | > 1 |
| 2 | 870 | 700 | 55 | 44 | 1740 | 1400 | 520 | 420 | < 1 | > 1 |
| 3 | 870 | 700 | 55 | 44 | 1740 | 1400 | 220 | 180 | < 1 | < 1 |
| * Input flow of vehicles | | | | ** provided capacity at on-ramp (estimated by running simulations) | | | | | | |

The design of the scenarios takes the following characteristics into account:

- The mainline includes three lanes in which the right lane is assigned to ACTs (see figure 5.2 in the previous chapter);
- A share of 10 % (in scenario 2) and 20% (respectively in scenarios 1 and 3) for ACTs in each assumed roadway (mainline and the on-ramp) is assumed;

- During the first half time of analysis, the assumed flow of both ACTs and MDVs in the downstream of the on-ramp area reaches capacity[1] in the first proposed scenario. In the second proposed scenario, only the flow of MDVs reaches capacity during the first half time of analysis. Finally, in the third proposed scenario, the traffic flow of both ACTs and MDVs will not reach capacity in none of the segments during all time steps of analysis;
- The input flow (demand) of ACTs and MDVs on the mainline in all scenarios is fixed.

In case of the buffer area, it is assumed that there are three buffers in this area. These buffers are located on segment “2” of the DFL (named mainline buffer), and segment “2” of the on-ramp (separately for ACTs and MDVs). All the buffers are assumed to have a length of 500 m with two lanes for parking. The buffers control the traffic flow of ACTs and MDVs just upstream of the merging area on both the DFL and the on-ramp[2].

Table 6.2 shows the results of the analysis for the situation in which buffer areas are applied, compared to the situation in which no buffer area is available. The first row in this table indicates the average running time on all segments of the layout, derived from the speed of the vehicles. The second row lists the average running time of the vehicles in the dynamic part of the buffer areas. The third row gives the average waiting time in the buffer area derived from the total waiting time of the vehicles in all buffer areas divided by the total number of generated vehicles. Finally the last row summarizes all the time components resulting in the average travel time of the vehicles.

The above times are calculated based on the weighted formulation taking into account the number of each group of vehicles (ACTs and MDVs) on each assumed roadway (e.g. DFL, mainline, on-ramp) multiplied by the average time for that specific user group divided by the total number of generated vehicles in the layout (see Appendix E).

**Table 6.2. The impact of the creation of buffer areas on improving the performance of the traffic flow**

(Sec.)

| Indicator | Scenario 1 | | Scenario 2 | | Scenario 3 | |
|---|---|---|---|---|---|---|
| | Without buffer | With buffer | Without buffer | With buffer | Without buffer | With buffer |
| Average running time of vehicles on roadways | 105.6 | 90.1 | 98 | 89.7 | 93 | 93 |
| Average running time of vehicles in buffer areas | 0 | 1 | 0 | 0.6 | 0 | 0 |
| Average waiting time of vehicles in buffer areas | 0 | 1.8 | 0 | 1.5 | 0 | 0 |
| Average travel time of vehicles | 105.6 | 92.9 | 98 | 91.8 | 93 | 93 |

If the stopping of ACTs in buffer areas takes a long time, then it would be necessary to form platoons of ACTs in which a high number of ACTs (waiting in buffer area) would

[1] In order to estimate the capacity at the on-ramp area, the simulation tool is applied.
[2] For a more clear picture about the assumed layout see figures 3.20 and 3.21 in chapter 3.

pass the merging area during a short time period. Such a rule (definition of maximum waiting time of ACTs in buffer areas) can be defined as an additional constraint in the model structure to limit the maximum waiting time of vehicles in buffer areas.
To address, clearly, the impact of the creation of the buffer areas, figure 6.1 represents the comparative results of analysis concerning the average running and travel time of the vehicles in both conditions: “with” and “without buffer areas”.

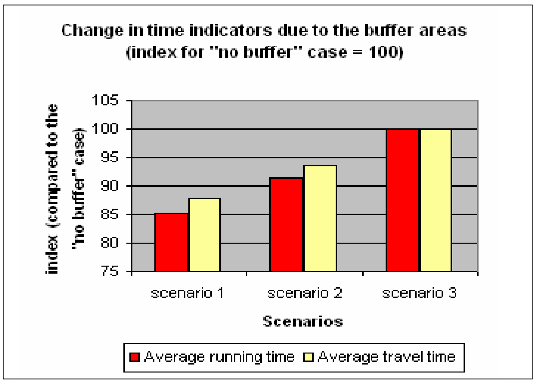



**Figure 6.1. Change in time indicators due to the buffer**

As it can be seen in figure 6.1, the creation of buffer areas decreases the average travel time of vehicles by about 15% (scenario 1). However, when the input flow does not reach capacity (e.g. scenario 3) the buffer area will not be used anymore. The creation of buffer areas, thus helps specially during critical intervals (threshold of congestion) when the interaction of the flow of ACTs and MDVs, or merging of the ACTs from the on-ramp to the DFL reaches capacity. In such situations, the rapid decrease of the speed of ACTs and MDVs (due to congestion) will justify an intermediate stop of some ACTs and MDVs in the buffer areas.

During congested time intervals the buffer areas provide for a limited number of vehicles an intermediate stop in order to reduce the overall traffic density. The stored vehicles in the buffer areas are directed to the roadway until a time period with a lower traffic demand occurs. Therefore, a trade-off between the reduced speed of the vehicles due to the high density of traffic flow at the merging areas and the required waiting time of the vehicles in the buffer areas determines the optimal capacity of the buffer areas. This is the main reason why buffer areas have not been used in the scenario 3. Indeed, in such a case increasing the speed of the vehicles can not compensate the waiting time of vehicles in buffer areas. Conversely, in scenario 1, the extra waiting time of some vehicles in the buffer areas is compensated by the increased average speed of vehicles.

Since buffer areas act like reservoirs, the input-output flow of them can be determined based on actual traffic flow in the merging area and the provided capacity at each time interval.

The control of flow of ACTs on both the DFL and the on-ramp can easily be achieved via transmitting the required commands to the ACTs to maintain the optimal speed and achieve the desired traffic density. However, this control of flow for MDVs would not be as simple as for ACTs. Because, as it has been discussed in the previous chapters, the control of each MDV is the driver's decision whose behavior may vary a lot. The flow characteristics (e.g. speed) which lead to an optimal situation (minimum average travel time of all vehicles) will be shown to drivers on roads via DRIPs or VMS, however, they will not necessarily obey these commands. Therefore, other means of control like traffic signals would be needed to efficiently control the flow of MDVs at on-ramps.

### 6.2.1 Estimation of actual time saving due to buffer areas

In order to have an elementary estimation about the total time saved due to buffer areas on a road network with a larger scale, the results of the first scenario is analyzed more in detail. The results of analysis indicate that in such a case the number of generated ACTs and MDVs during the total time period of analysis (e.g. 15 min) is 230 and 570 vehicles on both roadways (mainline and on-ramp), respectively. As it was addressed above, the creation of buffer areas leads to a reduction of 15% in the average travel time of vehicles.

**Table 6.3. The estimation of the total time saving due to buffer areas on a larger road network**

| Number of generated vehicles per 15 min. | | Number of on-/off-ramps per 50 km | VOT factor for trucks compared to cars | Average VOT for car drivers (Euro) | The total saving cost (Euro/hr) |
|---|---|---|---|---|---|
| ACTs | MDVs | | | | |
| 230 | 570 | 5 | 2 | 20 | 61,800 |
| 230 | 570 | 10 | 2 | 50 | 309,000 |
| 230 | 570 | 20 | 2 | 100 | 1,236,000 |
| 230 | 570 | 5 | 5 | 20 | 103,200 |
| 230 | 570 | 10 | 5 | 50 | 516,000 |
| 230 | 570 | 20 | 5 | 100 | 2,064,000 |

Thus, in order to estimate the total time saving due to buffer areas on a larger road network scale, several combinations of number of bottleneck points (e.g. on-/off-ramps) along a motorway with a length of 50 km, Value Of Time (VOT) of Freight Transport system (e.g. trucks) compared to the ordinary traffic flow (e.g. cars), and the absolute VOT values of car drivers are estimated. The findings of this elementary analysis are indicated in table 6.3.

As it can be seen in the above table, by assuming 10 on-/off-ramp within the total length of 50 km, the VOT factor of 5 for trucks compared to cars, and an average VOT of 50 Euros for car drivers, creation of buffer areas during a peak hour period[3] may value about 0.5 million Euros per hour, due to the reduction of waiting time of vehicles in the congested situation.

In order to provide a more detailed analysis of scenarios with regard to the function of buffer areas, a range of indicators can be provided to evaluate the performance of the buffer area for each of the proposed scenarios. The next section addresses the important indicators that are selected for the comparison of the proposed scenarios in which the buffer area is used.

[3] Which might lead to a reduction of 15% in the average travel time of vehicles

### 6.2.2 Buffer-related indicators

In order to compare the effectiveness of buffer areas in each of the proposed scenarios the following indicators are selected:

(1) Total number of vehicles stored in each of the buffer areas;
(2) Total input flow to the buffer area;
(3) Percentage of time in which the entrance / exit gate of buffer areas have been used (gate utilization);
(4) Maximum waiting time of vehicles in the buffer area.

*(1) Total number of vehicles stored in each of the buffer areas*
Table 6.4 shows the total number of vehicles which are stored in each of the buffer areas in all proposed scenarios. It can be seen that all buffer areas are used in the first scenario. While, in the second scenario, only the on-ramp buffer of MDVs is used to control the number of MDVs merging to the mainline flow of MDVs. Since in this case, the input flow of ACTs, even in the downstream segment of the on-ramp on the DFL does not reach capacity, none of the buffer areas related to the flow of ACTs are used. As it was described earlier, no buffer is used in the third scenario of traffic flow of ACTs and MDVs.

**Table 6.4. Number of generated vehicles and vehicles stored in buffer areas**

| Scenario | Number of generated vehicles | | | | | Number of vehicles in buffer areas | | |
|---|---|---|---|---|---|---|---|---|
| | DFL | | On-ramp | | Total | Mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| | ACT | MDV | ACT | MDV | | | | |
| 1 | 207 | 453 | 29 | 116 | 805 | 11 | 32 | 103 |
| 2 | 197 | 453 | 13 | 116 | 779 | 0 | 0 | 114 |
| 3 | 197 | 411 | 13 | 50 | 671 | 0 | 0 | 0 |

A comparison of the number of generated vehicles and number of vehicles which are stored in the buffer areas during the total time period of analysis indicates that nearly all generated MDVs on the on-ramp are directed to the buffer area before merging to the mainline flow. It stresses the important role of the on-ramp buffer for MDVs in this scenario.

*(2) Total input flow to the buffer area*
Table 6.5 indicates the total input flow of vehicles to each of the buffer areas in all proposed scenarios. Indeed, a combination of findings of tables 6.5 and 6.4 verifies the average waiting time of vehicles in the buffer areas. Because, the number of vehicles stored in the buffer areas (given in the table 6.4) is a production of average input flow of vehicles to the buffer areas (given in the table 6.5) and the average waiting time of that flow in the buffer areas. The findings of these two tables (e.g. tables 6.4 and 6.5) show that although the total input flow of MDVs to the buffer area in the second scenario is less than in the first one (e.g. 9504 veh/h compared to 12357 veh/h), the total number of stored MDVs in the second scenario is higher (e.g. 114 compared to 103). It means that the average waiting time of MDVs in the second scenario is longer (compared to the first scenario).

**Table 6.5. The total input flow of vehicles to buffer areas**

| Scenario | Total input flow to the buffer area (veh/h) | | |
|---|---|---|---|
| | Mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1 | 1435 | 1924 | 12357 |
| 2 | 0 | 0 | 9504 |
| 3 | 0 | 0 | 0 |

*(3) Gate utilization of the buffer area*

Table 6.6 presents a summary of the results of the optimization models for each of the proposed scenarios, concerning the gate utilization of buffers.

**Table 6.6. Gate utilization of buffer areas**

| Scenario | Gate utilization (%) | | | | | |
|---|---|---|---|---|---|---|
| | Entrance gate | | | Exit gate | | |
| | Mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs | Mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1 | 20 | 22 | 47 | 14 | 14 | 46 |
| 2 | 0 | 0 | 45 | 0 | 0 | 38 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 |

It can be seen that the highest rate of gate utilization is related to scenario 1, in which the on-ramp buffer for MDVs plays a major role, compared to the two other buffers (assigned to ACTs). In this case, about 47% of the total time period of analysis a flow of vehicles enters (or exits) to (from) the on-ramp buffer. Moreover, the comparison of gate utilization for the entrance and exit gate of buffers for ACTs indicates a lower utilization rate for the exit gate compared to the entrance gate. It means that the input flow of vehicles to these buffer areas is clustered within the buffers and then sent to the exit gate.

*(4) Maximum waiting time of vehicles in buffer areas*

In order to assess the maximum waiting time of vehicles in each of the buffer areas, it is required to draw the cumulative input and output flow of vehicles in each of the buffer areas versus the time. Then, the maximum horizontal distance between the two graphs represents the maximum waiting time of the vehicles in that specific buffer area. Figure 6.2 illustrates how the maximum waiting time of ACTs in the on-ramp buffer for the scenario 1 is calculated.

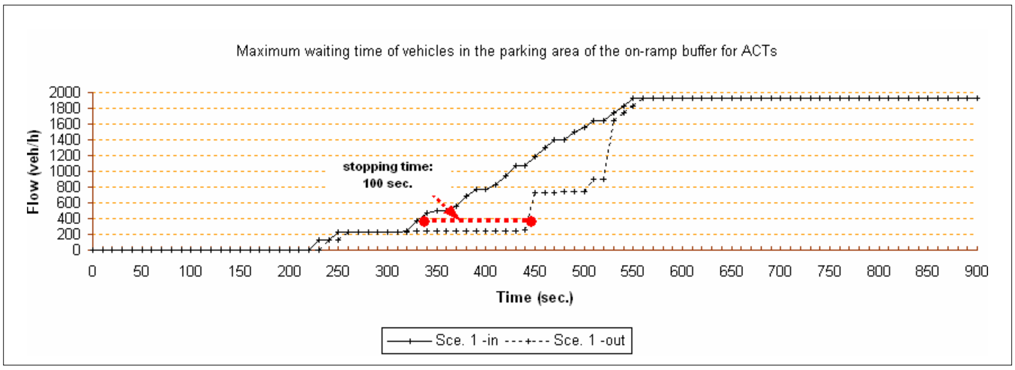



**Figure 6.2. Cumulative input-output flow of ACTs in the on-ramp buffer of ACTs (Scenario 1)**

Table 6.7 indicates the summary of the results concerning the maximum waiting time of vehicles in each of the buffer areas in all scenarios. According to this table, the maximum waiting time of the vehicles in the first scenario occurs in the mainline buffer where a maximum waiting time of (about) 2 minutes is reported. The maximum waiting time of the MDVs in the buffer areas is also limited by about 1 minute.

**Table 6.7. Maximum waiting time of vehicles in buffer areas**

| Scenario | Maximum waiting time of vehicles in buffers | | |
|---|---|---|---|
| | Mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1 | 110 | 100 | 50 |
| 2 | 0 | 0 | 60 |
| 3 | 0 | 0 | 0 |

The findings of this part of analysis support the effective role of the application of buffer areas during the time periods in which the traffic demand reaches capacity. In such situations, a maximum decrease of 15% of the average travel time of each vehicle (taking into account both ACTs and MDVs) can be expected. Of course, each ACT which is directed to the buffer area requires a time interval to do switch the control mode of driving and to be checked at the buffer area. This may take some minutes, particularly in the near future. This amount of time is neglected in our analysis.

In the next section, the impact of change of some parameters of the model on the function of the buffer area will be evaluated. This analysis determines to which extent the capability of a buffer area changes if an increase or decrease of the assumed parameters happens.

## 6.3 Sensitivity analysis of the models' parameters

In the introduction part of this chapter, a variety of factors were explained that are defined as inputs of the model. These factors were divided into three groups: design elements, flow dynamic characteristics, and time-related factors. Among all these elements the following items are selected to be analyzed more in detail:

(1) critical flow density of ACTs
(2) relaxation factor for traffic flow of ACTs
(3) length of buffer areas
(4) number of lanes in buffer areas
(5) location of the buffer area
(6) number of buffer areas.

While the first two factors are related to the flow characteristics of vehicles (specially ACTs), the remaining factors represent the design charateristics of buffer areas. In the remaining parts of this chapter, the impact of change in each of the above factors will be discussed separately.

In order to compare the results of the change of each of these factors on the function of the buffer area, the first scenario[4] is selected as the reference scenario in this section.

### 6.3.1 The impact of change in critical flow density of ACTs

In this analysis, for reasons of simplification, only the impact of change in critical density of flow of ACTs on the DFL is analyzed. However, the structure of the model is able to assess the impact of change in critical density of ACTs on the on-ramp, too. Since, still no real data is available concerning the flow dynamics of ACTs, it is assumed that the operation of ACTs (instead of ordinary trucks) could increase the critical density of ACTs considerably. So, an increase of 25% and 50% of critical density of ACTs on the DFL, corresponding to 23 and 27 ACTs/km respectively, are analyzed.

The critical density of ACTs can be increased by decreasing the required reaction time of ACTs compared to normal trucks which are driven manually. Platooning of ACTs can be considered as another option to increase in critical density of ACTs, compared to ordinary trucks. This would lead to an increase of the capacity of each segment of the DFL, and indirectly would increase the remaining capacity at the merging area. Figure 6.3 depicts the flow-density diagram of the assumed scenarios in this part of analysis. In the following sections, a summary of the findings of analysis is presented.

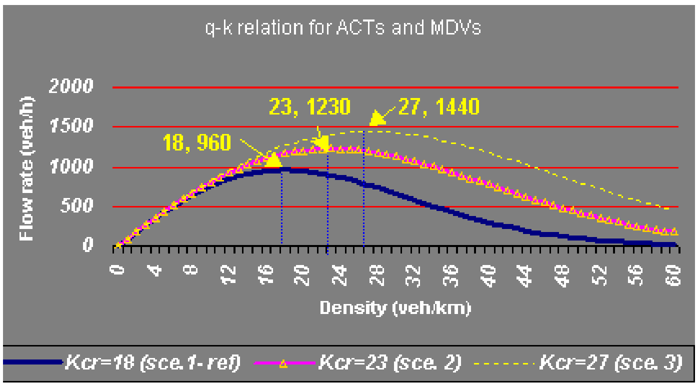



**Figure 6.3. Assumed scenarios in impact assessment of critical density of ACTs**

*(1) Time related indicators*

Figure 6.4 illustrates the relation between the possible increase in critical density of ACTs on the DFL and major time-related indicators, like average running vehicle time in the assumed road section and in the dynamic part of the buffers, average waiting time of a vehicle, and the average travel time of vehicles.

By increasing the critical density of flow of ACTs on the DFL by about 50%, a reduction of only 5% in the average travel time of all vehicles can be expected. However, the average waiting time of vehicles would decrease by up to 40%, compared to the reference scenario.

[4] Refers to “scenario 1” in table 6.1.

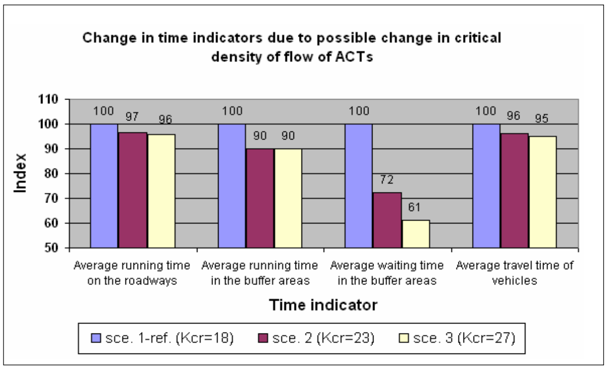



**Figure 6.4. Relation of time indicators and changes in critical density of ACTs on the DFL**

*(2) Total number of vehicles stored in each of the buffer areas*
By increasing the critical density of flow of ACTs on the DFL, the mainline buffer and also the on-ramp buffer for ACTs are not been used (by ACTs). This increase also leads to a reduction of 14% of the total number of MDVs stored in the on-ramp buffer of MDVs (scenario 3).

*(3) Other indicators*
The analysis of gate utilization of the on-ramp buffer for MDVs shows no meaningful difference. The maximum waiting time of MDVs in the on-ramp buffer is not changed anyhow.

Thus, even a major increase in critical density of flow of ACTs (compared to flow of ordinary trucks) does not necessarily lead to a change in the average travel time of vehicles in mixed flow of ACTs and MDVs at merging areas. However, the increase in critical density of ACTs would decrease the required capacity of buffer areas for MDVs at merging areas.

### 6.3.2 The impact of change in relaxation factor $(\tau)$ on the flow of ACTs

Actually, the relaxation term in the speed dynamics equation describes the tendency of flow to relax to an equilibrium flow. Due to the potential capability of ACTs, which can be controlled by the traffic control center automatically, the impact of change in the relaxation factor $(\tau)$ on the function of buffer areas is tested. Although a more detailed analysis of the possible change of the value of the relaxation term for the operation of ACTs would be required, here the impact of the change of the relaxation term from 20.4 in the reference scenario to 30, 40, and 50, in the scenarios 2 to 4, respectively, are evalauted.

The results of the analysis indicate a maximum reduction of 3% in average travel time of the vehicles due to the increase of this parameter from 20.4 in the reference scenario to 50 in the scenario 4. Other results of analysis are as follows:

*(1) Total number of vehicles stored in each of the buffer areas*

Table 6.8 shows the number of vehicles that are stored in the buffer areas in all scenarios. As it can be seen, due to the increase of relaxation factor from 20.4 to 50, a maximum reduction of 40% of the total number of vehicles stopped in the buffer areas can be expected. It also indicates a major reduction of the number of ACTs directed to the on-ramp buffer.

**Table 6.8. Total number of vehicles stored in buffer areas**

| Scenario | Number of vehicles in buffer areas | | | |
|---|---|---|---|---|
| | Mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs | Total |
| 1- ref. | 11 | 32 | 103 | 146 |
| 2 | 19 | 0 | 108 | 127 |
| 3 | 27 | 0 | 99 | 126 |
| 4 | 14 | 3 | 72 | 89 |

*(2) Total input flow of vehicles to buffer areas*

Table 6.9 presents the total flow of vehicles that enter to the buffer areas during the total time of analysis in all scenarios. Although the number of ACTs stopping in the mainline buffer in scenario 4 is lower than in scenario 3 (according to table 6.8), table 6.9 reports a higher flow of ACTs entering to the mainline buffer. It can thus be concluded that the average waiting time of ACTs in the mainline buffer in the forth scenario is much less than in the third scenario. The same is true for MDVs concerning the on-ramp buffer.

**Table 6.9. Total input flow of vehicles to buffer areas**

| Scenario | Total input flow to the buffer area (veh/h) | | |
|---|---|---|---|
| | Mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1- ref. | 1435 | 1924 | 12357 |
| 2 | 5997 | 0 | 10314 |
| 3 | 2963 | 0 | 10536 |
| 4 | 4839 | 936 | 11382 |

*(3) Maximum waiting time of vehicles in buffer areas*

Figure 6.5 indicates the cumulative input-output flow of the mainline buffer in all assumed scenarios. According to this figure the maximum waiting time of the vehicles in this buffer is equal to 110, 40, 140, and 20 sec., respectively for scenarios 1 to 4. The similar results for other buffer areas indicate that:

- the maximum waiting time of ACTs in the on-ramp buffer (scenario 4) is limited to 10 seconds[5];
- the maximum waiting time of MDVs in the on-ramp buffer are the same (50 sec.).

[5] Regardless of the switching and inspection time.

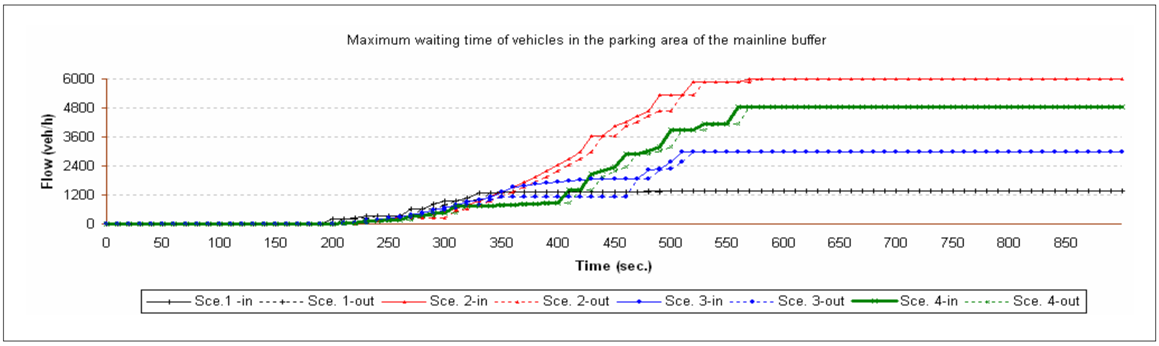



**Figure 6.5. Cumulative input-output flow of vehicles in the mainline buffer for all assumed scenarios**

Generalizing the first part of analysis, e.g. the impact assessment of traffic flow parameters on the function of buffer areas and on the efficiency of existing motorways, it can be stated that:

- even a major change of the characteristics, like critical density of flow of ACTs (about 50%), and relaxation term of flow of ACTs (by about 250%) due to the operation of ACTs instead of ordinary trucks, leads only to a decrease of 15% in average travel time of vehicles at merging areas;

- any change in the flow characteristics has a major influence on the number of vehicles using the buffer areas and the way in which a buffer area is charged and discharged.

In the next sections, the impact of the change of the design of buffer areas will be analyzed in order to assess whether they could lead to a higher (or lower) efficiency of buffer areas.

### 6.3.3 The impact of length of buffer areas

In order to assess the impact of the length of buffer areas, various lengths of 400, 500 (ref. scenario), 600 and 700 m for the buffer areas are compared. The results of the analysis indicate no meaningful difference among all scenarios with respect to the average travel time of all vehicles. However, a major change can be seen in the behavior of buffer areas with respect to time-related indicators. Indeed, the buffer areas prove to act as a flexible mean to maintain a similar average travel time of all vehicles.

Table 6.10 states the number of vehicles which are stored in each of the buffer areas, separately for all scenarios.

**Table 6.10. Total number of vehicles stored in buffer areas**

| Scenario | Number of vehicles in buffer areas | | | |
|---|---|---|---|---|
| | Mainline buffer | On-ramp buffer for ACTs | On-ramp buffer | Total |
| 1 | 3 | 47 | 112 | 162 |
| 2 (ref.) | 11 | 32 | 103 | 146 |
| 3 | 19 | 17 | 93 | 129 |
| 4 | 4 | 45 | 79 | 128 |

According to table 6.10, by increasing the length of the buffer areas from 400 to 700 m, the total number of vehicles stored in buffer areas is decreased by about 20%. This means there is no necessity for increasing the length of buffer areas. Any increase of the length of buffer areas increases the total running time of vehicles in the dynamic part of buffer areas would increase, whereas the extra capacity of the static part of buffer areas can not be used effectively.

By decreasing the length of buffer areas to 250 meters the problem becomes infeasible to be solved. Thus, a length of 250-400 m can be considered as a reasonable design value for the length of buffer areas. These values correspond to a reasonable number of trucks in the buffer area and are related to geometric design of on-/off-ramps. However, in order to assess the optimal length of buffer areas, it is necessary to look more in detail to other indicators like the maximum waiting time of vehicles in buffer areas (Figure 6.6).

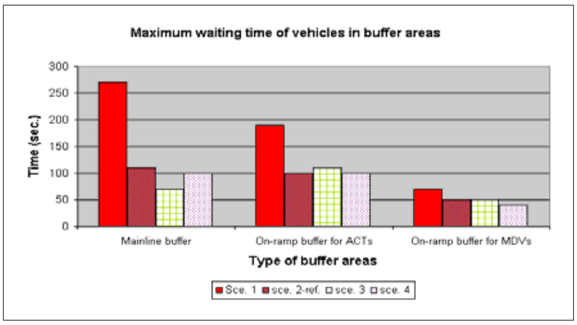



**Figure 6.6. Maximum waiting time of vehicles in buffer areas for different lengths of buffer areas**

By decreasing the length of buffer areas to 400 m the maximum waiting time of vehicles in buffer areas increases substantially. The maximum waiting time of ACTs in the mainline buffer in such a case increases up to 270 s which may not be acceptable in case of mainline buffers. A trade-off exists between the maximum waiting time of vehicles in buffer areas and the utilization of capacity of buffer areas (optimal length and number of lanes of buffer areas).

### 6.3.4 The impact of number of lanes of buffer areas

Three different scenarios are taken into account. In the first scenario, there is only one lane in the buffer areas which can be used for storing vehicles, in the second (reference) scenario two parking lanes and in the last scenario three lanes. The results of analysis are as follows:

*(1) Total number of vehicles stored in each of the buffer areas*

Table 6.11 indicates the total number of vehicles which are stored in each of the buffer areas in all scenarios. It can be seen that by decreasing the number of lanes of buffer areas from 2 lanes to 1 lane, the number of ACTs stored in the on-ramp buffer is decreased, too. Conversely, the number of stored ACTs in the mainline buffer is increased. This might happen due to the decrease of capacity of the on-ramp buffer of

ACTs. Thus, a part of the role of the on-ramp buffer of ACTs is transferred to the mainline buffer of ACTs.

By increasing the number of parking lanes from 2 to 3, the on-ramp buffer of ACTs recovers its initial role and therefore it leads to a decrease in the number of stored ACTs in the mainline buffer.

**Table 6.11. Number of stored vehicles in buffer areas**

| Scenario | Number of vehicles in buffer areas | | |
|---|---|---|---|
| | Mainline buffer | On-ramp buffer | On-ramp buffer |
| 1 | 20 | 20 | 103 |
| 2 (ref.) | 11 | 32 | 103 |
| 3 | 8 | 32 | 98 |

*(2) Gate utilization of buffer areas*

Figure 6.7 provides the utilization rates of entrance and exit gates of buffer areas in all assumed scenarios. A comparison of the entrance and exit gate utilization of buffer areas assigned to ACTs indicates a higher rate of utilization for the entrance gate, compared to the exit gate. It confirms that ACTs directed to buffer areas (either the mainline buffer or the on-ramp buffer for ACTs) are clustered while exiting these buffers. In contrast, a lower rate of utilization is reported for the entrance gate of the on-ramp buffer for MDVs, compared to the exit gate. It means that the MDVs directed to the on-ramp buffer, are decomposed to smaller groups while exiting the buffer area.

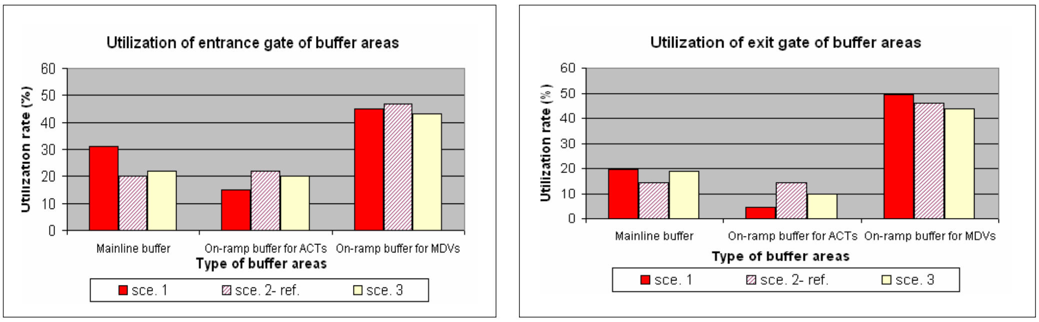



**Figure 6.7. Entrance/ exit gate utilization of buffer areas**

A decrease in the number of lanes of buffer areas from 2 to 1, leads to a 10% and 5% increase of the utilization rate of the entrance and exit gate of the mainline buffer, respectively. By reducing the number of lanes, a higher frequency of input flow to the buffer areas is caused due to a decrease in the role of the on-ramp buffer for ACTs.

*(3) Maximum waiting time of vehicles in buffer areas*

The maximum waiting time of vehicles is presented in figure 6.8. It can be summarized that the maximum waiting time of vehicles in buffer areas is limited to 160 seconds. Even by reducing the number of buffer lanes to only 1 lane, the maximum waiting time of vehicles is limited to 2 min. It indicates that in the assumed traffic flow conditions, the number of lanes in the buffer areas can be reduced to one lane. By increasing the number of lanes in the on-ramp buffer for MDVs, the maximum waiting time of MDVs in this buffer is decreased gradually.

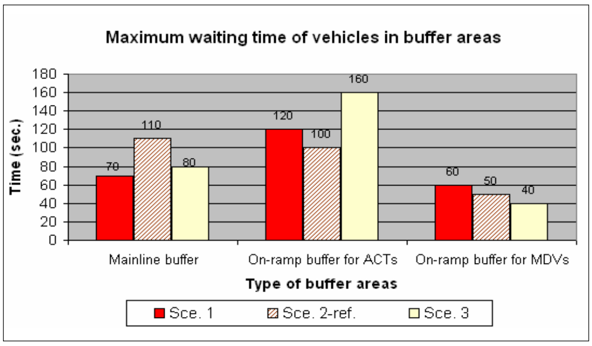



**Figure 6.8. Maximum waiting time of vehicles in buffer areas**

### 6.3.5 The impact of location of buffer areas

In this part of analysis we determine the optimal location of buffer areas. It identifies how much the distance of a buffer area to the on-ramp area affects the utilization of the buffer. For reasons of simplicity, only the impact of location of the mainline buffer is evaluated. A similar analysis can be performed to assess the impact of the location of on-ramp buffers.

Four different locations for the mainline buffer are compared. The location of the buffer area in each of the scenarios is correspondent to the name of the scenario. For instance in scenario 2 (reference) , the mainline buffer is located in the second segment of the DFL, and in the forth scenario the mainline buffer is located on segment 4 of the DFL. It means that in the last scenario (scenario 4), the impact of location of the mainline buffer at downstream of the on-ramp area is evaluated. The findings of analysis can be summarized as follows:

*(1) Total number of vehicles stored in each of the buffer areas*

The results of analysis concerning the number of vehicles which are stored in each of the buffer areas are summarized in table 6.12. This table clearly indicates that the mainline buffer only plays an effective role, when this buffer area is located in segments 2 or 3. In scenarios in which the mainline buffer is assumed to be located in segments 1 or 4, this buffer has not been used effectively. If the mainline buffer is located in the first segment (about 1.5 km from the merging area), it can not control the input flow of vehicles effectively in order not to reach capacity at the segments just upstream of the on-ramp area (e.g. segments 2 and 3). The location of the buffer area just downstream of the on-ramp area (in the segment 4) would not help, too, to avoid congestion at the merging area.

**Table 6.12. Number of vehicles stored in buffer areas**

| Scenario | Number of vehicles in buffer areas | | |
|---|---|---|---|
| | Mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1 | 0 | 43 | 113 |
| 2 (ref.) | 11 | 32 | 103 |
| 3 | 6 | 63 | 98 |
| 4 | 0 | 49 | 102 |

*(2) Gate utilization of buffer areas*

Table 6.13 indicates how much percent of total time, an entrance (or exit) of flow to (from) buffer areas is recorded. Scenario 3 shows nearly an equal gate utilization rate of the on-ramp buffer for ACTs (both in the entrance and exit gates) compared to scenario 2. Whereas, according to table 6.12, a higher number of ACTs used this buffer area. It proves that in scenario 3, the ACTs are directed to the on-ramp buffer in larger groups (clusters), compared to the reference scenario, which might affect the required time for switching the control mode of driving and other required inspection times.

**Table 6.13. Entrance/ exit gate utilization of buffer areas**

| Scenario | Gate utilization of buffer areas (%) | | | | | |
|---|---|---|---|---|---|---|
| | Mainline buffer | | On-ramp buffer for ACTs | | On-ramp buffer for MDVs | |
| | In-door | Out-door | In-door | Out-door | In-door | Out-door |
| 1 | 0 | 0 | 31 | 18 | 42 | 43 |
| 2- ref. | 20 | 14 | 22 | 14 | 47 | 46 |
| 3 | 12 | 7 | 20 | 13 | 47 | 46 |
| 4 | 0 | 0 | 38 | 20 | 47 | 46 |

*(3) Maximum waiting time of vehicles in buffer areas*

Table 6.14 presents the findings of the analysis concerning the maximum waiting time of vehicles in buffer areas, for all proposed scenarios. This table reveals a higher [maximum] waiting time of vehicles in the on-ramp buffer of ACTs in scenario 3, compared to the other scenarios. It indicates that in such a case, the on-ramp buffer for ACTs enforces the ACTs to stop for a longer time, since the mainline buffer for ACTs is too close to the on-ramp area to be able to control the flow of ACTs on the DFL more effectively. Such a high value of waiting time of ACTs in the on-ramp buffer (e.g. 170 s) may not be accepted.

**Table 6.14. Maximum waiting time of vehicles in buffer areas**

| Scenario | Maximum waiting time of vehicles in buffers (sec.) | | |
|---|---|---|---|
| | Mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1 | 0 | 120 | 70 |
| 2- ref. | 110 | 100 | 50 |
| 3 | 110 | 170 | 50 |
| 4 | 0 | 100 | 40 |

Similar to the most of previous cases, the above table confirms a shorter [maximum] waiting time of MDVs, compared to ACTs in the buffer areas. Since both ACTs and

MDVs are given an equivalent weight in the objective function, due to the higher [average] speed of MDVs compared to ACTs the model aims to maximize the role of MDVs on the road layout. It might result in a lower waiting time of MDVs compared to ACTs in the buffer areas. The maximum waiting time of each of the user groups (e.g. ACTs or MDVs) in buffer areas also depends on the provided capacity for each of the user groups at merging areas (while crossing or merging). In the next chapter, the impact of giving different weights for different user groups (e.g. ACTs or MDVs) or flow directions (e.g. the mainline or on-ramp) is evaluated.

Taking into account all the above indicators, it can be summarized that the location of the mainline buffer in the second segment of the DFL at a distance of 500 m to the on-ramp area, can be estimated as an effective location for the mainline buffer. By moving the mainline buffer to segment 3 (just upstream of the on-ramp) a higher number of vehicles would be transferred to the mainline buffer without any increase in efficiency of flow at the merging area.

A similar analysis has been performed to assess the optimal location of on-ramp buffers for ACTs and MDVs. The results of analysis indicate that the location of the on-ramp buffers in the second segment, e.g. at a distance of 500 m to the merging area, leads to a lower load of the buffer areas while the average travel time is minimum.

### 6.3.6 The impact of number of buffer areas

The main aim of this part of analysis is to assess whether the number of buffer areas improve the efficiency of operations considerably? In order to answer to this question, the reference scenario in which a unique buffer is assumed on the DFL (on segment 2) is compared with the following two scenarios:

- two mainline buffers are located on segments 1 and 2 of the DFL (Scenario 2),
- three mainline buffers are located on segments 1,2 and 3 of the DFL (Scenario 3).

The results of the analysis indicate that the average travel time of vehicles in these two scenarios are decreased by about 2 and 5%, respectively compared to the reference scenario in which only one buffer exists on the DFL. Taking into account the required costs for the construction, maintenance and management of buffer areas, it can be concluded that adding extra buffers does not contribute to a significant higher efficiency of operations.

## 6.4 Summary

This chapter addressed the impact of creation of buffer areas, quantitatively. It also presented a sensitivity analysis of the impact of various elements and parameters of the proposed optimization model (for synchronizing the speed and density of ACTs and MDVs at merging areas).

The findings in the first part of the analysis support the expectation that creating buffer areas with an adequate capacity, may lead to a reduction of average travel time of vehicles at merging areas by about 15%. Generally, the impact of buffer areas heavily depends on three factors: the fluctuation of traffic flow per user groups, the capacity of the merging area, and the capacity of the buffer area. However, a dramatic change in average travel time of the vehicles due to buffer areas can not be expected in cases with a mixed flow of ACTs and MDVs at merging areas.

In the second part of the analysis, a sensitivity analysis was performed concerning various elements, on the results of the optimization model. These elements were divided in two parts: traffic flow characteristics and buffer design elements. The first group includes factors like critical density of flow of ACTs, and relaxation factor of the speed equation of ACTs. The second group addresses design elements, like length of buffer areas, number of lanes in buffer areas, location of buffer areas, and number of buffer areas.

The impact assessment of change in critical flow density of ACTs indicates that by increasing this factor by about 50%, only a minor reduction of 5% in average travel time of vehicles can be expected. However, an increase of 50% in the critical density of ACTs, would lead to a reduction of 14% of capacity of the on-ramp buffers for MDVs.

The results of analysis support the benefits of providing buffer areas to control mixed flows of ACTs and MDVs, as an increase in the relaxation term of the speed equation would lead to a 40% reduction in the required capacity of buffer areas.

The optimal length of buffer areas should be determined based on the required capacity of the buffer area and in combination with the number of parking lanes of buffer areas. For the assumed traffic flow conditions, an increase of the length of buffer areas leads to a decrease of the number of vehicles stored in buffer areas, due to a higher running time of vehicles in the dynamic part of buffer areas. Decreasing the length of buffer areas to 400 m, causes a maximum waiting time of vehicles in buffer areas up to 260 s. Of course, in order to design the entry/exit lane of buffer areas the acceptable length for decelerating/accelerating of vehicles should be taken into account. While the insertion of narrow curves in the dynamic section of buffer areas are not allowed, in the static section of buffer areas the application of narrow curves – due to slow speed of ACTs in this section- is allowed.

When the number of lanes in a buffer area is decreased, the other buffer areas would compensate for it until capacity is saturated. The selection of the optimal number of lanes of buffer areas should be based on a cost-benefit analysis.

Different locations of buffer areas emphasize its impact on the effectiveness. When the mainline buffer is located at a distance of 500 m to the merging area, the mainline buffer is used effectively by ACTs. Whereas, a distance of 1 km upstream of the on-ramp area or its downstream would not stimulate ACTs to use the mainline buffer. Our results also support the conclusion that the creation of extra buffer areas do not lead to a higher efficiency.

In the next chapter the impact of the selection of different objective functions for the design and control of the system on the function of buffer areas will be evaluated. Moreover, the next chapter reveals how giving a priority to a specific user group or a specific flow direction would affect the function of the buffer areas.

# 7
# Evaluation of Different System Design Objectives

The previous chapter described the impact of the creation of buffer areas, compared to situation in which no buffer areas are applied. It also addressed the impact of changes of some parameters of the proposed optimization model, which might be relevant when trucks are automatically controlled, for the function of buffer areas. In all scenarios that were analyzed in the previous chapter, the minimization of the average travel time of all user groups was selected as basis of the comparative analysis.

The main aim of analysis in this chapter is to assess the impact of changes in the design objective of the system on the function of the buffer area. For instance, how the function of the buffer area would change if the minimization of average travel time of all vehicles (as the objective function of the optimization model) is replaced by another objective function like the minimization of fuel consumption of vehicles.

To reach proposed aims, the optimal flow of different user groups in each time instant of analysis will be calculated based on the results of the proposed optimization model. The results of the model determine how many vehicles can enter to (and similarly exit from) the buffer area within a certain time period. Based on this result, the buffer traffic controller can decide upon the most effective measures like checking or platooning of trucks within a certain time period.

In addition, in this chapter we assess the impact of giving priority to a specific user group, like ACTs, or a specific flow, like that on the DFL, on the function of buffer areas. Several combinations of coefficients for each term of the design objective function of the model, representing the role of a specific user group or a specific flow, are compared with each other.

## 7.1 Definition of objective functions

To assess how the role of a buffer area would change, depending on the assumed strategy of flow control, first it is required to define the list of objective functions that might be used in practice. We have distinguished five categories of design objectives (refer to chapter 5). The selected objective functions are as follows:

1) Minimization of average travel time of vehicles
2) Minimization of total travel time of vehicles
3) Maximization of throughput
4) Maximization of safety (minimization of speed difference)
5) Minimization of fuel consumption

In the following sections the impact assessment of each of the above design objectives on the function of buffer areas will be addressed. In all these analyses, the selected structure of the model (constraints) is the same, whereas the objective function of the model changes depending on the priority given to a specific term of the objective function equation.

To do this analysis quantitatively, the characteristics which were addressed for the reference scenario in section 6.2 of the previous chapter, have been applied in this anlaysis, too. Therefore, more detailed information about the model input and also the required indicators describing the comparative results of scenarios can be found in sections 6.1 and 6.2 of the previous chapter.

### 7.1.1 Minimization of the average travel time of vehicles

In this category of the system design objectives, the following four options are compared:

option 1: reference option, in which all user groups are defined in the objective function of the model with a coefficient of 1 (similar coefficient for all terms). Thus, in this option no priority is given to a specific user group or a specific flow direction (e.g. DFL or on-ramp);

option 2: a relative coefficient of 2:1 is considered for the flow of vehicles (both ACTs and MDVs) on the mainline compared to the flow of vehicles on the on-ramp;

option 3: contrary to option 2, a relative coefficient of 1:2 is considered for the flow of vehicles (both ACTs and MDVs) on the mainline compared to flow of vehicles on the on-ramp;

option 4: a relative coefficient of 2:1 is applied for ACTs compared to MDVs on both roadway types (e.g. the mainline and the on-ramp).

The results of the analysis of the above options can be summarized as follows (for more detailed information see appendix G):

*(1) Total number of vehicles stored in buffer areas*

Table 7.1 indicates the total number of vehicles that are stored in buffer areas for each of the proposed options. It shows that by giving priority to ACTs on the DFL (option 2), the total equivalent number of ACTs stored in the on-ramp buffer of ACTs will increase by about 60%. Nearly in all options it can be seen that by giving priority to a specific user group or a specific roadway, the role of buffer areas assigned to the remaining users is increased. The number of stored vehicles in each of the buffer areas also depends on the absolute number of generated vehicles on each of the roadways. For instance in option 4, although priority is given to ACTs, the number of stored ACTs in the on-ramp buffer of ACTs is increased, compared to the reference option. Thus, the required capacity of each of the buffer areas can be estimated if each of the options of control (giving priority to different user groups or roadways) is applied.

**Table 7.1. Total number of vehicles stored in buffer areas**

| Option | Summary description | Equivalent number of vehicles stored in buffer areas | | |
|---|---|---|---|---|
| | | mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1- ref. | ATT | 11 | 32 | 103 |
| 2 | ATT- 2DFL+1RAMP | 4 | 51 | 97 |
| 3 | ATT- 1DFL+2RAMP | 13 | 29 | 100 |
| 4 | ATT- 2ACT+1MDV | 6 | 36 | 97 |

*(2) Total input flow of vehicles to buffer areas*

Figure 7.1 shows the total input flow of vehicles to each of the buffer areas in all proposed options. It can be seen that the maximum input flow of ACTs to the mainline buffer is related to option 3 in which the on-ramp flow has priority. This figure also illustrates that the maximum usage of the on-ramp buffer for MDVs is related to option 2 in which the flow on the mainline (for both ACTs and MDVs) has been given a double weight compared to the on-ramp flow in the objective function.

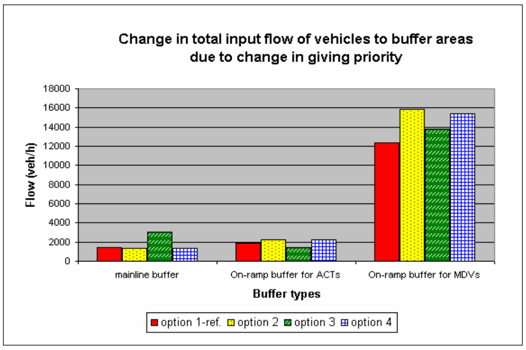



**Figure 7.1. Change in total input flow of vehicles to buffer areas**

This figure also shows a meaningless difference, concerning the usage of the on-ramp buffer of ACTs, between options 2 and 4. A comparison of findings of table 7.1 and figure 7.1 also realizes that the average waiting time of MDVs in the on-ramp buffer is almost the same in options 2 and 4.

*(3) Flow inventory in buffer areas versus time*

This indicator is applied to show more clearly how a buffer area is charged and discharged by vehicles within the time period of analysis. As it is indicated in figure 7.2, in almost all options of analysis, the stored flow of ACTs in the on-ramp buffer is increased until the time instant 500 s- 550 s. The increase of stored flow of ACTs in this buffer is due to congested flow which is originated from the higher number of generated vehicles (traffic demand) on the roadways during the first half time of analysis. In fact, it is found advantageous to store some vehicles in buffer areas in order to use the provided capacity at the on-ramp area, more effectively. Although in all scenarios the discharge of the on-ramp for ACTs in the on-ramp buffer started in almost the similar time instant (e.g. 500-550 s), the maximum stored flow of ACTs in this buffer is related to option 2 in which the mainline flow is given a double priority.

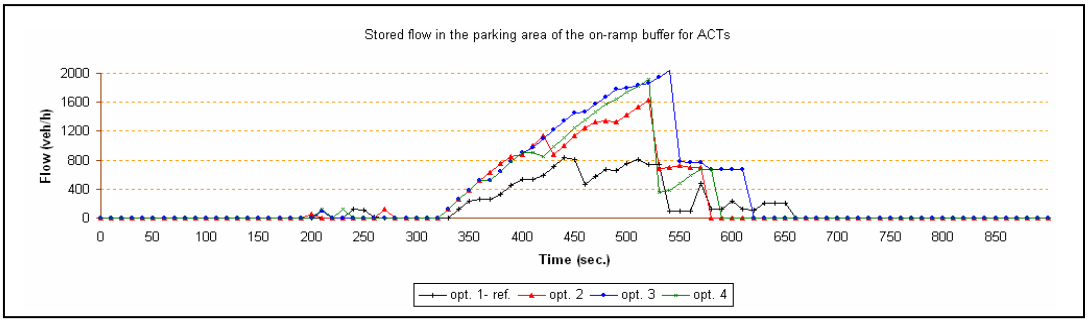



**Figure 7.2. Flow inventory-time diagram of ACTs in the on-ramp buffer for the ACTs**

*(4) Maximum waiting time of vehicles in buffer areas*

Table 7.2 indicates the maximum waiting time of vehicles in buffer areas for all options.

**Table 7.2. Maximum waiting time of vehicles in buffer areas**

| Option | Summary description | Maximum waiting time of vehicles in buffer areas (sec.) | | |
|---|---|---|---|---|
| | | mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1- ref. | ATT | 110 | 100 | 50 |
| 2 | ATT- 2DFL+1RAMP | 10 | 120 | 50 |
| 3 | ATT- 1DFL+2RAMP | 110 | 130 | 40 |
| 4 | ATT- 2ACT+1MDV | 70 | 110 | 40 |

According to table 7.2, giving a priority factor of 2 to the mainline flow leads to an extreme decrease in total waiting time of ACTs in the mainline buffer (e.g. 10 sec.), compared to the reference option. This table also indicates that the maximum waiting time of vehicles in buffer areas in all options has been limited to 130 sec which might be acceptable.

Taking into account all indicators together, it can be summarized that giving priority to a specific user group or a specific roadway results in a lower utilization of the respected buffer for the corresponding user classes.

### 7.1.2 Minimization of total travel time of vehicles

In this design objective, other combinations of options are compared with each other. The options, which are evaluated in this category of objective functions, are as follows:

option 1: reference option, in which all user groups and roadways are given a similar coefficient (named as TTT-ref.);
option 2: only the minimization of total travel time of ACTs on the DFL has been taken into account (named as TTT-ACT-DFL);
option 3: only the minimization of total travel time of ACTs on the on-ramp has been taken into account (named as TTT-ACT-RAMP);
option 4: only the minimization of total travel time of MDVs on the on-ramp has been taken into account (named as TTT-MDV-RAMP).

Thus, in each of the options 2 to 4, the flow controller tries to focus only on a specific user group on either the main roadway or on-ramp. For instance, in option 2 a priority is given to ACTs on the DFL while passing the on-ramp area, while in option 3 it is the flow of ACTs on the on-ramp. Tables 7.3, 7.4 and 7.5 and also figure 7.3 indicate some analysis results concerning the above options.

*(1) Total number of vehicles stored in buffer areas*

Table 7.3 shows the number of vehicles that are stored in buffer area in all these options. As can be seen from table 7.3, the minimum number of stored vehicles in each buffer area is related to the option in which the respected user group of the buffer area is given a higher priority. For instance, in option 2 where ACTs on the DFL have been given a priority, the mainline buffer is not used by ACTs anymore. Similarly, in option 3 where the flow of ACTs on the on-ramp buffer has a high priority, only 4 equivalent vehicles use the on-ramp buffer of ACTs.

**Table 7.3. Total number of vehicles stored in buffer areas**

| Option | Summary description | Equivalent number of vehicles stored in buffer areas | | |
|---|---|---|---|---|
| | | mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1- ref. | TTT | 6 | 34 | 100 |
| 2 | TTT-ACT-DFL | 0 | 127 | 135 |
| 3 | TTT-ACT-RAMP | 60 | 4 | 151 |
| 4 | TTT-MDV-RAMP | 9 | 80 | 95 |

Consequently, any decrease in the number of vehicles using a certain buffer area leads to a higher utilization of other buffer areas by the other user groups.

*(2) Total input flow of vehicles to buffer areas*

As it is addressed before, a combination of this indicator and the previous indicator provides the comparative analysis concerning the average waiting time of vehicles in buffer areas. Table 7.4 indicates the total input flow of vehicles to buffer areas in all options.

**Table 7.4. Total input flow of vehicles to buffer areas**

| Option | Summary description | Total input flow of vehicles to buffer areas (veh/h) | | |
|---|---|---|---|---|
| | | mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1- ref. | TTT | 1373 | 2400 | 12871 |
| 2 | TTT-ACT-DFL | 0 | 3223 | 14406 |
| 3 | TTT-ACT-RAMP | 4287 | 1235 | 14990 |
| 4 | TTT-MDV-RAMP | 2563 | 2305 | 13268 |

For instance, focusing on the "on-ramp buffer for MDVs" column for options 1 and 4 in table 7.4 is realized an increase in total input flow of MDVs to the on-ramp buffer (in option 4), whereas a decrease in the total number of stored MDVs in the on-ramp buffer for the same buffer area happens (table 7.3). This results in a slightly lower average waiting time of MDVs in option 4, compared to the reference scenario. This is expected, because in the option 4, a priority is given to MDVs on the on-ramp. Thus, there is no need to stay for a long time in the buffer area. In comparison, the "on-ramp buffer for ACTs" cell in these two options indicates a completely opposite trend which means a higher average waiting time of ACTs in the on-ramp buffer for this user group in option 4, compared to the reference scenario.

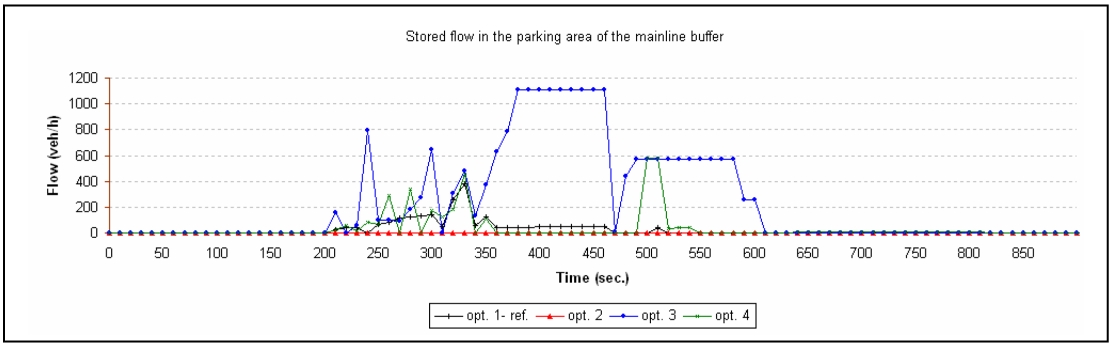
*(3) Flow inventory in buffer areas versus time*

Figure 7.3 indicates the changes in the stored flow of vehicles in buffer areas versus time. The part (a) refers to the flow inventory in the mainline buffer, while the part (b) indicates the flow inventory of ACTs in the on-ramp buffer for ACTs.

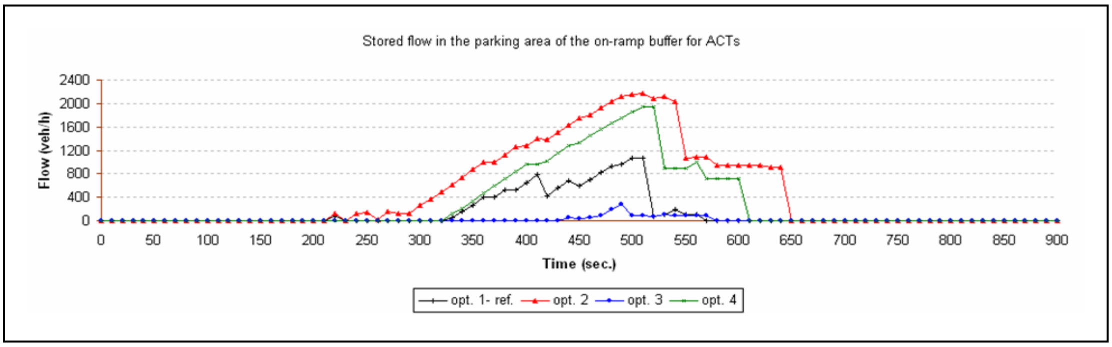
As it is indicated in part (a), the highest flow inventory of ACTs in the mainline buffer is related to option 3. In this option, ACTs on the mainline are directed to the mainline buffer to create the required space for enabling the ACTs (on the on-ramp) to merge to the DFL more easily. Alternatively, the on-ramp buffer for ACTs in this option shows a minimum flow inventory which might lead the capacity of the on-ramp buffer for ACTs to be reduced.

Similarly, in option 2 where the ACTs on the DFL have been considered as a prioritized user group, no inventory of flow of ACTs in the mainline buffer is built. Whereas, the on-ramp buffer of ACTs shows the highest flow inventory, compared to all other options.

The results of analysis also indicate that all buffer areas are discharged from vehicles almost every 600 s time intervals.




*(a) mainline buffer*




*(b) on-ramp buffer for ACTs*

**Figure 7.3. Flow inventory in buffer areas assigned to ACTs**

The shape of the flow inventory graph of buffer areas depends on factors like the absolute generated flow of vehicles at origins, the provided capacity at on-ramp, the priority given to a specific user group or roadway, etc. Since the generated flow of ACTs on the on-ramp is lower compared to the flow of ACTs on the DFL, the stored vehicles in the mainline buffer leave the mainline buffer much sooner compared to the stored flow of ACTs on the on-ramp. Thus, a more fluctuated inventory of flow of ACTs in the mainline buffer is expected, compared to the on-ramp buffers. In addition, the solutions are not necessarily, the unique optimal results. It means that other optimal results (e.g. caused by a cumulative flow inventory in the mainline buffer) could be found to lead to similar (optimal) values of the objective function.

*(4) Maximum waiting time of vehicles in buffer areas*

Table 7.5 indicates the maximum waiting time of vehicles in buffer areas for all options.

**Table 7.5. Maximum waiting time of vehicles in buffer areas**

| Option | Summary description | Maximum waiting time of vehicles in buffer areas (sec.) | | |
|---|---|---|---|---|
| | | mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1- ref. | TTT | 110 | 90 | 40 |
| 2 | TTT-ACT-DFL | 0 | 220 | 50 |
| 3 | TTT-ACT-RAMP | 110 | 30 | 100 |
| 4 | TTT-MDV-RAMP | 20 | 160 | 40 |

As it can be seen, giving a priority to ACTs on the DFL leads to a waiting time of 220 s for ACTs in the on-ramp buffer. Compared to maximum cycle time of traffic control signals in urban areas (e.g. 3 min.), the maximum waiting time of 220 s for truck drivers on motorways seems to be unacceptable. Therefore, the operator would need to change the control strategy in order to reduce the maximum waiting time of ACTs in the on-ramp buffer. This can be achieved by putting a higher weight for the flow of ACTs in the on-ramp, compared to the existing situation. This table also indicates that options 1 and 3 achieve a more even distribution of the maximum waiting time of vehicles among all buffer areas. In these options, the ACTs on the on-ramp are given a higher priority compared to two other options.

Thus, buffer areas can play a very important role to provide a minimum travel time of specific user groups on the main roadway or at the on-ramp. Buffer areas which have been assigned to specific user groups may be occupied more intensively. Conversely, the buffer area, which is assigned to the user group (or flow direction) with a very high priority, would be used less.

### 7.1.3 Maximization of throughput at the merging area

The throughput at the merging area is the summation of four different flow directions at the merging area: traffic flow of ACTs on the DFL, traffic flow of ACTs on the on-ramp, traffic flow of MDVs on the mainline, and traffic flow of MDVs on the on-ramp. Thus, in order to give priority to a specific flow direction, it is necessary to put a heavier weight (larger coefficient) for that specific flow direction term in the objective function equation. This weight should be selected in such a way that a balance between the absolute value of each of the terms of the objective function is created. Table 7.6 presents three different options of the analysis with three different combinations of coefficients for various terms of the objective function.

**Table 7.6. Weights of flow directions in options of analysis**

| Option | Summary description | Weight of flow in the objective function | | | |
|---|---|---|---|---|---|
| | | flow of ACTs on the DFL | flow of ACTs on the on-ramp | flow of MDVs on the mainline | flow of MDVs on the on-ramp |
| 1- ref. | TP | 1 | 1 | 1 | 1 |
| 2 | TP-1-4-1-1 | 1 | 4 | 1 | 1 |
| 3 | TP-1-6-1-1 | 1 | 6 | 1 | 1 |

In the reference option, all flow directions are given an equal weight (e.g. 1). While, in the second option the flow of ACTs on the on-ramp is given a priority of 4, compared to other flow directions. Finally, in the last option, it is assumed that the summation of flow of ACTs on the on-ramp at the merging area has a six times value, compared to other flow directions. Taking into account the absolute summation of values of traffic flow of ACTs on the on-ramp, the factor 6 would lead to a higher absolute value compared to respected term to the flow of MDVs on the on-ramp.

The results of the analysis indicate that compared to the reference option, the average waiting time of all vehicles increases by about 4% and 22% in options 2 and 3, respectively. Specifically, in the third option, due to a balance between related terms of flow of ACTs and MDVs on the on-ramp, a considerable increase in average waiting time of MDVs in the on-ramp buffer is observed. More detailed results of analysis can be found in the following.

*(1) Total number of vehicles stored in buffer areas*

Figure 7.4 shows the change in total number of vehicles stored in buffer areas, compared to the reference option in which all flow directions are equally considered. In the reference option, the total number of vehicles stored in the mainline buffer, on-ramp buffer for ACTs and the on-ramp buffer for MDVs are equal to 10, 54, and 118 vehicles, respectively.

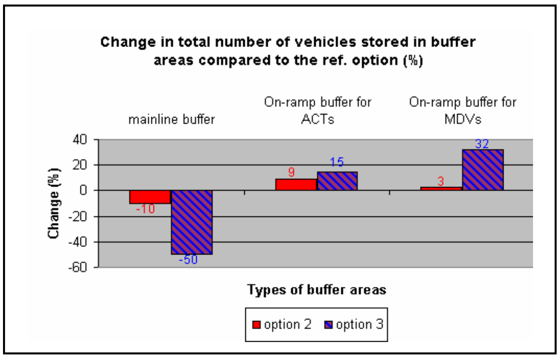



**Figure 7.4. Change in total number of vehicles stored in buffer areas**

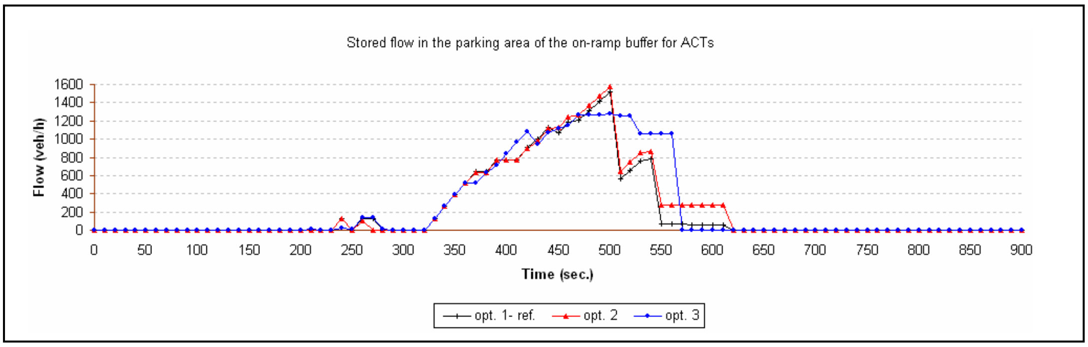
This figure shows that by increasing the weight of the throughput of ACTs on the on-ramp in the objective function, by about 4 (e.g. in option 2), no major difference occurs in the total number of vehicles stored in all buffer areas. However, by increasing this weight up to 6 (e.g. in option 3), the on-ramp buffer for MDVs is used more intensively, whereas the utilization of the mainline buffer is decreased considerably (by about 50%). Multiplying the related term of flow of ACTs on the on-ramp by 6 in the objective function leads to a higher absolute value for this specific user group, rather than the flow of MDVs on the on-ramp. This leads to a higher usage of the on-ramp buffer by MDVs, compared to ACTs. By decreasing the number of crossing MDVs from the on-ramp (e.g. by storing some of them in the on-ramp buffer, temporarily), the need for storing ACTs on the mainline buffer decreases. This is the reason why the number of ACTs stored in the mainline buffer in the option 3 is decreased compared to the reference option.

*(2) Flow inventory in buffer areas versus time*

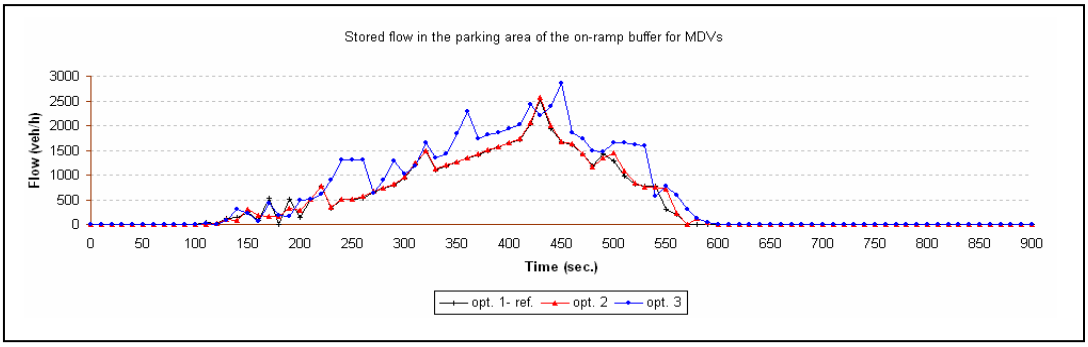
Figure 7.5 indicates the flow inventory of vehicles in the on-ramp buffers, assigned to ACTs and MDVs, separately. The figure realizes that the inventory of vehicles in the on-ramp buffers starts from time instants 230 and 120 seconds, in the on-ramp buffers for ACTs and MDVs respectively. The discharge of these on-ramp buffers ends at time instants around 600 sec. It means that the on-ramp buffer for MDVs holds back the MDVs for a longer time, compared to ACTs.

*(3) Maximum waiting time of vehicles in buffer areas*

As it can be seen from table 7.7, the maximum waiting time of vehicles in buffer areas is limited to 170 s which seems to be acceptable. It is emphasized that in spite of assigning a high weight to the throughput of ACTs on the on-ramp at the merging area, there results still a considerable waiting time of ACTs in the on-ramp buffer (e.g. 170 sec.).




(a) on-ramp buffer for ACTs




(b) on-ramp buffer for MDVs

**Figure 7.5. Flow inventory of vehicles in the on-ramp buffers**

Alternatively, the maximum waiting time of ACTs in the mainline buffer is limited to 80 sec. The maximum waiting time of MDVs in the on-ramp buffer is limited to 70 sec which is due to the need to let the ACTs approach to the merging area more easily.

**Table 7.7. Maximum waiting time of vehicles in buffer areas**

| Option | Summary description | Maximum waiting time of vehicles in buffer areas (sec.) | | |
|---|---|---|---|---|
| | | mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1- ref. | TP | 80 | 150 | 60 |
| 2 | TP-1-4-1-1 | 50 | 150 | 70 |
| 3 | TP-1-6-1-1 | 10 | 170 | 60 |

Thus, buffer areas can be used as a helpful mean to provide the possibility for increasing the throughput of a specific user group or a specific flow direction at merging areas more effectively. However, when the input flow to the merging area does not reach capacity, then a buffer area is not necessary. In such a case, the direction of the flow of vehicles via the buffer area would lead to a decrease in the total throughput of vehicles at the merging area.

### 7.1.4 Maximization of safety

A buffer area may improve the safety in mixed flow of ACTs and MDVs at merging areas by controlling the flow of ACTs on the on-ramp in order to merge to the flow of ACTs on the DFL. It may control, too, the flow of MDVs on the on-ramp which cross the flow of ACTs on the DFL. It also may provide a higher probability for merging the on-ramp flow of MDVs to the mainline flow (of MDVs).

In our assumed flow configuration three intersections between different flow directions exist:

(a) the intersection (merging) point between the flow of ACTs on the DFL and the on-ramp flow of ACTs;
(b) the intersection (crossing) point between the flow of ACTs on the DFL and the on-ramp flow of MDVs;
(c) the intersection (merging) point between the flow of MDVs on the mainline and the on-ramp flow of MDVs.

Thus, a means to increase safety at the merging area is to assure a limited speed difference between the flows in all these three intersection points. Consequently, in order to maximize safety at the merging area, we try to minimize the speed difference among flows that merge or cross each other at the merging area. For ACTs, such an optimal speed difference between two flow directions (e.g. mainline flow and on-ramp flow of ACTs) helps the controller of the operation of ACTs in the traffic control center to regulate the speed of ACTs upstream on-ramp areas.

Moreover, to evaluate the impact of focusing on a single intersection point on the function of buffer areas, the following options are tested:

Option 1: the reference option, in which the main aim of control is to minimize the speed difference of flow directions in all three intersection points at the merging area;
Option 2: named as A-A, in which the main focus is on the flow of ACTs and therefore the controller of the system tries to only minimize the speed difference of ACTs on the DFL and on the on-ramp (intersection point (a) described at above);
Option 3: named as A-M, in which the main focus is on the intersection point of the flow of ACTs on the DFL and of the flow of MDVs on the on-ramp (intersection point (b));
Option 4: named as M-M, in which the intersection point of two flows of MDVs (intersection point (c)) is the main focus of the traffic control plan.

The major findings of the analysis of the above options can be summarized as follow:

*(1) Total number of vehicles stored in buffer areas*

Table 7.8 presents the (equivalent) number of vehicles stored in all buffer areas for each of the proposed options.

**Table 7.8. Total number of vehicles stored in buffer areas**

| Option | Summary description | Equivalent number of vehicles stored in buffer areas | | |
|---|---|---|---|---|
| | | mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1- ref. | ref. | 15 | 80 | 132 |
| 2 | A-A | 47 | 84 | 124 |
| 3 | A-M | 50 | 58 | 169 |
| 4 | M-M | 10 | 48 | 365 |

The above table indicates the important role of the buffer areas in providing a uniform speed of flow directions that intersect each other. For instance, in option 2, where the main aim is to provide a uniform speed of ACTs (alone) at the merging area, the mainline buffer plays a more important role, compared to the reference option, as the number of vehicles entering to the mainline buffer is tripled. Similarly, in options 3 and 4 where MDVs are involved, a higher number of MDVs are stored in the on-ramp buffer. Specially, in the last option where the main focus is on the flow of MDVs, the number of entering MDVs to the on-ramp buffer of MDVs is tripled. Conversely, in the option 4, the number of ACTs stored in buffer areas is decreased, effectively. In brief, the higher the number of vehicles stored in a buffer area during a short time period, the more complex the function of that buffer area.

*(2) Average waiting time per vehicle*

The optimization results indicate that the average waiting time per vehicle[1] in the reference option is 2.8 s. Figure 7.6 compares the average waiting time of the vehicles in the other options, compared to the reference option. A major increase in this indicator (by about 90 %) happens in the fourth option, whereas, in the other options this increase is limited to 21%.

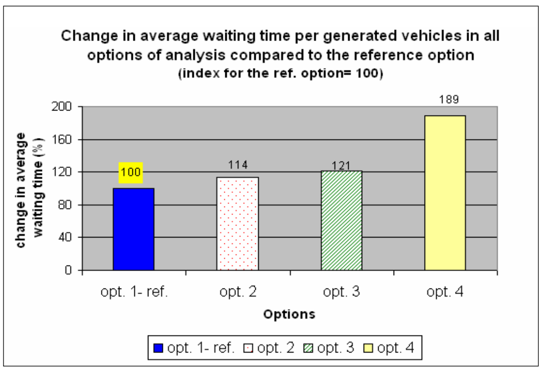



**Figure 7.6. The comparative (average) waiting time of vehicles**

[1] The total number of generated vehicles are taken into account in this calculation. Therefore, the indicator does not represent the average waiting time of a vehicle in the buffer area.

The main reason is the existence of a single buffer for MDVs (on the on-ramp) to regulate the speed of MDVs at the merging area coming from two directions. In two other options at least two buffers work together to provide a uniform speed of two flow directions at the merging area. For instance, in option 3 the mainline buffer for ACTs and the on-ramp buffer for MDVs co-operate in such a way to provide a minimum difference in speed of ACTs and MDVs at the merging area.

This figure also indicates that the reference option represents the minimum average waiting time among all assumed options of analysis. It means that a higher average waiting time must be expected if the control of speed difference is concentrated on a specific intersection, because in such cases no control is applied for the rest of user groups and a higher decrease of hindrance is to be expected at the merging area resulting in a longer waiting times of vehicles.

*<u>(3) Flow inventory in buffer areas versus time</u>*

Figures 7.7 and 7.8 show the flow inventory of vehicles in the mainline buffer and the on-ramp buffer for MDVs, respectively. Figure 7.7 indicates more clearly the major role of the mainline buffer in options 2 and 3, whereas, in the fourth option the mainline buffer does not play an effective role. Conversely, figure 7.8 depicts the important role of the on-ramp buffer of MDVs in the fourth option.

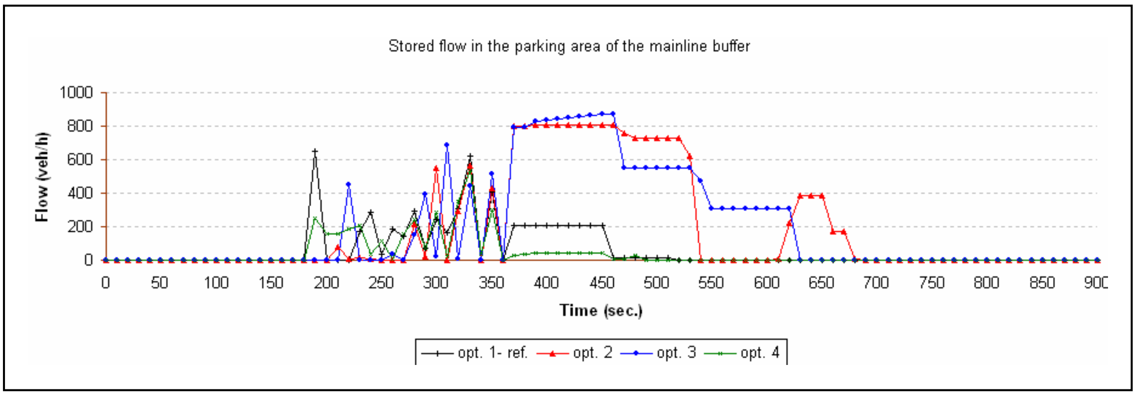



**Figure 7.7. Flow inventory of vehicles in the mainline buffer**

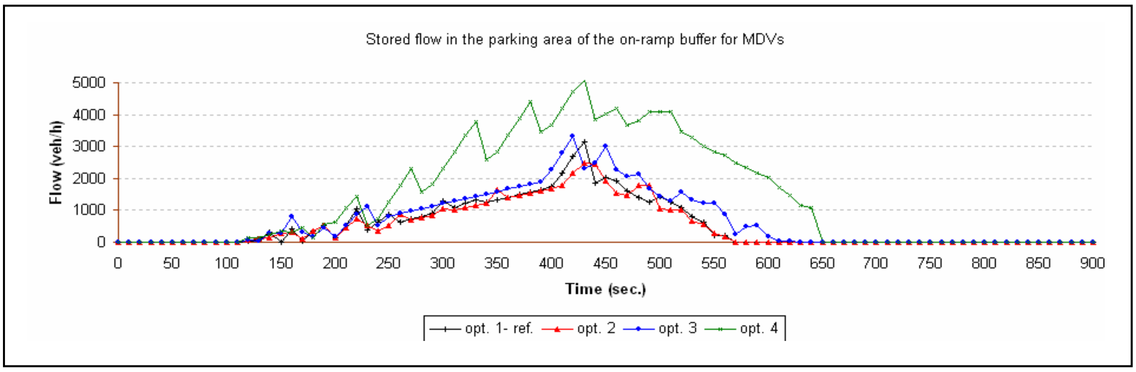



**Figure 7.8. Flow inventory of vehicles in the on-ramp buffer for MDVs**

Both figures emphasize the effective role of buffer areas in the options where the assigned user groups (or flow directions) to those buffer areas are represented directly in the objective function.

Figure 7.7 also illustrates that the flow inventory of vehicles in buffer areas takes a longer time compared to other objective functions that are analyzed till now. For instance, in option 2, the discharge of the mainline buffer from ACTs lasts until the time instant 700 s. Such a long duration of flow inventory of vehicles in buffer areas has not been recorded else yet.

*(4) Maximum waiting time of vehicles in buffer areas*

Table 7.9 specifies the maximum waiting time of the vehicles in buffer areas for all proposed options. According to this table, the maximum waiting time of vehicles in the mainline buffer, the on-ramp buffer for ACTs, and the on-ramp buffer for MDVs are equal to 260, 200, and 200 sec. These values of the waiting time are longer compared to all other options that are analyzed yet. It indicates the complexity of traffic management in buffer areas for mixed flows of ACTs and MDVs.

This table also indicates that the maximum waiting time of the vehicles in a buffer area occurs in the options where the related user group to that specific buffer area is the main goal of the objective function. For instance, in option 4 where the main focus of the control objective is on the flow of MDVs, the maximum waiting time of vehicles in the on-ramp buffer for MDVs is produced.

In general, table 7.9 depicts that there is a trade off between the minimization of the waiting time of the vehicles and the maximization of safety at merging areas. The higher the expected degree of safety at the merging area in mixed flow of ACTs and MDVs, the higher the waiting time of vehicles in buffer areas.

**Table 7.9. Maximum waiting time of vehicles in buffer areas**

| Option | Summary description | Maximum waiting time of vehicles in buffer areas (sec.) | | |
|---|---|---|---|---|
| | | mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1- ref. | ref. | 90 | 150 | 40 |
| 2 | A-A | 170 | 200 | 70 |
| 3 | A-M | 260 | 130 | 60 |
| 4 | M-M | 90 | 100 | 200 |

In practice, in order to provide a safe crossing (of MDVs) and merging (of ACTs) at the on-ramp area, a slight speed difference between flows in different directions is required to provide the probability for safe crossing or merging. Thus, it is recommended to assess the impact of various speed differences between flow directions on the maximization of safety at merging areas.

### 7.1.5 Minimization of fuel consumption

Buffer areas, as infrastructural reservoirs in the road network, might keep the required number of vehicles off the main flow to provide a uniform speed of vehicles along the different segments of motorways, particularly upstream of merging areas. At merging areas, due to the merging of vehicles to the mainline, the density of vehicles increases considerably. It increases the variation of flow and speed of vehicles operating on the mainline (or the DFL) and causes an increase of the number of accelerations and decelerations of vehicles which leads to an increase in fuel consumption of vehicles.

Therefore, the existence of a buffer area would help to control the flow and density of vehicles on a specific segment of the motorway. A more uniform density would lead to less variance of the speed of vehicles along that specific segment of the motorway, and consequently to a decrease in fuel consumption.

In order to evaluate the impact of the creation of buffer areas on the fuel consumption of vehicles, the speed difference of vehicles in successive segments of all assumed roadways is taken into account. Thus, the assumed objective function is the combination of the following four terms:

term 1: the speed difference of ACTs on successive segments of the DFL,
term 2: the speed difference of MDVs on successive segments of the mainline,
term 3: the speed difference of ACTs on successive segments of the on-ramp,
term 4: the speed difference of MDVs on successive segments of the on-ramp.

Table 7.10 indicates the various combinations of importance (weight) of each of the above terms which are tested to compare the impact of buffer areas in each of the control strategies.

**Table 7.10. Weights of each of the terms in analysis options**

| Option | Summary description | Weight of trerms in the objective function | | | |
|---|---|---|---|---|---|
| | | term 1 | term 2 | term 3 | term 4 |
| 1- ref. | Fuel-ref. | 1 | 1 | 1 | 1 |
| 2 | Fuel-4-3-2-1 | 4 | 3 | 2 | 1 |
| 3 | Fuel-1-2-3-4 | 1 | 2 | 3 | 4 |
| 4 | Fuel-2-4-1-3 | 2 | 4 | 1 | 3 |

In the first option, *the reference option*, all terms have an equal weight in the objective function. In the second option, the minimization of speed difference over DFL segments has been given the highest weight (e.g. 4), whereas the harmonization of speed of MDVs along on-ramp segments is given the lowest priority (e.g. 1). The third option, actually the contrary of the second one, means that the highest priority is given to the vehicles on the on-ramp, and specially to MDVs. In the last option, the heaviest weight is given to the flow of MDVs on both the mainline and the on-ramp, by assigning the highest factors (e.g. 4 and 3) to them, compared to the flow of ACTs. A summary of the results of analysis is reported in the following:

*(1) Total number of vehicles stored in buffer areas*

Figure 7.9 presents the number of vehicles stored in all buffer areas for each of the proposed options.

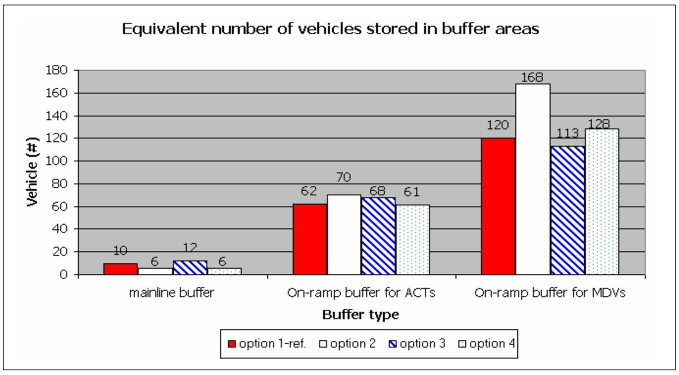



**Figure 7.9. Total number of vehicles stored in buffer areas**

According to figure 7.9, the highest number of vehicles stored in the on-ramp buffers (for both ACTs and MDVs) is related to option 2 in which the mainline flow has the highest weights in the objective function. Similarly, the mainline buffer represents the highest number of vehicles in the third option in which the minimization of speed variance in the mainline direction has been given the lowest priority. Thus, buffer areas designed for a roadway (like on-ramp buffers) reserve a number of vehicles (both ACTs and MDVs) temporarily to minimize the hindrance of flow of ACTs operating on the DFL, as well as the total fuel consumption. A similar process is performed for ACTs in the mainline buffer, if the on-ramp flow is given a priority.

Figure 7.9 also emphasizes, once more, the role of the on-ramp buffer for MDVs compared to other buffer areas. This buffer absorbs the maximum number of vehicles, compared to all other buffer areas. The main reason is the multiple function of such a buffer area in each of the options of analysis. For instance, it minimizes the hindrance of flow of ACTs on the DFL, caused by MDVs entering from the on-ramp. Simultaneously, this buffer minimizes the hindrance of flow of mainine flow of MDVs by the same flow of entering MDVs from the on-ramp. It may contribute to the entrance of a higher number of MDVs to this buffer area during peak periods.

*(2) Total input flow of vehicles to buffer areas*

Figure 7.10 presents the total input flow of vehicles to the buffer areas in all proposed options. A combination of this figure and figure 7.9 provides a comparative result concerning the average waiting time of vehicles in buffer areas.

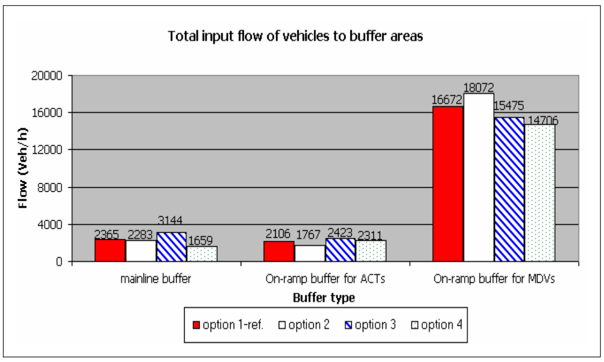



**Figure 7.10. Total number of vehicles stored in buffer areas**

The comparison of figures 7.9 and 7.10 shows that the average waiting time of ACTs in the on-ramp buffer is much higher than the average waiting time of ACTs in the mainline buffer, in all proposed options. Because figure 7.10 reveals a lower total input flow of vehicles to the on-ramp buffer of ACTs, compared to the mainline buffer, whereas, figure 7.9 shows a higher number of stored vehicles in this buffer compared to the mainline buffer. In spite of this fact, figure 7.9 depicted a higher value of stored vehicles in the on-ramp buffer of ACTs, compared to the mainline buffer.

Such a comparative analysis also can be achieved for a specific buffer area. For instance, figure 7.9 indicates a similar number of vehicles stored in the mainline buffer between options 2 and 4, whereas figure 7.10 shows a considerable lower total input flow of vehicles to this buffer area in the option 4, compared to the option 2 (e.g. 1659 against 2283). It means that the average waiting time of ACTs in the mainline buffer in option 4 is higher than in option 2. This is due to a lower weight which is applied for the mainline flow of ACTs in this option, compared to option 4 (e.g. a coefficient of 2 in the option 4 against a coefficient of 4 in the option 2). Thus, the results of the analysis are consistent with what was expected and confirms the validity of the proposed model.

*(3) Flow inventory in buffer areas versus time*

This indicator describes how the flow charge and discharge of a buffer area takes place. For instance, as it can be seen in option 2 of figure 7.11, a higher stored flow of MDVs in the on-ramp buffer for MDVs is reported compared to all other options. It indicates the more effective function of the on-ramp buffer for MDVs during the time that the controller of the system gives a higher priority to the harmonization of speed of the mainline flow.

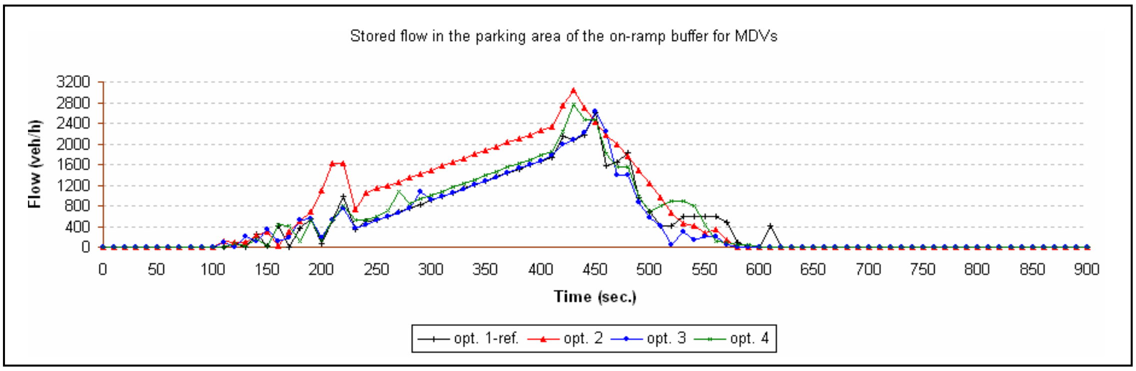



**Figure 7.11. Flow inventory of vehicles in the on-ramp buffer for MDVs**

*(4) Maximum waiting time of vehicles in buffer areas*

Table 7.11 shows the maximum waiting time of vehicles in all buffer areas for the proposed options. As it can be seen in this table, the maximum waiting time of ACTs in the mainline buffer is related to options 1 and 3 in where the synchronization of speed of ACTs on the DFL is not the main focus of the system controller. Conversely, in options 2 and 4 where the main focus has been on the harmonization of speed of ACTs along the DFL - or the mainline flow of MDVs- the maximum waiting time of ACTs in the mainline buffer is limited to 10 sec. In all options, the maximum waiting time of

ACTs in the on-ramp buffer reaches about 3 minutes which can be used for the change of the mode of control from manual to automatic.

**Table 7.11. Maximum waiting time of vehicles in buffer areas**

| Option | Summary description | Maximum waiting time of vehicles in buffer areas (sec.) | | |
|---|---|---|---|---|
| | | mainline buffer | On-ramp buffer for ACTs | On-ramp buffer for MDVs |
| 1- ref. | Fuel-ref. | 100 | 170 | 60 |
| 2 | Fuel-4-3-2-1 | 10 | 180 | 60 |
| 3 | Fuel-1-2-3-4 | 100 | 170 | 50 |
| 4 | Fuel-2-4-1-3 | 10 | 170 | 60 |

This maximum waiting time of ACTs in the on-ramp buffer can be decreased by assigning a higher weight for the speed synchronization of ACTs on the on-ramp, compared to the rest of user groups. The results of analysis also address a maximum waiting time of only 60 sec for MDVs in the on-ramp buffer.

## 7.2 Summary

This chapter focused on the impact of the selection of different design objectives of the traffic control system on the function of buffer areas. In order to evaluate such impact, the following objectives were taken into account: the minimization of average travel time of vehicles, the minimization of total travel time of vehicles, the maximization of throughput, the minimization of speed difference among all directions of the flow at the merging area, and finally the minimization of speed of user groups along the roadways.

Indicators like the total number of vehicles stored in each of the buffer areas, average waiting time of vehicles, total input flow to each of the buffer areas, change in flow inventory of vehicles in buffer areas, and finally the maximum waiting time of vehicles in buffer areas were selected as the main indicators to compare the change in function of buffer areas among the proposed options of analysis.

In each category of objective functions, a different configuration of system design objectives were compared with each other (e.g. different coefficients for different terms of the objective function formula) to indicate the possibility of the existing model for evaluating a wide range of control strategies.

The findings of the analysis clearly indicate the major role of buffer areas to reach to the proposed design objective. For instance, to minimize the total travel time of vehicles in a mixed flow of ACTs and MDVs at merging areas, buffer areas could help to store some vehicles during a peak interval and then to release the stored vehicles during off-peak time. The optimal flow of different user groups in each time instant of analysis is calculated based on the results of the proposed optimization model. The results of the model determine how many vehicles can enter to (and similarly exit from) the buffer area within a certain time period. Based on this result, the buffer traffic controller can decide upon the most effective measures like checking or platooning of trucks within a certain time period.

The analysis also confirms that giving priority to a specific user group or a specific flow direction results in a lower utilization of buffer areas which are assigned to that specific user group or flow direction.

The comparison of different objective functions for the reference option presents a more complex behavior of buffer areas with respect to objective functions like the maximization of safety or the minimization of fuel consumption, compared to the other proposed objectives. By means of applying these objective functions, it may take a longer time (more than 3 min.) for vehicles to be stored in a buffer area. The difference in flow characteristics of different user groups involved in these objective functions, for instance the speed difference among user groups at merging areas, plays a major role. The lower the difference in flow characteristics among the user groups, the shorter the waiting time in the buffer areas when applying the objective functions (e.g. minimization of speed difference along a roadway or among different user groups hampered by each other at the merging area).

# 8
# Conclusions and Recommendations

At the beginning of this research thesis we referred to the growing traffic congestion on the Dutch motorways that may endanger maintaining the pivot point function of the Netherlands in European freight distribution network in future. So, since the prospect of building new motorways or additional lanes has become increasingly difficult, looking for possibilities to increase the existing capacity of motorways was proposed as an essential need, at least for the freight transport sector.

Thus, to preserve the major role of freight transport fleet, which is vital for the Dutch economy, one of the policies which is implemented from the past, is to offer preferential treatment on the existing infrastructure to specific target groups (e.g. trucks in this case). However, due to limit of space and budget and also growing demand of other user groups of motorways, a completely dedicated route for the operation of ordinary trucks on the existing motorways might be impossible.

Therefore, the main crucial point in this research thesis has been to focus on a solution, which would increase the efficiency of the existing motorways for trucks. The proposed solution should however take into account other user groups and should not hamper the traffic flow of other user groups, considerably.

To reach to such a goal, we have investigated the proposal of the operation of automatically controlled trucks on existing motorways. Throughout this thesis we have addressed the major design and control requirements for the operation of automatically controlled trucks at on-/off-ramps of existing motorways, where the hindrance of flow of automatically controlled trucks by manually driven vehicles would be expected. In this closing chapter, we conclude findings of this research theme, briefly, and give recommendations for further research.

## 8.1 Research results

In the introductory chapter, we have identified four key questions which should be answered to verify 'why' and 'how' the proposed solution may be feasible. These questions are repeated, briefly, for convenience:

1. What are the main benefits of the operation of automatically controlled trucks?
2. Which requirements should we think about to provide the operation of ACTs automatically controlled trucks?
3. Which impacts have the proposed solution on other user groups of roads?
4. What are the required model extensions and how it can be implemented in reality?

Throughout this thesis, we have tried to provide adequate answers for each of the above questions. This contribution can be characterized from other similar researches in the field of AHS from the following points of view:

a) it has focused on using the existing infrastructure (motorways) for the operation of automatically controlled trucks;
b) it has concentrated on crucial time and space situations like focusing on peak hours and bottlenecks, among which the maximum level of hindrance between user groups would be expected;
c) it has introduced the wide application of optimization methods in developing control strategies at bottlenecks.

Taking into account the first characteristic, would lead us to the conclusion to focus on control strategies and design aspects which will not require a high investment. Because, as it has been described in the introductory chapter, the required high investment for building the additonal lanes and also the negative environmental impact can be considered as major opposite factors for developing Dutch road infrastructures. Therefore, we have focused on using existing lanes of motorways and within this contribution it has been tried to increase the efficiency of existing infrastructures. Only a very limited extension of number of lanes at on-/off-ramps is assumed to be feasible.

Secondly, this research study has focused on crucial situations from a time and space point of view. For instance, it has focused on on- and off-ramps and peak hour traffic situations as the main space and time bottlenecks of existing motorways. So, any increase in the efficiency of existing motorways, caused by the proposed solution in this contribution, would indicate the minimum capability of the proposed solution for improving the existing situation. Thus, the derived benefits of the proposed AHS system in this contribution for increasing the efficiency of existing motorways would be much less than what normally has been seen in the literature. In order to emphasize on the first characteristic, throughout this thesis it is assumed that there is no possibility for the construction of fly-overs or tunnels at on-/off-ramps. It means that the crossing flow of vehicles should be solved by focusing on at-grade design and control options.

Finally, this research study has recommended the wider application of optimization methods for developing control strategies on motorways, while the operation of automatically controlled trucks has been proposed. Applying optimization algorithms might lead to a higher efficiency of existing motorways, compared to situations in which no optimization model is included in the control strategy.

The following subsections will give a brief overview of findings of this research work with respect to each of the key questions, mentioned above. It is clear that to provide the absolute answer to each of the questions further research should be achieved. A summary of topics for further research is addressed in the section 8.2.

### 8.1.1 Main benefits from operation of ACTs

The major benefits of the operation of ACTs which are addressed throughout this study can be summarized as follows:

(1) Operation of ACTs instead of ordinary trucks would provide the possibility for platooning of trucks. The results of analysis in chapter 4 indicate that the selection of an appropriate platooning strategy for trucks would lead to an increase of 18% in capacity of off-ramps. A decrease of 10% in average travel time of all vehicles, a decrease of 40% in average number of accelerations and decelerations of vehicles (which can be interpreted indirectly as a fuel consumption indicator), and an increase by about 55% in safety aspects (represented by TTC values less than 1.5 s) are among other benefits of platooning of trucks at off-ramps. It also was indicated that the development and application of ISA systems for manually driven vehicles also helps to reach to a higher degree of efficiency, in future. The findings also indicate that at on-ramp areas, the selection of an appropriate platooning strategy of ACTs would improve the traffic performance with regard to energy consumption and safety (respectively by about 20% and 24%), rather than capacity;

(2) ACTs could be driven during night (off-peak) hours, since normally the driver has a limited role in driving ACTs. This is allowed if legal barriers are eliminated. Such a possibility can increase the efficiency of motorways during night (off-peak) hours. It also may create more space for other user groups (manually driven vehicles which mostly are passenger cars, vans and buses) during the existing peak hours. Consequently, it would result in a decrease of total travel time of all user groups of motorways. Due to the necessity for being the driver on the board of an ACT and also the role of human in other parts of the operation (like the role of operators in the traffic control center or buffer areas) to ensure rapid incident handling needs, the

operation of ACTs (instead of the ordinary trucks) may not lead to a major increase of freight transport on motorways during night hours [1](and consequently may lead to an overall uniform hourly traffic flow of trucks on motorways during 24 hours of the day), but could help to provide a smoother peak traffic flow along motorways;

(3) Operation of ACTs paves the way for optimizing the control of traffic flow of ACTs more broadly. This capability can create a more smooth flow of ACTs, compared to ordinary trucks. Findings of chapter 6 support the expectation that the provision of the required infrastructure for the operation of ACTs and the application of optimization methods for the traffic control of ACTs, would lead to a reduction of average travel time of all vehicles, by about 15% at merging areas.

### 8.1.2 Main requirements for the operation of ACTs

For the operation of ACTs on existing motorways, we have addressed four major requirements. The first requirement is *the creation of a Dedicated Freight Lane* (DFL) for the operation of ACTs. As it has been discussed in chapter 3, dedicated lanes for ACTs prevent a mix of ACTs and MDVs on motorway links. The segregation of flow of ACTs and MDVs would have the following advantages:

- it minimizes the hindrance of flow of ACTs by MDVs;
- it ensures traffic safety; and
- it simplifies the operation of ACTs.

Moreover, creating DFLs on existing motorways would save investment costs for the construction of additional lanes for the operation of ACTs on motorway links.

In case if the total number of lanes can not be extended, redistribution of existing lanes between ACTs and MDVs may lead to a sub-optimum condition if the DFL is not fully occupied during the whole time periods.

The second requirement which has been addressed through this research thema *is the creation of buffer areas*. This innovative concept has been described in the chapter 3. Later, chapter 5 has developed the theoretical framework of such a concept and finally chapters 6 and 7 have represented the numerical results of application of buffer areas.

As it has been described in chapter 3, buffer areas, originally, were introduced as a new element in Dutch motorways, in order to reduce secondary congestion on motorways. However, the concept of a buffer area in this contribution has a different meaning. In fact, the operation of ACTs would provide the opportunity to distribute the flow of trucks more evenly over the whole day. In such a case, the share of trucks (ACTs) during peak hours of car traffic might decrease. Nevertheless, the existence of a DFL for the operation of ACTs would increase the throughput of ACTs approaching to on-/off-ramps, at crossing points with MDVs. Consequently, the flow of ACTs approaching on a DFL to a bottleneck (e.g. on- or off-ramp) may hinder (or be hindered by) the flow of

[1] Because of less traffic demand compared to day time

MDVs at on-/off-ramp areas. Therefore, the input flow of vehicles to the on-/off-ramp areas has to be controlled in order to minimize congestion. Increasing the possibility for dynamic traffic management of motorways nearby bottlenecks, and also incident management of ACTs have been addressed (in chapter 3) among other functions of buffer areas.
Thus, the main idea underlying the concept of buffer areas for ACTs has been that trucks would follow strictly messages transmitted by the traffic control center in each time instant. This capability (fully automation) can provide the opportunity to miminimize the hindrance of traffic flow of ACTs and MDVs at on-/off-ramps. In fact, the buffer areas act as transition areas for changing the mode of control of trucks from manual to automatic and vice versa, as well as for regulating the traffic flow of ACTs (and even for MDVs on the on-ramps) to minimize the delay for the whole of the traffic at on-/off-ramp areas.

Buffer areas, as reservoirs in the motorway network, also can facilitate the synchronization of speed and density of ACTs while approaching to on-/off-ramp areas. It would help to reach to various aims in flow operation management of motorway networks, like the minimization of fuel consumption or the maximization of safety. This characteristic of application of buffer areas is explained in the chapter 6, quantitatively.

Of course, the realization of buffer areas in densely built-up areas would be difficult due to available space, but in industrial areas where most of the heavy traffic is concentrated and in rural areas there might be better opportunities for the construction of buffer areas along motorways. This requires a more detailed analysis of the local conditions to assess the feasibility of the construction of individual buffer areas.

Findings of this research study also have indicated that *applying traffic signals* on motorways also should be taken into account as a complementary (third) means of control which ensures safety. Although in the beginning of this research study, the application of traffic signals on the mainline (e.g. DFL) were not distinguished as an essential means of control, the findings of analysis in chapter 4 emphasized the need for applying traffic signals, either on the mainline (for ACTs on the DFL and for the off-ramp flow of MDVs on the mainline) and on the on-ramp.

These extra traffic signals specially would play a critical role while applying a platooning strategy to ensure safety. In situations where putting traffic signals would hinder the other flow directions considerably, the construction of fly-overs has been recomended. For instance, when the queue of an off-ramp flow of MDVs leaving the mainline due to a traffic signal would hamper the approaching flow of MDVs on the mainline, the construction of a fly-over would be recommended. This decision only can be made when the results of the simulations and optimizations of all options confirm the need for the construction of a fly-over.

Due to restrictions for assigning a complete network of dedicated lanes of existing motorways to ACTs, the wide application of optimization methods for developing suitable traffic control strategies, specially at bottlenecks like on-/off-ramps, has been highly recommended in this research study. Thus, *the development of optimization method algorithms*, to verify the optimal state of flow of ACTs (and even MDVs) has been distinguished as the fourth major requirement for the operation of ACTs on existing motorways, in future.

The deterministic state of flow of ACTs would strengthen the idea of application of optimization methods while operating ACTs. Since, ACTs can strictly follow commands transmitted by the traffic control center, which are results of solving the proposed optimization model. This capability would reduce the degree of hindrance of MDVs, caused by ACTs at on-/off-ramp areas. The analysis performed in chapters 6 and 7 indicated that the proposed optimization models for controlling the mixed flow of ACTs and MDVs at on-/off-ramp areas can be executed rapidly (e.g. less than 1 sec.). Due to this very short execution time, it would be possible to implement the results of the models for the on-line traffic control measures. However, it should be emphasized here that the proposed model is developed for a single on-ramp. Due to the large dimension of the model, the application of the model for a complete motorway network brings difficulties. Thus, further research is needed to assess how to solve such a model structure for a larger motorway network.

### 8.1.3 Impacts of operation of ACTs on other user groups

The impact assessment of the operation of ACTs on other user groups can be classified in two parts. The first part reflects the disadvantages of operation of ACTs on other user groups of motorways (e.g. MDVs), whereas the second part returns to benefits of other user groups of motorways, named as MDVs in this contribution, caused by the operation of ACTs instead of ordinary trucks. In this section we have summarized both impacts, based on findings of all analysis achieved throughout this research thesis.

For instance, the major benefits of operation of ACTs on the DFLs were described in the previous section. However, it is clear that the reduction of the number of existing lanes for other vehicles than trucks would reduce the remaining capacity of the motorway and may lead to severe congestions. The principal results of the analysis (carried out in the chapter 3) have indicated that in case of a high share of trucks in the traffic flow (e.g. >20% which would be expected for links connecting major freight distribution centers in future) the creation of a dedicated freight lane at the shoulder lane of existing motorways is the most efficient option for all user groups of motorways (A more detailed analysis of impact of creation of DFL for the operation of ACTs, in various shares of trucks in the traffic flow can be seen in the chapter 3).

The location of the DFL also would have a major impact on other user groups of motorways. (In chapter 3) We have concluded that the location of the DFL at the median (left) lane of existing motorways is disadvantageous if dedicated (grade-separated) on-/off-ramps for ACTs are missing. Such dedicated fly-overs for ACTs would be needed to ensure safety while ACTs enter or leave the DFL, and minimizes the hindrance of flow of MDVs by leaving ACTs to the off-ramps. The latter option is, in general, considered infeasible in densely built-up areas and therefore neglected in this research thesis.

The results of simulations (referred in the chapter 4) also have indicated that at on-/off-ramps, the approaching platoon of ACTs, would make difficulties for other user groups and may cause accidents. So, two solutions for applying platooning strategies at on-/off-ramps have been proposed:

The first solution is to apply traffic signals at on-/off-ramps on the mainline (motorway), too, and not only for ramp metering as already exists. This solution, e.g. putting signal on motorway mainlines, would be opposite to the functional characteristics of motorways being main connectors in the national road network. It also needs some extra variable message signs to be applied upstream of on-/off-ramps, in adequate distances, to inform drivers about the application of traffic signals on the motorway to ensure safety. In this solution, no capacity gain has been reported.

The results of simulations have indicated that the necessity of traffic signals at **on-ramps** while platooning of ACTs, would even lead to a 5% reduction in capacity at on-ramps. However, a reduction of 25%-75% in the congestion indicator, represented by the total time loss due to standing of vehicles in queues at a bottleneck during the total period of analysis, would be expected. The selection of an appropriate green and cycle time of the signal for each direction of flow would play an important role in reducing the level of congestion at on-ramps.

At **off-ramps**, the results of simulation have shown a reduction of 13% in the capacity of the off-ramp while applying traffic signals on the motorway. It also has led to an increase of at least 35% in the level of congestion, compared to the no platooning strategy. Therefore, the selection of such a solution would require extra means of traffic control like extra VMS boards and/or applying ISA systems for MDVs. Using optimization methods for traffic control and applying buffer areas would compensate a part of negative impacts. However, it is emphasized that the application of such extra means of control, may even not lead to a safe situation and, thus, may instead require the construction of fly-overs at off-ramps.

The second solution to gain benefits from the dissolution of platooning of ACTs at on-/off-ramps is to release platooning of ACTs at off-ramp areas to change the control mode of ACTs from automatic mode to the manual mode at off-ramps. Conversely, at on-ramp areas, the manual mode of driving of ACTs would be changed to automatic mode. In order to change the mode of control of ACTs, all ACTs approaching to the on-/off-ramp areas must be directed to buffer areas for check-in/ check-out. Clearly, the required time for changing the mode of control of ACTs in buffer areas would increase the waiting time of trucks. In general, the higher the average distance of ACTs, the higher the effectiveness of such a solution. As it has been addressed in the chapter 4, such a solution would increase the capacity of on-/off-ramp areas by about 3% and 18%, respectively. However, in such a case, extra buffers are required at downstream of on-/off-ramps to check the proper change in the control mode of driving of trucks from the manual to the automatic mode. Thus, the application of traffic signals may be preferred for both ACTs and MDVs.

To assess the impact of creation of buffer areas, we refer to the results of solving optimization models (which have been described in chapters 6 and 7). The results of analysis in these two chapters have indicated that although the creation of buffer areas would increase the waiting time of stopping vehicles in buffer areas, they can lead to a total reduction of 6%-15% in the average travel time of all vehicles (for both ACTs and MDVs). This saving of time is realized due to the control of input flow to bottlenecks, like on-/off-ramps, which is provided by buffer areas.

The results of analysis (in the chapter 5 of this thesis) also have indicated that by increasing the critical density of ACTs compared to ordinary trucks by about 25%, an extra decrease of 5% in the average travel time of vehicles can be achieved. The introduction of other possible improvements in the flow dynamics of ACTs compared to ordinary trucks incorporated into the proposed optimization model (e.g. trucks platooning) also might lead to additional benefits. In this research thesis we have not analyzed these impacts directly, however the impact of change in some parameters of the flow dynamics of ACTs (compared to ordinary trucks) has been addressed (in chapter 6).

In general, findings of this thesis (described in chapter 6) have indicated that the impact of creation of buffer areas heavily depends on three factors: the fluctuation of traffic flow per user group, the capacity of the bottleneck, and the capacity of the buffer area. However, a dramatic change in average travel time of the vehicles due to buffer areas during peak hours can not be expected. Such a dramatic change would happen only when the flow of ACTs would be well distributed over the whole day in order to shave the peak which is not preferred by the freight industry due to additional waiting time in the the freight transport chain.

Also in chapter 7, it has been shown clearly that buffer areas would contribute to various design objectives like the minimization of average or total travel time of all vehicles, the maximization of throughput of all vehicles at bottlenecks, the synchronization of speed of conflicting flows at bottlenecks (which might improve the safety at bottlenecks), and the minimization of speed difference along a motorway section for user groups of that specific route which might lead to a reduction of fuel consumption. The results of this chapter also indicate how the existance of buffer areas would facilitate to give priorities to specific user groups of motorways or on-/off-ramps, individually.

In brief, taking into account all requirements for the operation of ACTs, it can be concluded that the manually driven vehicles would be affected by the operation of ACTs by:

- leaving a lane of existing motorways for the assignment as DFL for the operation of ACTs,

- applying traffic signals on motorways at on-/off-ramp areas.

According to the above findings, the impact of these two restrictions on other user groups of motorways can be compensated, if:

- buffer areas with adequate capacities will be designed on motorway links (for ACTs) and in on-ramp areas (for both ACTs and MDVs),
- appropriate platooning strategies be implemented for ACTs nearby on-/off-ramps,
- optimization methods be applied in which the adequate attention is paid to MDVs.

The decrease in average travel time of (all) vehicles by about 15% due to the creation of buffer areas and applying optimization methods for the control of traffic flows, in addition to the benefits enabled by the application of platooning strategies of ACTs can compensate the extra waiting time of the vehicles standing before red traffic signals on motorways.

## 8.2 Recommendations for further research

Further work on various research aspects obviously is necessary to overcome the remaining questions, which directly or indirectly are addressed in different parts of this research thesis. These topics can be developed along three lines of research:

(1) cost-benefit and risk analysis for all possible solutions,
(2) further development of the simulation tool, and
(3) further development of the optimization model for traffic control at bottlenecks.

### 8.2.1 Cost-benefit and risk analysis for all possible solutions

In the first chapter of this thesis we addressed other solutions for increasing the efficiency of existing motorways, like dynamic traffic management of DFLs for the operation of ordinary trucks, or the operation of ultra long trucks instead of ACTs, as major competitive scenarios. Moreover, within this research study we found out that the existance of traffic signals at on-/off-ramp areas on motorways would be necessary when trucks in an automatic mode approach to the on-/off-ramp areas (to ensure safety aspects). The application of traffic signals on motorways could create difficulties, specially from a legal point of view. We have also recommended the construction of fly-overs in dense traffic situations at off-ramps. The limit of space and budget, also may cause restrictions in the construction of fly-overs, as was discussed in the first chapter. Thus, it would support this research to perform a comprehensive cost-benefit and risk analysis to verify in which conditions the proposed solution would be more interesting and encounter less risks, compared to other competitive solutions.

As it was discussed in the first chapter, reliability of transport plays a major role in the freight transport sector. Throughout this research thesis we did not focus directly on advantages of the operation of ACTs, compared to ordinary trucks, from this point of view. Fortunately, increasing the reliability of transport and traffic has been defined as one of the spearhead directions of research of TRAIL research school for the next few years. Therefore, it may contribute further to analyze the impact of operation of ACTs on the reliability of the road network.

### 8.2.2 Further development of the simulation tool

To assess the impact of creation of DFLs for the operation of ACTs, and to elaborate the impact of trucks platooning an existing simulation tool (i.e. SiMoNe from TU-Delft) has been used extensively. Due to the required inter-relations among various research works within the framework of the FTAM programme, some extensions in the required simulation tool SiMoNe have been realized in parallel of this research work. However, still extra works would be needed to: (1) adapt the existing version of the SiMoNe to answer to some of the remaining issues in this research work; and (2) create a higher capability by the SiMoNe to be used as an advanced simulation tool for the specific area of operating ACTs, in future.

The following further developments of the SiMoNe tool are recommended:

- to introduce the aerodynamic drag of trucks platooning as an output of the program,
- to introduce other indicators which represent the fuel consumption of vehicles more clearly,
- to include storing, platooning and splitting of ACTs within buffer areas,
- to provide the possibility for interrupted platooning of trucks at on-/off-ramp areas,
- to validate the vehicle dynamics parameters for ACTs in the model,
- to provide the required links to the optimization model for traffic control of mixed operation of ACTs and MDVs, developed in this research thesis. This interlink would provide the possibility for an iterative solution of the simulation program and the optimization method. The iterative solution would make it easier to find optimal solutions for various options of traffic flow input, introduced in the simulation tool. For instance, estimation of capacity at bottlenecks for a different share of ACTs and MDVs, and also the share of passing flow versus the merging (or crossing) flow.

### 8.2.3 Further development of the optimization tool

The main aim of development of the optimization model in this research thesis were to maximize the existing capacity of the provided infrastructure by operating ACTs and to assess the impact of creation of buffer areas and the required capacity of the buffer areas. We indicated that optimization models can play a very important role in the traffic flow control in future, when automatically controlled vehicles are operating on exclusive lanes and mix with manually driven vehicles at on-/off-ramps. Thus, applying and further developing the optimization approach in the following lines would be recommended as topics of further research:

- More detailed sensitivity analysis of each of the parameters of the model, reflecting the characteristics of flow of ACTs or other model inputs, to assess their impact on changing optimal control strategies,
- Including a higher number of indicators in the output of the model, like the average waiting and travel time per user class,

- Extension of the model structure in such a way that it can represent platooning strategies or other advanced vehicle control systems like ISA, etc.,
- Development of the structure of the model in such a way that the optimal location of buffer areas along motorway segments is included into the decision variables,
- Increase in total time duration of analysis up to about one or two hours through working on other techniques for solving optimization models;
- Provision of links with the applied simulation tool (e.g. SiMoNe) to facilitate the iterative transfer of data ant the test of options by both tools,
- Extension of the structure of the (optimization) model to support dynamic traffic management of the mixed flow of ACTs and MDVs at merging/diverging areas in the network level;
- Development of similar optimization models which represent the flow dynamics at a microscopic level. The main aim of developing such models would be to define the optimal number of trucks in a platoon leading to minimum congestion at on-/off-ramps. Thus, this group of optimization models could be applied to verify the optimal platooning strategies at on-/off-ramp areas.

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# Appendix A
# Freight Transport Facts and Figures

**Table A.1. Freight mobility on roads**

| Year | Goods Transport (1000 mio ton-km) | | Index 1970= 100 | | Modal share in EU (%) |
|---|---|---|---|---|---|
| | EU Countries | NL | EU Countries | NL | |
| 1970 | 415.6 | 16.3 | 100 | 100 | 47.9 |
| 1980 | 628 | 23.2 | 151 | 142 | 56.4 |
| 1990 | 932.5 | 31.8 | 224 | 195 | 68 |
| 1998 | 1254.9 | 46.5 | 302 | 285 | 73.7 |

Source: Eurostat (2002).

**Table A.2. Length of the network of motorways**

| Year | Length of the network of motorways (km) | | Index (1970=100) | |
|---|---|---|---|---|
| | EU Countries | NL | EU Countries | NL |
| 1970 | 16051 | 1209 | 100 | 100 |
| 1980 | 30838 | 1780 | 192 | 147 |
| 1990 | 39242 | 2092 | 244 | 173 |
| 1998 | 49233 | 2360 | 307 | 195 |

Source: Eurostat (2002).

## Table A.3. Major technologies belonging to ADAS/AVG systems

| Technology | Description | System type | Designed mostly for: |
|---|---|---|---|
| Adaptive Cruise Control | Based on front vehicle information, mainly distance and speed, it ensures that the speed of the vehicle is constant or adjusts to the speed of the preceding vehicle. | (b) | C |
| Lane Departure Warning | a system warning the driver when the vehicle threatens to leave the driving lane. It intends to prevent voluntary lane departures. | (a) | T&B |
| Lane keeping Assistance | Assists the driver to use narrower width of the road (narrower lanes) for driving. | (b) | T&B |
| Side-obstacle Warning | detects the side obstacles by applying a side looking radar. | (a) | T&B |
| Intersection Collision warning | informs the driver about possible collisions while approaching to (dangerous) intersections. | (a) | C |
| Parking Assistance | offers a very limited assistance through through audio or visual feedback of the distance to close obstacles. | (b) | T&B |
| Forward Collision Warning | intends to detect stationary as well as moving vehicles ahead of the equipped vehicle. | (a) | C |
| Night Vision Enhancement | shows to the driver a thermal image of the front scene to increase the visibility of the driver during night times. | (a) | C |
| Intelligent Speed Adaptation | intends to limit the speed of the vehicle to the official limit (by warning the driver or enforcing him to not to ride higher than maximum allowed speed). | (b) | C |
| Fully Automated Driving | a system by which both the vehicle and the infrastructure are intelligent, making it possible for the driver to make all driving duties fully automatic under certain circumstances. | (c) | T&B |

Legend: **C:** cars **T&B:** trucks and buses
**(a)** collision warning systems **(b)** collision avoidance systems **(c)** vehicle automation

Source: http://www.adase2.net

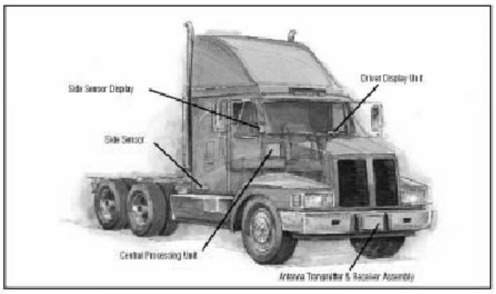
## Table A.4. Impacts of ADAS/AVG systems

| Technology | Impacts | | | |
|---|---|---|---|---|
| | Safety | Comfort | Congestion | Environment |
| Adaptive Cruise Control | ▲ | ▲▲ | ▲ | ▲ |
| Lane Departure Warning | ▲▲ | | | |
| Lane keeping Assistance | ▲ | ▲▲ | ▲ | ▲ |
| Side-obstacle Warning | ▲▲ | | | |
| Intersection Collision warning | ▲▲ | | | |
| Parking Assistance | ▲▲ | ▲ | | |
| Forward Collision Warning | ▲▲ | | ▲ | |
| Night Vision Enhancement | ▲▲ | ▲ | | |
| Intelligent Speed Adaptation | ▲▲ | ▲ | | ▲ |
| Fully Automated Driving | ▲ | ▲▲ | ▲▲▲ | ▲ |

Legend:
▲ Impact ▲▲ Strong impact ▲▲▲ Very strong impact

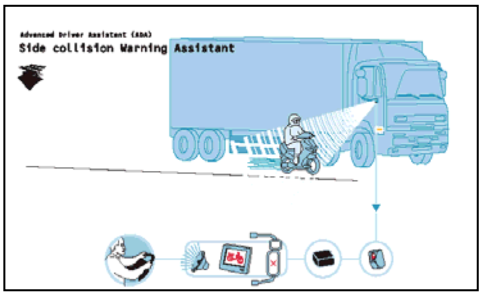
Source: http://www.adase2.net

# Appendix B
# Truck Automation Technologies




a) Longitudinal

**(source:** http://www.roadranger.com**)**




b) Lateral

**(source: AVV (2001))**

**Figure B.1. Examples of longitudinal and lateral Collision Warning Systems**

a) Normal car following

b) Warning for the risk of collision

**Figure B.2. A visualization of an ACC system on the dashboard of a truck**
**(source: [http:// www.chauffeur2.net](http://www.chauffeur2.net))**

**Figure B.3. Night vision system on Cadillac Deville**
**(source: [http:// www.cadillac.com](http://www.cadillac.com))**

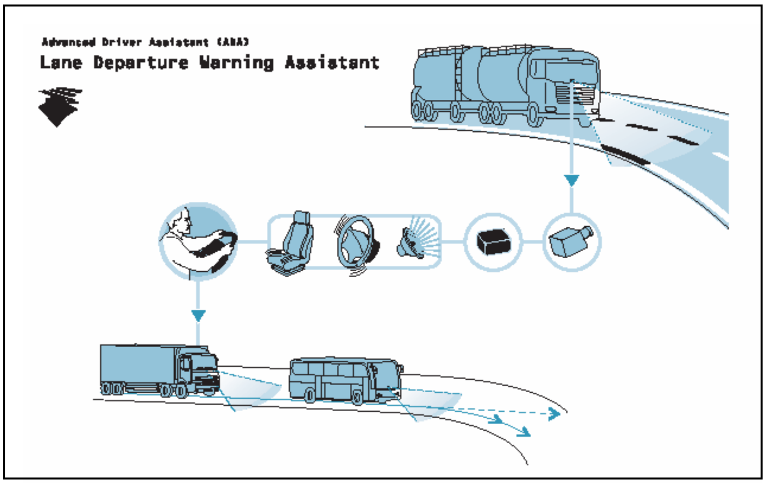



**Figure B.4. The LDWA system on a truck**
**(source:** AVV (2001))

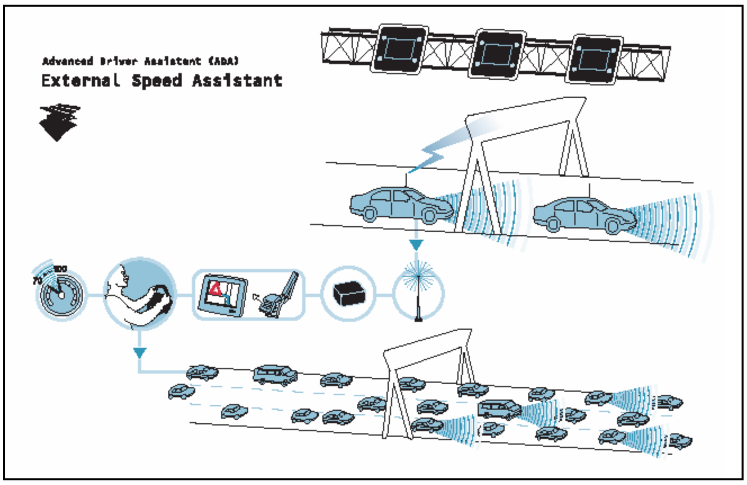



**Figure B.5. The application of an ISA system on a road network**
**(source:** AVV (2001))

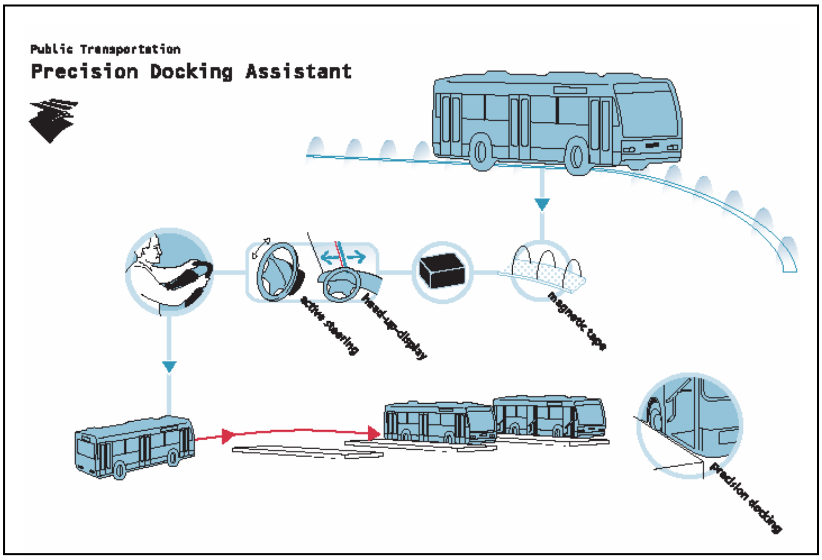



**Figure B.6. A precision docking assistant system**
**(source:** AVV (2001))

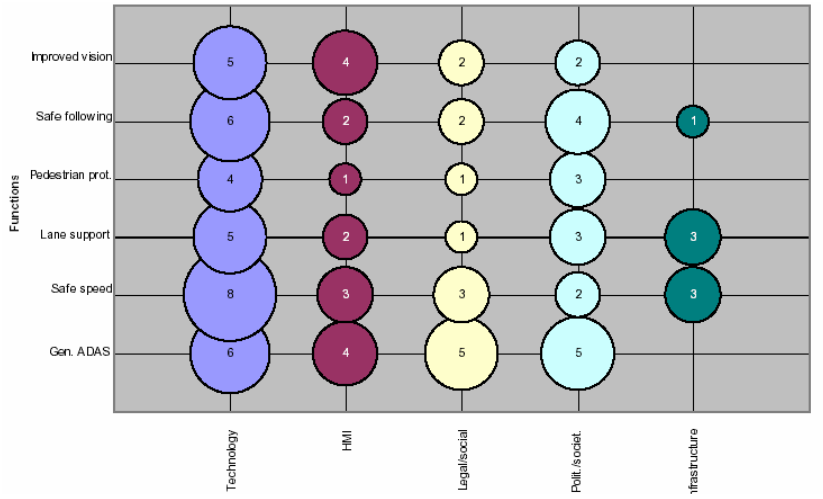



**Figure B.7. Main focus of ADAS studies in the EU per research area**
**(source:** www.adase2.net)

# Appendix C
# Simulation Results for Dedicated Freight Lanes

### Table C.1. An overview of the (absolute) results of simulation for all shares of trucks in the mainline and the on-ramp flow (simulation of the on-ramp area)

| Indicator | Share of trucks in the mainline flow (%) | Share of trucks in the on-ramp flow (%) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 5 | | | | 10 | | | | 20 | | | | 40 | | | |
| | | RB sce. | RP sce. | DR sce. | DL sce. | RB sce. | RP sce. | DR sce. | DL sce. | RB sce. | RP sce. | DR sce. | DL sce. | RB sce. | RP sce. | DR sce. | DL sce. |
| capacity mean* | 5 | CN | CN | CN | CN | CN | CN | CN | 4497.8 | CN | CN | CN | 4006.7 | CN | CN | CN | 3068.6 |
| | 10 | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | 4137.5 | CN | CN | CN | 3267.7 |
| | 15 | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | 4256.2 | CN | CN | CN | 3444.5 |
| | 20 | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | 4418.9 | CN | CN | CN | 3522.1 |
| | 25 | CN | CN | CN | CN | CN | CN | CN | CN | CN | 4415.6 | CN | 4622.5 | CN | 4173.4 | 4268 | 3523.2 |
| average travel time of vehicles | 5 | 2.3 | 2.3 | 2.4 | 2.5 | 2.3 | 2.3 | 2.4 | 2.8 | 2.3 | 2.3 | 2.4 | 4.1 | 2.4 | 2.4 | 2.4 | 5.9 |
| | 10 | 2.4 | 2.4 | 2.4 | 2.5 | 2.4 | 2.4 | 2.4 | 2.5 | 2.4 | 2.4 | 2.4 | 3.9 | 2.4 | 2.4 | 2.4 | 5.7 |
| | 15 | 2.4 | 2.4 | 2.5 | 2.5 | 2.4 | 2.4 | 2.5 | 2.5 | 2.4 | 2.4 | 2.5 | 4 | 2.4 | 2.5 | 2.5 | 5.5 |
| | 20 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 3.8 | 2.5 | 2.6 | 2.6 | 5.6 |
| | 25 | 2.5 | 2.6 | 2.6 | 2.5 | 2.5 | 2.6 | 2.6 | 2.6 | 2.5 | 3.1 | 2.7 | 2.9 | 2.5 | 3.5 | 3.4 | 6 |
| average energy consumption | 5 | 64.9 | 64.1 | 77.6 | 97.6 | 66.1 | 63.5 | 80.4 | 165.2 | 66.7 | 64.3 | 75.7 | 381.6 | 67.3 | 63.4 | 73 | 642.7 |
| | 10 | 69.7 | 64.7 | 75.8 | 87.2 | 69.2 | 64.4 | 75.3 | 99.1 | 69.3 | 64.4 | 72.7 | 346.1 | 69.4 | 65.4 | 71.8 | 590.1 |
| | 15 | 71.3 | 66.1 | 73.4 | 81.6 | 70.3 | 65.3 | 72.7 | 88.8 | 72.1 | 68.1 | 70.8 | 351.5 | 70.6 | 69 | 72.4 | 551.7 |
| | 20 | 71.3 | 66.4 | 71.7 | 73.4 | 71.5 | 68.3 | 75.2 | 78.5 | 71 | 73.3 | 73.8 | 293.3 | 71.4 | 73.9 | 78.2 | 553.8 |
| | 25 | 69.2 | 70.5 | 73.5 | 65.1 | 69.5 | 75.1 | 74.5 | 76.9 | 70.2 | 120.7 | 84.1 | 138.7 | 71.2 | 175 | 156.3 | 576.1 |
| total passing vehicles | 5 | 19887 | 19927 | 19682 | 19780 | 19854 | 19814 | 19841 | 19417 | 19824 | 19756 | 19698 | 17097 | 19867 | 19601 | 19655 | 13155 |
| | 10 | 19886 | 19646 | 19792 | 19805 | 19879 | 19691 | 19971 | 19679 | 19802 | 19783 | 19795 | 17629 | 19741 | 19580 | 19734 | 13983 |
| | 15 | 19819 | 19671 | 19904 | 19864 | 19728 | 19681 | 19747 | 19693 | 19866 | 19818 | 19592 | 18180 | 19675 | 19571 | 19723 | 14828 |
| | 20 | 19949 | 19588 | 19905 | 19745 | 19781 | 19708 | 19874 | 19643 | 19840 | 19671 | 19642 | 18805 | 19923 | 19257 | 19431 | 15050 |
| | 25 | 19553 | 19332 | 19372 | 19708 | 19788 | 19262 | 19375 | 19869 | 19727 | 18816 | 19228 | 19557 | 19762 | 18001 | 18300 | 15007 |
| car count | 5 | 19010 | 19054 | 18763 | 18823 | 18761 | 18709 | 18715 | 18244 | 18268 | 18254 | 18155 | 15575 | 17551 | 17329 | 17232 | 11142 |
| | 10 | 18159 | 17970 | 18071 | 18092 | 17929 | 17783 | 17940 | 17710 | 17489 | 17484 | 17399 | 15314 | 16668 | 16595 | 16561 | 11123 |
| | 15 | 17351 | 17216 | 17325 | 17299 | 17039 | 17015 | 17024 | 17029 | 16789 | 16643 | 16554 | 15014 | 15876 | 15730 | 15840 | 11255 |
| | 20 | 16646 | 16348 | 16575 | 16421 | 16322 | 16210 | 16293 | 16182 | 15885 | 15839 | 15743 | 14946 | 15267 | 14891 | 14791 | 10669 |
| | 25 | 15611 | 15376 | 15458 | 15707 | 15578 | 15116 | 15178 | 15572 | 15073 | 14419 | 14715 | 14902 | 14196 | 13485 | 13571 | 10226 |
| truck count | 5 | 877 | 873 | 919 | 957 | 1093 | 1105 | 1126 | 1173 | 1556 | 1502 | 1543 | 1522 | 2316 | 2272 | 2423 | 2013 |
| | 10 | 1727 | 1676 | 1721 | 1713 | 1950 | 1908 | 2031 | 1969 | 2313 | 2299 | 2396 | 2315 | 3073 | 2985 | 3173 | 2860 |
| | 15 | 2468 | 2455 | 2579 | 2565 | 2689 | 2666 | 2723 | 2664 | 3077 | 3175 | 3038 | 3166 | 3799 | 3841 | 3883 | 3573 |
| | 20 | 3303 | 3240 | 3330 | 3324 | 3459 | 3498 | 3581 | 3461 | 3955 | 3832 | 3899 | 3859 | 4656 | 4366 | 4640 | 4381 |
| | 25 | 3942 | 3956 | 3914 | 4001 | 4210 | 4146 | 4197 | 4297 | 4654 | 4397 | 4513 | 4655 | 5566 | 4516 | 4729 | 4781 |
| throughput (pce) 1T=2car | 5 | 20764 | 20800 | 20601 | 20737 | 20947 | 20919 | 20967 | 20590 | 21380 | 21258 | 21241 | 18619 | 22183 | 21873 | 22078 | 15168 |
| | 10 | 21613 | 21322 | 21513 | 21518 | 21829 | 21599 | 22002 | 21648 | 22115 | 22082 | 22191 | 19944 | 22814 | 22565 | 22907 | 16843 |
| | 15 | 22287 | 22126 | 22483 | 22429 | 22417 | 22347 | 22470 | 22357 | 22943 | 22993 | 22630 | 21346 | 23474 | 23412 | 23606 | 18401 |
| | 20 | 23252 | 22828 | 23235 | 23069 | 23240 | 23206 | 23455 | 23104 | 23795 | 23503 | 23541 | 22664 | 24579 | 23623 | 24071 | 19431 |
| | 25 | 23495 | 23288 | 23286 | 23709 | 23998 | 23408 | 23572 | 24166 | 24381 | 23213 | 23741 | 24212 | 25328 | 22517 | 23029 | 19788 |
| average travel time of cars | 5 | 2.3 | 2.3 | 2.4 | 2.5 | 2.3 | 2.3 | 2.4 | 2.8 | 2.4 | 2.3 | 2.4 | 4.2 | 2.4 | 2.4 | 2.5 | 6.5 |
| | 10 | 2.3 | 2.3 | 2.4 | 2.4 | 2.3 | 2.3 | 2.4 | 2.5 | 2.3 | 2.3 | 2.4 | 4.1 | 2.4 | 2.4 | 2.5 | 6.4 |
| | 15 | 2.3 | 2.3 | 2.3 | 2.4 | 2.3 | 2.3 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 4.3 | 2.4 | 2.4 | 2.5 | 6.3 |
| | 20 | 2.3 | 2.3 | 2.3 | 2.4 | 2.4 | 2.3 | 2.3 | 2.4 | 2.4 | 2.4 | 2.4 | 3.9 | 2.5 | 2.5 | 2.5 | 6.6 |
| | 25 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.4 | 2.3 | 2.4 | 2.4 | 2.5 | 2.4 | 2.8 | 2.5 | 2.6 | 2.6 | 7 |
| average travel time of trucks | 5 | 2.9 | 2.8 | 2.9 | 2.9 | 2.6 | 2.6 | 2.6 | 2.6 | 2.2 | 2.2 | 2.3 | 2.5 | 1.9 | 1.9 | 1.9 | 2.5 |
| | 10 | 3.1 | 3.1 | 3.1 | 3.1 | 2.9 | 2.9 | 2.9 | 2.9 | 2.6 | 2.6 | 2.6 | 2.8 | 2.2 | 2.3 | 2.3 | 2.8 |
| | 15 | 3.2 | 3.2 | 3.2 | 3.2 | 3 | 3.1 | 3.1 | 3 | 2.8 | 2.9 | 2.9 | 3 | 2.5 | 2.7 | 2.6 | 3.1 |
| | 20 | 3.2 | 3.3 | 3.3 | 3.2 | 3.1 | 3.3 | 3.3 | 3.2 | 2.9 | 3.2 | 3.1 | 3.1 | 2.6 | 3.1 | 3.1 | 3.4 |
| | 25 | 3.2 | 3.6 | 3.5 | 3.3 | 3.1 | 3.6 | 3.4 | 3.2 | 3 | 5.2 | 3.6 | 3.1 | 2.7 | 6.2 | 5.7 | 3.8 |
| average energy consumption of cars | 5 | 67.6 | 66.6 | 81 | 102.3 | 69.6 | 66.8 | 84.8 | 175.1 | 71.8 | 68.8 | 81.5 | 416.5 | 75 | 70.3 | 81.9 | 750.2 |
| | 10 | 75.2 | 69.3 | 81.7 | 95 | 75.5 | 69.8 | 82.3 | 109.3 | 77 | 70.7 | 80.8 | 395.1 | 79.8 | 74 | 82.5 | 729.7 |
| | 15 | 79.4 | 72.4 | 81.3 | 92.6 | 79.2 | 72.1 | 80.9 | 101.2 | 82.5 | 76.1 | 80.2 | 419.7 | 83.7 | 77.9 | 83.7 | 710.7 |
| | 20 | 81.8 | 73.3 | 80.2 | 86.2 | 82.8 | 75.3 | 84.5 | 92.8 | 84.1 | 79.9 | 83.2 | 360.6 | 87.2 | 79.6 | 86.4 | 752.2 |
| | 25 | 81.5 | 74.6 | 81.2 | 78.5 | 82.8 | 77.6 | 82 | 93.7 | 85.4 | 86 | 87.7 | 174.3 | 89.9 | 111.7 | 107.2 | 794.9 |
| average energy consumption of trucks | 5 | 6.8 | 8.6 | 8 | 4.5 | 7.1 | 7.8 | 7.7 | 11.1 | 7.8 | 9.6 | 7.8 | 23.9 | 8.9 | 11.2 | 9.2 | 47.7 |
| | 10 | 11.7 | 15 | 13.6 | 5.6 | 11.2 | 14.8 | 13.1 | 8 | 11.8 | 16.1 | 13.5 | 21.9 | 12.6 | 17.6 | 15.4 | 47 |
| | 15 | 14.3 | 21.9 | 20.5 | 7.5 | 14 | 22.4 | 21.7 | 9.4 | 15.1 | 26.4 | 19.7 | 27.8 | 15.8 | 32.8 | 26.3 | 51 |
| | 20 | 18.4 | 31.9 | 29.5 | 10.1 | 18.6 | 35.7 | 33.2 | 11.6 | 18.5 | 46 | 36 | 32.6 | 19.5 | 54.5 | 52 | 70.6 |
| | 25 | 20.9 | 54.6 | 43.3 | 12.6 | 20.5 | 66.1 | 47.4 | 15.9 | 21.1 | 234.6 | 72.3 | 24.7 | 23.4 | 364.2 | 297.3 | 108.2 |
| total number of TTC<1.5 sec. | 5 | 2 | 3 | 7 | 9 | 2 | 1 | 15 | 60 | 4 | 6 | 6 | 279 | 3 | 4 | 6 | 687 |
| | 10 | 6 | 8 | 7 | 5 | 6 | 6 | 11 | 21 | 4 | 5 | 13 | 279 | 8 | 9 | 10 | 678 |
| | 15 | 1 | 8 | 20 | 11 | 3 | 8 | 21 | 15 | 3 | 15 | 18 | 289 | 4 | 14 | 21 | 751 |
| | 20 | 6 | 16 | 17 | 4 | 9 | 21 | 20 | 21 | 7 | 25 | 25 | 300 | 6 | 23 | 30 | 720 |
| | 25 | 4 | 27 | 33 | 15 | 6 | 30 | 31 | 14 | 8 | 67 | 40 | 104 | 8 | 107 | 104 | 753 |
| total number of 1.5<TTC<3 | 5 | 9 | 13 | 11 | 32 | 7 | 11 | 19 | 219 | 9 | 13 | 13 | 1545 | 15 | 19 | 24 | 4263 |
| | 10 | 12 | 30 | 28 | 33 | 17 | 15 | 35 | 59 | 12 | 33 | 24 | 1520 | 16 | 26 | 29 | 4160 |
| | 15 | 9 | 39 | 41 | 27 | 18 | 24 | 58 | 49 | 11 | 49 | 46 | 1564 | 10 | 75 | 77 | 4220 |
| | 20 | 8 | 36 | 59 | 23 | 16 | 57 | 73 | 32 | 22 | 109 | 72 | 1477 | 24 | 163 | 167 | 4466 |
| | 25 | 11 | 92 | 79 | 15 | 17 | 126 | 98 | 52 | 24 | 294 | 167 | 453 | 27 | 536 | 403 | 5093 |

* if capacity is not reached then "CN" is used.

**Table C.2. An overview of the (comparative) results of simulation for all shares of trucks in the mainline and the on-ramp flow compared to the RB scenario (RB index for each case = 100)**

| Indicator | Share of trucks in the mainline flow (%) | Share of trucks in the on-ramp flow (%) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 5 | | | | 10 | | | | 20 | | | | 40 | | | |
| | | RB sce. | RP sce. | DR sce. | DL sce. | RB sce. | RP sce. | DR sce. | DL sce. | RB sce. | RP sce. | DR sce. | DL sce. | RB sce. | RP sce. | DR sce. | DL sce. |
| average travel time of vehicles | 5 | 100 | 100 | 104 | 109 | 100 | 100 | 104 | 122 | 100 | 100 | 104 | 178 | 100 | 100 | 100 | 246 |
| | 10 | 100 | 100 | 100 | 104 | 100 | 100 | 100 | 104 | 100 | 100 | 100 | 163 | 100 | 100 | 100 | 238 |
| | 15 | 100 | 100 | 104 | 104 | 100 | 100 | 104 | 104 | 100 | 100 | 104 | 167 | 100 | 104 | 104 | 229 |
| | 20 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 152 | 100 | 104 | 104 | 224 |
| | 25 | 100 | 104 | 104 | 100 | 100 | 104 | 104 | 104 | 100 | 124 | 108 | 116 | 100 | 140 | 136 | 240 |
| average energy consumption | 5 | 100 | 99 | 120 | 150 | 100 | 96 | 122 | 250 | 100 | 96 | 113 | 572 | 100 | 94 | 108 | 955 |
| | 10 | 100 | 93 | 109 | 125 | 100 | 93 | 109 | 143 | 100 | 93 | 105 | 499 | 100 | 94 | 103 | 850 |
| | 15 | 100 | 93 | 103 | 114 | 100 | 93 | 103 | 126 | 100 | 94 | 98 | 488 | 100 | 98 | 103 | 781 |
| | 20 | 100 | 93 | 101 | 103 | 100 | 96 | 105 | 110 | 100 | 103 | 104 | 413 | 100 | 104 | 110 | 776 |
| | 25 | 100 | 102 | 106 | 94 | 100 | 108 | 107 | 111 | 100 | 172 | 120 | 198 | 100 | 246 | 220 | 809 |
| total passing vehicles | 5 | 100 | 100 | 99 | 99 | 100 | 100 | 100 | 98 | 100 | 100 | 99 | 86 | 100 | 99 | 99 | 66 |
| | 10 | 100 | 99 | 100 | 100 | 100 | 99 | 100 | 99 | 100 | 100 | 100 | 89 | 100 | 99 | 100 | 71 |
| | 15 | 100 | 99 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 92 | 100 | 99 | 100 | 75 |
| | 20 | 100 | 98 | 100 | 99 | 100 | 100 | 100 | 99 | 100 | 99 | 99 | 95 | 100 | 97 | 98 | 76 |
| | 25 | 100 | 99 | 99 | 101 | 100 | 97 | 98 | 100 | 100 | 95 | 97 | 99 | 100 | 91 | 93 | 76 |
| car count | 5 | 100 | 100 | 99 | 99 | 100 | 100 | 100 | 97 | 100 | 100 | 99 | 85 | 100 | 99 | 98 | 63 |
| | 10 | 100 | 99 | 100 | 100 | 100 | 99 | 100 | 99 | 100 | 100 | 99 | 88 | 100 | 100 | 99 | 67 |
| | 15 | 100 | 99 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 99 | 89 | 100 | 99 | 100 | 71 |
| | 20 | 100 | 98 | 100 | 99 | 100 | 99 | 100 | 99 | 100 | 100 | 99 | 94 | 100 | 98 | 97 | 70 |
| | 25 | 100 | 98 | 99 | 101 | 100 | 97 | 97 | 100 | 100 | 96 | 98 | 99 | 100 | 95 | 96 | 72 |
| truck count | 5 | 100 | 100 | 105 | 109 | 100 | 101 | 103 | 107 | 100 | 97 | 99 | 98 | 100 | 98 | 105 | 87 |
| | 10 | 100 | 97 | 100 | 99 | 100 | 98 | 104 | 101 | 100 | 99 | 104 | 100 | 100 | 97 | 103 | 93 |
| | 15 | 100 | 99 | 104 | 104 | 100 | 99 | 101 | 99 | 100 | 103 | 99 | 103 | 100 | 101 | 102 | 94 |
| | 20 | 100 | 98 | 101 | 101 | 100 | 101 | 104 | 100 | 100 | 97 | 99 | 98 | 100 | 94 | 100 | 94 |
| | 25 | 100 | 100 | 99 | 101 | 100 | 98 | 100 | 102 | 100 | 94 | 97 | 100 | 100 | 81 | 85 | 86 |
| throughput (pce) 1T=2car | 5 | 100 | 100 | 99 | 100 | 100 | 100 | 100 | 98 | 100 | 99 | 99 | 87 | 100 | 99 | 100 | 68 |
| | 10 | 100 | 99 | 100 | 100 | 100 | 99 | 101 | 99 | 100 | 100 | 100 | 90 | 100 | 99 | 100 | 74 |
| | 15 | 100 | 99 | 101 | 101 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 93 | 100 | 100 | 101 | 78 |
| | 20 | 100 | 98 | 100 | 99 | 100 | 100 | 101 | 99 | 100 | 99 | 99 | 95 | 100 | 96 | 98 | 79 |
| | 25 | 100 | 99 | 99 | 101 | 100 | 98 | 98 | 101 | 100 | 95 | 97 | 99 | 100 | 89 | 91 | 78 |
| average travel time of cars | 5 | 100 | 100 | 104 | 109 | 100 | 100 | 104 | 122 | 100 | 96 | 100 | 175 | 100 | 100 | 104 | 271 |
| | 10 | 100 | 100 | 104 | 104 | 100 | 100 | 104 | 109 | 100 | 100 | 104 | 178 | 100 | 100 | 104 | 267 |
| | 15 | 100 | 100 | 100 | 104 | 100 | 100 | 104 | 104 | 100 | 100 | 100 | 179 | 100 | 100 | 104 | 263 |
| | 20 | 100 | 100 | 100 | 104 | 100 | 96 | 96 | 100 | 100 | 100 | 100 | 163 | 100 | 100 | 100 | 264 |
| | 25 | 100 | 100 | 100 | 100 | 100 | 104 | 100 | 104 | 100 | 104 | 100 | 117 | 100 | 104 | 104 | 280 |
| average travel time of trucks | 5 | 100 | 97 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 105 | 114 | 100 | 100 | 100 | 132 |
| | 10 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 108 | 100 | 105 | 105 | 127 |
| | 15 | 100 | 100 | 100 | 100 | 100 | 103 | 103 | 100 | 100 | 104 | 104 | 107 | 100 | 108 | 104 | 124 |
| | 20 | 100 | 103 | 103 | 100 | 100 | 106 | 106 | 103 | 100 | 110 | 107 | 107 | 100 | 119 | 119 | 131 |
| | 25 | 100 | 113 | 109 | 103 | 100 | 116 | 110 | 103 | 100 | 173 | 120 | 103 | 100 | 230 | 211 | 141 |
| average energy consumption of cars | 5 | 100 | 99 | 120 | 151 | 100 | 96 | 122 | 252 | 100 | 96 | 114 | 580 | 100 | 94 | 109 | 1000 |
| | 10 | 100 | 92 | 109 | 126 | 100 | 92 | 109 | 145 | 100 | 92 | 105 | 513 | 100 | 93 | 103 | 914 |
| | 15 | 100 | 91 | 102 | 117 | 100 | 91 | 102 | 128 | 100 | 92 | 97 | 509 | 100 | 93 | 100 | 849 |
| | 20 | 100 | 90 | 98 | 105 | 100 | 91 | 102 | 112 | 100 | 95 | 99 | 429 | 100 | 91 | 99 | 863 |
| | 25 | 100 | 92 | 100 | 96 | 100 | 94 | 99 | 113 | 100 | 101 | 103 | 204 | 100 | 124 | 119 | 884 |
| average energy consumption of trucks | 5 | 100 | 126 | 118 | 66 | 100 | 110 | 108 | 156 | 100 | 123 | 100 | 306 | 100 | 126 | 103 | 536 |
| | 10 | 100 | 128 | 116 | 48 | 100 | 132 | 117 | 71 | 100 | 136 | 114 | 186 | 100 | 140 | 122 | 373 |
| | 15 | 100 | 153 | 143 | 52 | 100 | 160 | 155 | 67 | 100 | 175 | 130 | 184 | 100 | 208 | 166 | 323 |
| | 20 | 100 | 173 | 160 | 55 | 100 | 192 | 178 | 62 | 100 | 249 | 195 | 176 | 100 | 279 | 267 | 362 |
| | 25 | 100 | 261 | 207 | 60 | 100 | 322 | 231 | 78 | 100 | 1112 | 343 | 117 | 100 | 1556 | 1271 | 462 |
| total number of TTC<1.6 sec. | 5 | 100 | 150 | 350 | 450 | 100 | 50 | 750 | 3000 | 100 | 150 | 150 | 6975 | 100 | 133 | 200 | 22900 |
| | 10 | 100 | 133 | 117 | 83 | 100 | 100 | 183 | 350 | 100 | 125 | 325 | 6975 | 100 | 113 | 125 | 8475 |
| | 15 | 100 | 800 | 2000 | 1100 | 100 | 267 | 700 | 500 | 100 | 500 | 600 | 9633 | 100 | 350 | 525 | 18775 |
| | 20 | 100 | 267 | 283 | 67 | 100 | 233 | 222 | 233 | 100 | 357 | 357 | 4286 | 100 | 383 | 500 | 12000 |
| | 25 | 100 | 675 | 825 | 375 | 100 | 500 | 517 | 233 | 100 | 838 | 500 | 1300 | 100 | 1338 | 1300 | 9413 |
| total number of 1.6<TTC<3 | 5 | 100 | 144 | 122 | 356 | 100 | 157 | 271 | 3129 | 100 | 144 | 144 | 17167 | 100 | 127 | 160 | 28420 |
| | 10 | 100 | 250 | 233 | 275 | 100 | 88 | 206 | 347 | 100 | 275 | 200 | 12667 | 100 | 163 | 181 | 26000 |
| | 15 | 100 | 433 | 456 | 300 | 100 | 133 | 322 | 272 | 100 | 445 | 418 | 14218 | 100 | 750 | 770 | 42200 |
| | 20 | 100 | 450 | 738 | 288 | 100 | 356 | 456 | 200 | 100 | 495 | 327 | 6714 | 100 | 679 | 696 | 18608 |
| | 25 | 100 | 836 | 718 | 136 | 100 | 741 | 576 | 306 | 100 | 1225 | 696 | 1888 | 100 | 1985 | 1493 | 18863 |

**Table C.3. An overview of the (absolute) results of simulation for all shares of trucks in the mainline flow and the exiting flow (simulation of the off-ramp area)**

| Indicator | Share of trucks in the mainline flow (%) | Share of trucks exiting the mainline (DFL) (%) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 5 | | | | 10 | | | | 20 | | | | 40 | | | |
| | | RB sce. | RP sce. | DR sce. | DL sce. | RB sce. | RP sce. | DR sce. | DL sce. | RB sce. | RP sce. | DR sce. | DL sce. | RB sce. | RP sce. | DR sce. | DL sce. |
| capacity mean* | 5 | CN | CN | CN | 4605.7 | CN | CN | CN | 4537.7 | CN | CN | CN | 4617.2 | CN | CN | CN | 4577.3 |
| | 10 | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | 4477.7 |
| | 15 | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | 4648.2 | CN | CN | CN | 4276 |
| | 20 | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | 4288.3 |
| | 25 | CN | 4470 | 4511 | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | CN | 3889.5 |
| average travel time of vehicles | 5 | 2.3 | 2.3 | 2.4 | 2.7 | 2.3 | 2.3 | 2.4 | 2.8 | 2.3 | 2.3 | 2.4 | 2.8 | 2.3 | 2.3 | 2.4 | 2.7 |
| | 10 | 2.4 | 2.4 | 2.4 | 2.6 | 2.4 | 2.4 | 2.4 | 2.5 | 2.4 | 2.3 | 2.4 | 2.5 | 2.3 | 2.3 | 2.4 | 2.7 |
| | 15 | 2.4 | 2.4 | 2.5 | 2.6 | 2.4 | 2.4 | 2.5 | 2.5 | 2.4 | 2.4 | 2.4 | 2.6 | 2.3 | 2.3 | 2.4 | 2.5 |
| | 20 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.4 | 2.4 | 2.4 | 2.5 | 2.3 | 2.3 | 2.3 | 2.6 |
| | 25 | 2.5 | 2.8 | 2.8 | 2.5 | 2.5 | 2.6 | 2.6 | 2.6 | 2.4 | 2.5 | 2.5 | 2.5 | 2.3 | 2.3 | 2.4 | 2.9 |
| average energy consumption | 5 | 67 | 65.1 | 80.7 | 139.9 | 65.7 | 63.5 | 80.4 | 161.7 | 64.4 | 64 | 76.4 | 157.6 | 62.2 | 62.2 | 77.8 | 155.4 |
| | 10 | 69.8 | 65.8 | 75.6 | 109.5 | 69.2 | 64.6 | 75.6 | 99.1 | 67.3 | 65 | 73.7 | 105.9 | 62.5 | 59.9 | 73.9 | 137.9 |
| | 15 | 72.1 | 67 | 73.7 | 92.2 | 70.3 | 64.9 | 72.7 | 88.8 | 67.1 | 64 | 71.2 | 106.1 | 66.2 | 60.7 | 68.8 | 100.2 |
| | 20 | 72.5 | 69.7 | 73.8 | 77.6 | 71.1 | 68.3 | 75.2 | 78.5 | 69.6 | 65.6 | 66.1 | 80.2 | 63.1 | 58.1 | 62.3 | 107.3 |
| | 25 | 70.4 | 94.1 | 100.4 | 66.4 | 69.5 | 75.1 | 76.9 | 76.9 | 67 | 66.4 | 67.5 | 75.9 | 62.3 | 55.2 | 61.4 | 144 |
| total passing vehicles | 5 | 20010 | 19866 | 19845 | 19511 | 19837 | 19814 | 19841 | 19582 | 19859 | 19705 | 19674 | 19723 | 19635 | 20011 | 19795 | 19702 |
| | 10 | 19824 | 19639 | 19818 | 19801 | 19879 | 19764 | 19820 | 19679 | 19666 | 19948 | 19678 | 19778 | 19709 | 19655 | 19884 | 19657 |
| | 15 | 19734 | 19827 | 19796 | 19793 | 19728 | 19757 | 19747 | 19693 | 19498 | 19644 | 19855 | 19845 | 19988 | 19721 | 19942 | 19758 |
| | 20 | 19775 | 19564 | 19485 | 19697 | 19683 | 19708 | 19874 | 19643 | 19773 | 19779 | 19597 | 19650 | 19598 | 19763 | 19703 | 19312 |
| | 25 | 19628 | 19103 | 19199 | 19635 | 19788 | 19262 | 19631 | 19869 | 19754 | 19590 | 19607 | 19909 | 19640 | 19389 | 19783 | 17744 |
| car count | 5 | 18884 | 18754 | 18714 | 18396 | 18721 | 18709 | 18715 | 18407 | 18742 | 18624 | 18535 | 18550 | 18493 | 18824 | 18620 | 18510 |
| | 10 | 17924 | 17734 | 17856 | 17924 | 17929 | 17909 | 17816 | 17710 | 17792 | 18087 | 17767 | 17835 | 17880 | 17715 | 17995 | 17668 |
| | 15 | 17056 | 17150 | 17074 | 17064 | 17039 | 17139 | 17024 | 17029 | 16837 | 16895 | 17175 | 17068 | 17242 | 17028 | 17131 | 16987 |
| | 20 | 16299 | 16157 | 16072 | 16210 | 16243 | 16210 | 16293 | 16182 | 16296 | 16278 | 16161 | 16159 | 16215 | 16334 | 16283 | 15773 |
| | 25 | 15339 | 14972 | 14988 | 15386 | 15578 | 15116 | 15402 | 15572 | 15556 | 15406 | 15393 | 15582 | 15411 | 15258 | 15644 | 13910 |
| truck count | 5 | 1126 | 1112 | 1131 | 1115 | 1116 | 1105 | 1126 | 1175 | 1117 | 1081 | 1139 | 1173 | 1142 | 1187 | 1175 | 1192 |
| | 10 | 1900 | 1905 | 1962 | 1877 | 1950 | 1855 | 2004 | 1969 | 1874 | 1861 | 1911 | 1943 | 1829 | 1940 | 1889 | 1989 |
| | 15 | 2678 | 2677 | 2722 | 2729 | 2689 | 2618 | 2723 | 2664 | 2661 | 2749 | 2680 | 2777 | 2746 | 2693 | 2811 | 2771 |
| | 20 | 3476 | 3407 | 3413 | 3487 | 3440 | 3498 | 3581 | 3461 | 3477 | 3501 | 3436 | 3491 | 3383 | 3429 | 3420 | 3539 |
| | 25 | 4289 | 4131 | 4211 | 4249 | 4210 | 4146 | 4229 | 4297 | 4198 | 4184 | 4214 | 4327 | 4229 | 4131 | 4139 | 3834 |
| throughput (pce) 1T=2car | 5 | 21136 | 20978 | 20976 | 20626 | 20953 | 20919 | 20967 | 20757 | 20976 | 20786 | 20813 | 20896 | 20777 | 21198 | 20970 | 20894 |
| | 10 | 21724 | 21544 | 21780 | 21678 | 21829 | 21619 | 21824 | 21648 | 21540 | 21809 | 21589 | 21721 | 21538 | 21595 | 21773 | 21646 |
| | 15 | 22412 | 22504 | 22518 | 22522 | 22417 | 22375 | 22470 | 22357 | 22159 | 22393 | 22535 | 22622 | 22734 | 22414 | 22753 | 22529 |
| | 20 | 23251 | 22971 | 22898 | 23184 | 23123 | 23206 | 23455 | 23104 | 23250 | 23280 | 23033 | 23141 | 22981 | 23192 | 23123 | 22851 |
| | 25 | 23917 | 23234 | 23410 | 23884 | 23998 | 23408 | 23860 | 24166 | 23952 | 23774 | 23821 | 24236 | 23869 | 23520 | 23922 | 21578 |
| average travel time of cars | 5 | 2.3 | 2.3 | 2.4 | 2.7 | 2.3 | 2.3 | 2.4 | 2.8 | 2.3 | 2.3 | 2.4 | 2.8 | 2.3 | 2.3 | 2.4 | 2.8 |
| | 10 | 2.3 | 2.3 | 2.4 | 2.5 | 2.3 | 2.3 | 2.4 | 2.5 | 2.3 | 2.3 | 2.4 | 2.5 | 2.3 | 2.3 | 2.4 | 2.7 |
| | 15 | 2.3 | 2.3 | 2.4 | 2.5 | 2.3 | 2.3 | 2.4 | 2.4 | 2.3 | 2.3 | 2.3 | 2.5 | 2.3 | 2.3 | 2.3 | 2.5 |
| | 20 | 2.3 | 2.3 | 2.3 | 2.4 | 2.3 | 2.3 | 2.3 | 2.4 | 2.3 | 2.3 | 2.3 | 2.4 | 2.3 | 2.3 | 2.3 | 2.6 |
| | 25 | 2.3 | 2.4 | 2.4 | 2.3 | 2.3 | 2.4 | 2.4 | 2.4 | 2.3 | 2.3 | 2.3 | 2.4 | 2.3 | 2.2 | 2.3 | 2.8 |
| average travel time of trucks | 5 | 2.7 | 2.7 | 2.7 | 2.7 | 2.6 | 2.6 | 2.6 | 2.7 | 2.4 | 2.5 | 2.5 | 2.6 | 2.2 | 2.2 | 2.2 | 2.2 |
| | 10 | 3 | 3 | 3 | 3.1 | 2.9 | 2.9 | 2.9 | 2.9 | 2.7 | 2.7 | 2.8 | 2.7 | 2.3 | 2.4 | 2.4 | 2.4 |
| | 15 | 3.1 | 3.2 | 3.2 | 3.2 | 3 | 3.1 | 3.1 | 3 | 2.8 | 2.9 | 2.9 | 2.9 | 2.4 | 2.5 | 2.5 | 2.5 |
| | 20 | 3.2 | 3.4 | 3.4 | 3.2 | 3.1 | 3.3 | 3.3 | 3.2 | 2.9 | 3 | 3 | 2.9 | 2.5 | 2.5 | 2.5 | 2.7 |
| | 25 | 3.2 | 4.5 | 4.4 | 3.3 | 3.1 | 3.6 | 3.4 | 3.2 | 2.9 | 3.2 | 3.1 | 3 | 2.5 | 2.6 | 2.6 | 3.3 |
| average energy consumption of cars | 5 | 70.5 | 68.4 | 85 | 147.8 | 69.2 | 66.8 | 84.8 | 171.3 | 67.8 | 67.2 | 80.7 | 166.9 | 65.6 | 65.7 | 82.3 | 164.6 |
| | 10 | 76 | 71.2 | 82.3 | 120.1 | 75.5 | 69.8 | 82.6 | 109.3 | 73.4 | 70.3 | 80.4 | 116.4 | 68.1 | 65.4 | 80.7 | 152 |
| | 15 | 81 | 73.6 | 81.8 | 105.3 | 79.2 | 71.5 | 80.9 | 101.2 | 75.7 | 71 | 79.6 | 121.6 | 75.1 | 68 | 78 | 114.4 |
| | 20 | 83.9 | 75.6 | 82.2 | 91.7 | 82.3 | 75.3 | 84.5 | 92.8 | 81.1 | 73.7 | 75.2 | 94.8 | 73.7 | 66.8 | 72.4 | 125.2 |
| | 25 | 83.7 | 81.9 | 93.1 | 80.7 | 82.8 | 77.6 | 85 | 93.7 | 80.1 | 73.7 | 77 | 92.7 | 75.1 | 64.5 | 72.4 | 161.3 |
| average energy consumption of trucks | 5 | 7.9 | 9.6 | 9.5 | 8.9 | 7.4 | 7.8 | 7.7 | 10.4 | 7.2 | 8.4 | 7.4 | 10.5 | 5.7 | 6.3 | 6.2 | 12.2 |
| | 10 | 11.7 | 15.5 | 14 | 8.8 | 11.2 | 14.5 | 13.2 | 8 | 9.3 | 13.3 | 11.8 | 9.2 | 7.4 | 10.1 | 8.4 | 13.4 |
| | 15 | 15.6 | 24.7 | 23.1 | 10.2 | 14 | 21.7 | 21.7 | 9.4 | 12.5 | 21 | 17.1 | 10.8 | 10.7 | 14 | 12.4 | 13.1 |
| | 20 | 18.8 | 41.3 | 34.1 | 12.2 | 18.1 | 35.7 | 33.2 | 11.6 | 16 | 28 | 23.3 | 12.4 | 12.4 | 17.1 | 14.2 | 27.6 |
| | 25 | 22.6 | 138.6 | 126.6 | 14.9 | 20.5 | 66.1 | 47.6 | 15.9 | 18.6 | 39.3 | 33 | 15.6 | 15.3 | 21.1 | 19.7 | 81.5 |
| total number of TTC<1.5 sec. | 5 | 6 | 1 | 3 | 35 | 6 | 1 | 15 | 55 | 2 | 6 | 9 | 46 | 4 | 4 | 4 | 48 |
| | 10 | 5 | 17 | 12 | 28 | 6 | 5 | 11 | 21 | 7 | 6 | 12 | 18 | 2 | 5 | 6 | 52 |
| | 15 | 4 | 15 | 20 | 19 | 3 | 7 | 21 | 15 | 5 | 9 | 16 | 29 | 0 | 16 | 18 | 19 |
| | 20 | 6 | 22 | 26 | 12 | 9 | 21 | 20 | 21 | 7 | 19 | 26 | 13 | 1 | 10 | 17 | 39 |
| | 25 | 8 | 42 | 49 | 13 | 6 | 30 | 35 | 14 | 2 | 24 | 22 | 14 | 4 | 11 | 11 | 64 |
| total number of 1.5<TTC<3 | 5 | 8 | 5 | 13 | 161 | 17 | 11 | 19 | 178 | 13 | 14 | 15 | 216 | 11 | 7 | 13 | 178 |
| | 10 | 14 | 24 | 19 | 100 | 17 | 13 | 31 | 59 | 14 | 18 | 28 | 56 | 12 | 13 | 20 | 200 |
| | 15 | 24 | 34 | 55 | 64 | 18 | 33 | 48 | 49 | 12 | 24 | 36 | 118 | 12 | 20 | 29 | 63 |
| | 20 | 15 | 70 | 94 | 23 | 28 | 57 | 73 | 32 | 27 | 43 | 40 | 33 | 7 | 19 | 27 | 124 |
| | 25 | 20 | 197 | 214 | 27 | 17 | 126 | 106 | 52 | 6 | 71 | 48 | 49 | 8 | 23 | 32 | 307 |

* if capacity is not reached then "CN" is used.

**Table C.4. An overview of the (comparative) results of simulation for all shares of trucks in the mainline flow and the exiting flow compared to the RB scenario (RB index for each case = 100)**

| Indicator | Share of trucks in the mainline flow (%) | Share of trucks in the on-ramp flow (%) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 5 | | | | 10 | | | | 20 | | | | 40 | | | |
| | | RB sce. | RP sce. | DR sce. | DL sce. | RB sce. | RP sce. | DR sce. | DL sce. | RB sce. | RP sce. | DR sce. | DL sce. | RB sce. | RP sce. | DR sce. | DL sce. |
| average travel time of vehicles | 5 | 100 | 100 | 104 | 117 | 100 | 100 | 104 | 122 | 100 | 100 | 104 | 122 | 100 | 100 | 104 | 117 |
| | 10 | 100 | 100 | 100 | 108 | 100 | 100 | 100 | 104 | 100 | 96 | 100 | 104 | 100 | 100 | 104 | 117 |
| | 15 | 100 | 100 | 104 | 108 | 100 | 100 | 104 | 104 | 100 | 100 | 100 | 108 | 100 | 100 | 104 | 109 |
| | 20 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 104 | 100 | 100 | 100 | 113 |
| | 25 | 100 | 112 | 112 | 100 | 100 | 104 | 104 | 104 | 100 | 104 | 104 | 104 | 100 | 100 | 104 | 126 |
| average energy consumption | 5 | 100 | 97 | 120 | 209 | 100 | 97 | 122 | 246 | 100 | 99 | 119 | 245 | 100 | 100 | 125 | 250 |
| | 10 | 100 | 94 | 108 | 157 | 100 | 93 | 109 | 143 | 100 | 97 | 110 | 157 | 100 | 96 | 118 | 221 |
| | 15 | 100 | 93 | 102 | 128 | 100 | 92 | 103 | 126 | 100 | 95 | 106 | 158 | 100 | 92 | 104 | 151 |
| | 20 | 100 | 96 | 102 | 107 | 100 | 96 | 106 | 110 | 100 | 94 | 95 | 115 | 100 | 92 | 99 | 170 |
| | 25 | 100 | 134 | 143 | 94 | 100 | 108 | 111 | 111 | 100 | 99 | 101 | 113 | 100 | 89 | 99 | 231 |
| total passing vehicles | 5 | 100 | 99 | 99 | 98 | 100 | 100 | 100 | 99 | 100 | 99 | 99 | 99 | 100 | 102 | 101 | 100 |
| | 10 | 100 | 99 | 100 | 100 | 100 | 99 | 100 | 99 | 100 | 101 | 100 | 101 | 100 | 100 | 101 | 100 |
| | 15 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 101 | 102 | 102 | 100 | 99 | 100 | 99 |
| | 20 | 100 | 99 | 99 | 100 | 100 | 100 | 101 | 100 | 100 | 100 | 99 | 99 | 100 | 101 | 101 | 99 |
| | 25 | 100 | 97 | 98 | 100 | 100 | 97 | 99 | 100 | 100 | 99 | 99 | 101 | 100 | 99 | 101 | 90 |
| car count | 5 | 100 | 99 | 99 | 97 | 100 | 100 | 100 | 98 | 100 | 99 | 99 | 99 | 100 | 102 | 101 | 100 |
| | 10 | 100 | 99 | 100 | 100 | 100 | 100 | 99 | 99 | 100 | 102 | 100 | 100 | 100 | 99 | 101 | 99 |
| | 15 | 100 | 101 | 100 | 100 | 100 | 101 | 100 | 100 | 100 | 100 | 102 | 101 | 100 | 99 | 99 | 99 |
| | 20 | 100 | 99 | 99 | 99 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 99 | 100 | 101 | 100 | 97 |
| | 25 | 100 | 98 | 98 | 100 | 100 | 97 | 99 | 100 | 100 | 99 | 99 | 100 | 100 | 99 | 102 | 90 |
| truck count | 5 | 100 | 99 | 100 | 99 | 100 | 99 | 101 | 105 | 100 | 97 | 102 | 105 | 100 | 104 | 103 | 104 |
| | 10 | 100 | 100 | 103 | 99 | 100 | 95 | 103 | 101 | 100 | 99 | 102 | 104 | 100 | 106 | 103 | 109 |
| | 15 | 100 | 100 | 102 | 102 | 100 | 97 | 101 | 99 | 100 | 103 | 101 | 104 | 100 | 98 | 102 | 101 |
| | 20 | 100 | 98 | 98 | 100 | 100 | 102 | 104 | 101 | 100 | 101 | 99 | 100 | 100 | 101 | 101 | 105 |
| | 25 | 100 | 96 | 98 | 99 | 100 | 98 | 100 | 102 | 100 | 100 | 100 | 103 | 100 | 98 | 98 | 91 |
| throughput (pce) 1T=2car | 5 | 100 | 99 | 99 | 98 | 100 | 100 | 100 | 99 | 100 | 99 | 99 | 100 | 100 | 102 | 101 | 101 |
| | 10 | 100 | 99 | 100 | 100 | 100 | 99 | 100 | 99 | 100 | 101 | 100 | 101 | 100 | 100 | 101 | 101 |
| | 15 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 101 | 102 | 102 | 100 | 99 | 100 | 99 |
| | 20 | 100 | 99 | 98 | 100 | 100 | 100 | 101 | 100 | 100 | 100 | 99 | 100 | 100 | 101 | 101 | 99 |
| | 25 | 100 | 97 | 98 | 100 | 100 | 98 | 99 | 101 | 100 | 99 | 99 | 101 | 100 | 99 | 100 | 90 |
| average travel time of cars | 5 | 100 | 100 | 104 | 117 | 100 | 100 | 104 | 122 | 100 | 100 | 104 | 122 | 100 | 100 | 104 | 122 |
| | 10 | 100 | 100 | 104 | 109 | 100 | 100 | 104 | 109 | 100 | 100 | 104 | 109 | 100 | 100 | 104 | 117 |
| | 15 | 100 | 100 | 104 | 109 | 100 | 100 | 104 | 104 | 100 | 100 | 100 | 109 | 100 | 100 | 100 | 109 |
| | 20 | 100 | 100 | 100 | 104 | 100 | 100 | 100 | 104 | 100 | 100 | 100 | 104 | 100 | 100 | 100 | 113 |
| | 25 | 100 | 104 | 104 | 100 | 100 | 104 | 104 | 104 | 100 | 100 | 100 | 104 | 100 | 96 | 100 | 122 |
| average travel time of trucks | 5 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 104 | 100 | 104 | 104 | 108 | 100 | 100 | 100 | 100 |
| | 10 | 100 | 100 | 100 | 103 | 100 | 100 | 100 | 100 | 100 | 100 | 104 | 100 | 100 | 104 | 104 | 104 |
| | 15 | 100 | 103 | 103 | 103 | 100 | 103 | 103 | 100 | 100 | 104 | 104 | 104 | 100 | 104 | 104 | 104 |
| | 20 | 100 | 106 | 106 | 100 | 100 | 106 | 106 | 103 | 100 | 103 | 103 | 100 | 100 | 100 | 100 | 108 |
| | 25 | 100 | 141 | 138 | 103 | 100 | 116 | 110 | 103 | 100 | 110 | 107 | 103 | 100 | 104 | 104 | 132 |
| average energy consumption of cars | 5 | 100 | 97 | 121 | 210 | 100 | 97 | 123 | 248 | 100 | 99 | 119 | 246 | 100 | 100 | 125 | 251 |
| | 10 | 100 | 94 | 108 | 158 | 100 | 92 | 109 | 145 | 100 | 96 | 110 | 159 | 100 | 96 | 119 | 223 |
| | 15 | 100 | 91 | 101 | 130 | 100 | 90 | 102 | 128 | 100 | 94 | 105 | 161 | 100 | 91 | 104 | 152 |
| | 20 | 100 | 90 | 98 | 109 | 100 | 91 | 103 | 113 | 100 | 91 | 93 | 117 | 100 | 91 | 98 | 170 |
| | 25 | 100 | 98 | 111 | 96 | 100 | 94 | 103 | 113 | 100 | 92 | 96 | 116 | 100 | 86 | 96 | 215 |
| average energy consumption of trucks | 5 | 100 | 122 | 120 | 113 | 100 | 105 | 104 | 141 | 100 | 117 | 103 | 146 | 100 | 111 | 109 | 214 |
| | 10 | 100 | 132 | 120 | 75 | 100 | 129 | 118 | 71 | 100 | 143 | 127 | 99 | 100 | 136 | 114 | 181 |
| | 15 | 100 | 158 | 148 | 65 | 100 | 155 | 155 | 67 | 100 | 168 | 137 | 86 | 100 | 131 | 116 | 122 |
| | 20 | 100 | 220 | 181 | 65 | 100 | 197 | 183 | 64 | 100 | 175 | 146 | 78 | 100 | 138 | 115 | 223 |
| | 25 | 100 | 613 | 560 | 66 | 100 | 322 | 232 | 78 | 100 | 211 | 177 | 84 | 100 | 138 | 129 | 533 |
| total number of TTC<1.5 sec. | 5 | 100 | 17 | 50 | 583 | 100 | 17 | 250 | 917 | 100 | 300 | 450 | 2300 | 100 | 100 | 100 | 1200 |
| | 10 | 100 | 340 | 240 | 560 | 100 | 83 | 183 | 350 | 100 | 86 | 171 | 257 | 100 | 250 | 300 | 2600 |
| | 15 | 100 | 375 | 500 | 475 | 100 | 233 | 700 | 500 | 100 | 180 | 320 | 580 | 100 | #DIV/0! | #DIV/0! | #DIV/0! |
| | 20 | 100 | 367 | 433 | 200 | 100 | 233 | 222 | 233 | 100 | 271 | 371 | 186 | 100 | 1000 | 1700 | 3900 |
| | 25 | 100 | 525 | 613 | 163 | 100 | 500 | 583 | 233 | 100 | 1200 | 1100 | 700 | 100 | 275 | 275 | 1600 |
| total number of 1.5<TTC<3 | 5 | 100 | 63 | 163 | 2013 | 100 | 65 | 112 | 1047 | 100 | 108 | 115 | 1662 | 100 | 64 | 118 | 1618 |
| | 10 | 100 | 171 | 136 | 714 | 100 | 76 | 182 | 347 | 100 | 129 | 200 | 400 | 100 | 108 | 167 | 1667 |
| | 15 | 100 | 142 | 229 | 267 | 100 | 183 | 267 | 272 | 100 | 200 | 300 | 983 | 100 | 167 | 242 | 525 |
| | 20 | 100 | 467 | 627 | 153 | 100 | 204 | 261 | 114 | 100 | 159 | 148 | 122 | 100 | 271 | 386 | 1771 |
| | 25 | 100 | 985 | 1070 | 135 | 100 | 741 | 624 | 306 | 100 | 1183 | 800 | 817 | 100 | 288 | 400 | 3838 |

# Appendix D
# Simulation Results for Trucks Platooning

**Table D.1. Impact assessment of the maximum number of trucks in platoons at on-ramps**

| Absolute values | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 5434.2 | 94.5 | 6.8 | 335.6 | 20626 | 4.9 | 16759 | 3867 | 24493 | 6.4 | 8.3 | 380.2 | 141.8 | 92 | 359 |
| P-MAX4 | 4964.4 | 96.8 | 7.1 | 356.9 | 19264 | 5 | 16803 | 2461 | 21725 | 6.5 | 11.1 | 393.8 | 104.6 | 73 | 221 |
| P-MAX6 | 4962.4 | 96.7 | 7.1 | 359.1 | 19248 | 5.5 | 16747 | 2501 | 21749 | 6.6 | 11 | 397.3 | 103 | 53 | 213 |
| P-MAX8 | 5016.6 | 97.4 | 7 | 343.1 | 19453 | 4.8 | 16952 | 2501 | 21954 | 6.5 | 10.7 | 379.3 | 97.5 | 45 | 191 |
| P-MAX10 | 5052.6 | 96.9 | 7 | 347.8 | 19473 | 4.9 | 16952 | 2521 | 21994 | 6.5 | 10.5 | 385 | 97.7 | 65 | 210 |
| **Relative values** | | | | | | | | | | | | | | | |
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| P-MAX4 | 91 | 102 | 104 | 106 | 93 | 102 | 100 | 64 | 89 | 102 | 134 | 104 | 74 | 79 | 62 |
| P-MAX6 | 91 | 102 | 104 | 107 | 93 | 112 | 100 | 65 | 89 | 103 | 133 | 104 | 73 | 58 | 59 |
| P-MAX8 | 92 | 103 | 103 | 102 | 94 | 98 | 101 | 65 | 90 | 102 | 129 | 100 | 69 | 49 | 53 |
| P-MAX10 | 93 | 103 | 103 | 104 | 94 | 100 | 101 | 65 | 90 | 102 | 127 | 101 | 69 | 71 | 58 |

**Table D.2. Impact assessment of the initial number of trucks in platoons at on-ramps**

**Absolute values**

| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 5434.2 | 94.5 | 6.8 | 335.6 | 20626 | 4.9 | 16759 | 3867 | 24493 | 6.4 | 8.3 | 380.2 | 141.8 | 92 | 359 |
| P-MIN2 | 5016.6 | 97.4 | 7 | 343.1 | 19453 | 4.8 | 16952 | 2501 | 21954 | 6.5 | 10.7 | 379.3 | 97.5 | 45 | 191 |
| P-MIN3 | 5251.4 | 96.2 | 6.7 | 311.7 | 20285 | 4.2 | 16988 | 3297 | 23582 | 6.4 | 8.6 | 361.8 | 53.3 | 51 | 160 |
| P-MIN5 | 5569.8 | 95 | 6.6 | 282.3 | 21041 | 3.5 | 17025 | 4016 | 25057 | 6.3 | 7.8 | 339.3 | 40.9 | 58 | 185 |
| P-MIN8 | 5544 | 94.8 | 6.8 | 316.2 | 20793 | 5.4 | 16766 | 4027 | 24820 | 6.5 | 8.2 | 379.3 | 53.3 | 144 | 417 |

**Relative values**

| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| P-MIN2 | 92 | 103 | 103 | 102 | 94 | 98 | 101 | 65 | 90 | 102 | 129 | 100 | 69 | 49 | 53 |
| P-MIN3 | 97 | 102 | 99 | 93 | 98 | 86 | 101 | 85 | 96 | 100 | 104 | 95 | 38 | 55 | 45 |
| P-MIN5 | 102 | 101 | 97 | 84 | 102 | 71 | 102 | 104 | 102 | 98 | 94 | 89 | 29 | 63 | 52 |
| P-MIN8 | 102 | 100 | 100 | 94 | 101 | 110 | 100 | 104 | 101 | 102 | 99 | 100 | 38 | 157 | 116 |

**Table D.3. Impact assessment of intra-distance of trucks in platoons at on-ramps**

**Absolute values**

| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 5434.2 | 94.5 | 6.8 | 335.6 | 20626 | 4.9 | 16759 | 3867 | 24493 | 6.4 | 8.3 | 380.2 | 141.8 | 92 | 359 |
| P-INTRA 5 | 5135.7 | 96.7 | 7 | 339.9 | 19778 | 4.4 | 17066 | 2712 | 22490 | 6.4 | 10.6 | 377.5 | 102.8 | 47 | 156 |
| P-INTRA 10 | 5016.6 | 97.4 | 7 | 343.1 | 19453 | 4.8 | 16952 | 2501 | 21954 | 6.5 | 10.7 | 379.3 | 97.5 | 45 | 191 |
| P-INTRA 15 | 4932 | 97.4 | 7.1 | 358.1 | 19144 | 5.7 | 16734 | 2410 | 21554 | 6.6 | 10.7 | 395.1 | 101.1 | 70 | 253 |
| P-INTRA 20 | 4890.3 | 97.2 | 7.1 | 367 | 18946 | 5.9 | 16700 | 2246 | 21192 | 6.6 | 10.9 | 402.2 | 105 | 77 | 274 |

**Relative values**

| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| P-INTRA 5 | 95 | 102 | 103 | 101 | 96 | 90 | 102 | 70 | 92 | 100 | 128 | 99 | 72 | 51 | 43 |
| P-INTRA 10 | 92 | 103 | 103 | 102 | 94 | 90 | 101 | 65 | 90 | 102 | 129 | 100 | 69 | 49 | 53 |
| P-INTRA 15 | 91 | 103 | 104 | 107 | 93 | 116 | 100 | 62 | 88 | 103 | 129 | 104 | 71 | 76 | 70 |
| P-INTRA 20 | 90 | 103 | 104 | 109 | 92 | 120 | 100 | 58 | 87 | 103 | 131 | 106 | 74 | 84 | 76 |

**Table D.4. Impact assessment of inter-distance of platoons at on-ramps**

**Absolute values**

| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 5434.2 | 94.5 | 6.8 | 335.6 | 20626 | 4.9 | 16759 | 3867 | 24493 | 6.4 | 8.3 | 380.2 | 141.8 | 92 | 359 |
| P-INTER 50 | 5633.6 | 94.4 | 6.6 | 292 | 21179 | 3.2 | 17149 | 4030 | 25209 | 6.3 | 7.9 | 350.8 | 41.9 | 41 | 150 |
| P-INTER 100 | 5225.8 | 95.8 | 6.9 | 332.6 | 20068 | 4.9 | 16827 | 3241 | 23309 | 6.5 | 9.1 | 384.1 | 65.1 | 64 | 215 |
| P-INTER 150 | 5016.6 | 97.4 | 7 | 343.1 | 19453 | 4.8 | 16952 | 2501 | 21954 | 6.5 | 10.7 | 379.3 | 97.5 | 45 | 191 |
| P-INTER 200 | 4895.1 | 97.5 | 7 | 344.5 | 18916 | 4.9 | 16791 | 2125 | 21041 | 6.5 | 11.2 | 374.5 | 107.6 | 66 | 181 |
| P-INTER 250 | 4829.2 | 97.1 | 7 | 350.2 | 18745 | 4.2 | 16844 | 1901 | 20646 | 6.5 | 11.4 | 376.9 | 113.8 | 62 | 217 |

**Relative values**

| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| P-INTER 50 | 104 | 100 | 97 | 87 | 103 | 65 | 102 | 104 | 103 | 98 | 95 | 92 | 30 | 45 | 42 |
| P-INTER 100 | 96 | 101 | 101 | 99 | 97 | 100 | 100 | 84 | 95 | 102 | 110 | 101 | 46 | 70 | 60 |
| P-INTER 150 | 92 | 103 | 103 | 102 | 94 | 98 | 101 | 65 | 90 | 102 | 129 | 100 | 69 | 49 | 53 |
| P-INTER 200 | 90 | 103 | 103 | 103 | 92 | 100 | 100 | 55 | 86 | 102 | 135 | 99 | 76 | 72 | 50 |
| P-INTER 250 | 89 | 103 | 103 | 104 | 91 | 86 | 101 | 49 | 84 | 102 | 137 | 99 | 80 | 67 | 60 |

**Table D.5. Impact assessment of desired speed of platoons at on-ramps**

| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Absolute values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 5434.2 | 94.5 | 6.8 | 335.6 | 20626 | 4.9 | 16759 | 3867 | 24493 | 6.4 | 8.3 | 380.2 | 141.8 | 92 | 359 |
| P-S 55 | 4753.6 | 90.9 | 7.5 | 406.2 | 18444 | 5.9 | 16556 | 1888 | 20332 | 6.7 | 14.7 | 440.1 | 108.9 | 64 | 223 |
| P-S 70 | 4874.7 | 93.9 | 7.3 | 388.8 | 18926 | 5.8 | 16698 | 2228 | 21154 | 6.6 | 12.3 | 426.9 | 103.2 | 63 | 259 |
| P-S 85 | 5016.6 | 97.4 | 7 | 343.1 | 19453 | 4.8 | 16952 | 2501 | 21954 | 6.5 | 10.7 | 379.3 | 97.5 | 45 | 191 |
| **Relative values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| P-S 55 | 87 | 96 | 110 | 121 | 89 | 120 | 99 | 49 | 83 | 105 | 177 | 116 | 77 | 70 | 62 |
| P-S 70 | 90 | 99 | 107 | 116 | 92 | 118 | 100 | 58 | 86 | 103 | 148 | 112 | 73 | 68 | 72 |
| P-S 85 | 92 | 103 | 103 | 102 | 94 | 98 | 101 | 65 | 90 | 102 | 129 | 100 | 69 | 49 | 53 |

**Table D.6. Impact assessment of the maximum acceleration and decleration rates of trucks in platoons at on-ramps**

| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Absolute values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 5434.2 | 94.5 | 6.8 | 335.6 | 20626 | 4.9 | 16759 | 3867 | 24493 | 6.4 | 8.3 | 380.2 | 141.8 | 92 | 359 |
| P-Accel. (-1/1) | 4991.7 | 96.1 | 7.1 | 358.9 | 19349 | 5.4 | 16697 | 2652 | 22001 | 6.6 | 10.2 | 401 | 94.1 | 230 | 403 |
| P-Accel. (-2/2) | 5016.6 | 97.4 | 7 | 343.1 | 19453 | 4.8 | 16952 | 2501 | 21954 | 6.5 | 10.7 | 379.3 | 97.5 | 45 | 191 |
| P-Accel. (-4/4) | 5030.2 | 96.3 | 7.1 | 357.2 | 19380 | 5.5 | 16816 | 2564 | 21944 | 6.6 | 10.5 | 396.9 | 97.1 | 55 | 200 |
| **Relative values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| P-Accel. (-1/1) | 92 | 102 | 104 | 107 | 94 | 110 | 100 | 69 | 90 | 103 | 123 | 105 | 66 | 250 | 112 |
| P-Accel. (-2/2) | 92 | 103 | 103 | 102 | 94 | 98 | 101 | 65 | 90 | 102 | 129 | 100 | 69 | 49 | 53 |
| P-Accel. (-4/4) | 93 | 102 | 104 | 106 | 94 | 112 | 100 | 66 | 90 | 103 | 127 | 104 | 68 | 60 | 56 |

**Table D.7. Impact assessment of continuous or discontinuous platooning of trucks at on-ramps**

| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Absolute values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 5434.2 | 94.5 | 6.8 | 335.6 | 20626 | 4.9 | 16759 | 3867 | 24493 | 6.4 | 8.3 | 380.2 | 141.8 | 92 | 359 |
| P-L 0.10000 | 5016.6 | 97.4 | 7 | 343.1 | 19453 | 4.8 | 16952 | 2501 | 21954 | 6.5 | 10.7 | 379.3 | 97.5 | 45 | 191 |
| P-L 0.2000 | 5812.4 | 93.5 | 6.4 | 285.4 | 21040 | 1.8 | 17549 | 3491 | 24531 | 6.2 | 7.5 | 334.8 | 37 | 22 | 53 |
| P-L 4000.10000 | 4860.6 | 97.2 | 7.8 | 464.9 | 18895 | 8.4 | 15711 | 3184 | 22079 | 6.8 | 12.8 | 451.8 | 529.4 | 272 | 1023 |
| **Relative values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| P-L 0.10000 | 92 | 103 | 103 | 102 | 94 | 98 | 101 | 65 | 90 | 102 | 129 | 100 | 69 | 49 | 53 |
| P-L 0.2000 | 107 | 99 | 94 | 85 | 102 | 37 | 105 | 90 | 100 | 97 | 90 | 88 | 26 | 24 | 15 |
| P-L 4000.10000 | 89 | 103 | 115 | 139 | 92 | 171 | 94 | 82 | 90 | 106 | 154 | 119 | 373 | 296 | 285 |

## Table D.8. Impact assessment of the maximum number of trucks in platoons at off-ramps (in case of a share of 10% for vehicles leaving the mainline)

| Absolute values | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | CN* | CN* | 6.1 | 162.1 | 18656 | 0.3 | 14633 | 4023 | 22679 | 5.8 | 7.2 | 197.1 | 34.9 | 2 | 6 |
| PP-MAX 4 | 4653 | 99.7 | 7 | 258.4 | 17366 | 3.7 | 14544 | 2822 | 20188 | 6.1 | 11.6 | 283.4 | 129.4 | 15 | 89 |
| PP-MAX 6 | 4575.7 | 100.5 | 7 | 258.2 | 17414 | 3.5 | 14571 | 2843 | 20257 | 6.1 | 11.3 | 284 | 126.1 | 25 | 79 |
| PP-MAX 8 | 4861.7 | 99.2 | 6.9 | 249.7 | 17456 | 3.2 | 14625 | 2831 | 20287 | 6.1 | 11.3 | 274.2 | 123.2 | 29 | 95 |
| PP-MAX 10 | 4582.7 | 100.6 | 7 | 271.6 | 17347 | 4.9 | 14499 | 2848 | 20195 | 6.2 | 11.3 | 300.2 | 125.8 | 32 | 87 |
| **Relative values** | | | | | | | | | | | | | | | |
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| PP-MAX 4 | < 100 | < 100 | 115 | 159 | 93 | 1233 | 99 | 70 | 89 | 105 | 161 | 144 | 371 | 750 | 1483 |
| PP-MAX 6 | < 100 | < 100 | 115 | 159 | 93 | 1167 | 100 | 71 | 89 | 105 | 157 | 144 | 361 | 1250 | 1317 |
| PP-MAX 8 | < 100 | < 100 | 113 | 154 | 94 | 1067 | 100 | 70 | 89 | 105 | 157 | 139 | 353 | 1450 | 1583 |
| PP-MAX 10 | < 100 | < 100 | 115 | 168 | 93 | 1633 | 99 | 71 | 89 | 107 | 157 | 152 | 360 | 1600 | 1450 |

* CN = Capacity is not reached.

## Table D.9. Impact assessment of the maximum number of trucks in platoons at off-ramps

| Absolute values | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 4718.8 | 98.8 | 7 | 314.8 | 17990 | 8.1 | 14123 | 3867 | 21857 | 6.5 | 8.7 | 348.8 | 190.6 | 51 | 254 |
| PP-MAX 4 | 4070.3 | 101.9 | 8.7 | 473 | 15771 | 15.1 | 13432 | 2339 | 18110 | 7.4 | 16.5 | 519.8 | 204.5 | 144 | 498 |
| PP-MAX 6 | 4051.3 | 101.8 | 8.9 | 497.8 | 15719 | 16.2 | 13385 | 2334 | 18053 | 7.5 | 16.5 | 549 | 203.9 | 128 | 520 |
| PP-MAX 8 | 4052.5 | 101.9 | 8.8 | 488.3 | 15731 | 15.7 | 13390 | 2341 | 18072 | 7.5 | 16.5 | 537.9 | 204.4 | 135 | 541 |
| PP-MAX 10 | 4066.9 | 101.5 | 8.8 | 485.1 | 15772 | 15.7 | 13415 | 2357 | 18129 | 7.4 | 16.5 | 533.9 | 207.2 | 142 | 518 |
| **Relative values** | | | | | | | | | | | | | | | |
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| PP-MAX 4 | 86 | 103 | 124 | 150 | 88 | 186 | 95 | 60 | 83 | 114 | 190 | 149 | 107 | 282 | 196 |
| PP-MAX 6 | 86 | 103 | 127 | 158 | 87 | 200 | 95 | 60 | 83 | 115 | 190 | 157 | 107 | 251 | 205 |
| PP-MAX 8 | 86 | 103 | 126 | 155 | 87 | 194 | 95 | 61 | 83 | 115 | 190 | 154 | 107 | 265 | 213 |
| PP-MAX 10 | 86 | 103 | 126 | 154 | 88 | 194 | 95 | 61 | 83 | 114 | 190 | 153 | 109 | 278 | 204 |

## Table D.10. Impact assessment of the initial number of trucks in platoons at off-ramps

| Absolute values | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 4718.8 | 98.8 | 7 | 314.8 | 17990 | 8.1 | 14123 | 3867 | 21857 | 6.5 | 8.7 | 348.8 | 190.6 | 51 | 254 |
| PP-MIN 2 | 4052.5 | 101.9 | 8.8 | 488.3 | 15731 | 15.7 | 13390 | 2341 | 18072 | 7.5 | 16.5 | 537.9 | 204.4 | 135 | 541 |
| PP-MIN 3 | 4299.9 | 100.6 | 8.6 | 463.5 | 16602 | 14.3 | 13626 | 2976 | 19578 | 7.5 | 13.6 | 537 | 127 | 105 | 456 |
| PP-MIN 5 | 4648.3 | 99.5 | 7.8 | 381.4 | 17526 | 13.3 | 13830 | 3696 | 21222 | 7.1 | 10.7 | 460 | 87.2 | 93 | 295 |
| PP-MIN 5 (10) | 4714.1 | 99.3 | 7.4 | 336.9 | 17623 | 11 | 13904 | 3719 | 21342 | 6.9 | 9.5 | 409 | 67.2 | 61 | 239 |
| PP-MIN 8 (10) | 4830.4 | 98.5 | 7.3 | 324.8 | 17862 | 10.1 | 13905 | 3957 | 21819 | 6.8 | 9.1 | 397.4 | 69.5 | 59 | 228 |
| **Relative values** | | | | | | | | | | | | | | | |
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| PP-MIN 2 | 86 | 103 | 126 | 155 | 87 | 194 | 95 | 61 | 83 | 115 | 190 | 154 | 107 | 265 | 213 |
| PP-MIN 3 | 91 | 102 | 123 | 147 | 92 | 177 | 96 | 77 | 90 | 115 | 156 | 154 | 67 | 206 | 180 |
| PP-MIN 5 | 99 | 101 | 111 | 121 | 97 | 164 | 98 | 96 | 97 | 109 | 123 | 132 | 46 | 182 | 116 |
| PP-MIN 5 (10) | 100 | 101 | 106 | 107 | 98 | 136 | 98 | 96 | 98 | 106 | 109 | 117 | 35 | 120 | 94 |
| PP-MIN 8 (10) | 102 | 100 | 104 | 103 | 99 | 125 | 98 | 102 | 100 | 105 | 105 | 114 | 36 | 116 | 90 |

## Table D.11. Impact assessment of the intra-distance of trucks in platoons at off-ramps

| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Absolute values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 4718.8 | 98.8 | 7 | 314.8 | 17990 | 8.1 | 14123 | 3867 | 21857 | 6.5 | 8.7 | 348.8 | 190.6 | 51 | 254 |
| PP-INTRA 5 | 4698.3 | 99.3 | 7.7 | 360.7 | 17679 | 12.1 | 13849 | 3830 | 21509 | 7 | 10.5 | 437.8 | 82 | 85 | 333 |
| PP-INTRA 10 | 4714.1 | 99.3 | 7.4 | 336.9 | 17623 | 11 | 13904 | 3719 | 21342 | 6.9 | 9.5 | 409 | 67.2 | 61 | 239 |
| PP-INTRA 15 | 4592.7 | 99.9 | 7.8 | 370 | 17383 | 12.3 | 14029 | 3354 | 20737 | 6.9 | 11.8 | 434.6 | 99.8 | 69 | 240 |
| PP-INTRA 20 | 4424.4 | 100.8 | 7.8 | 355 | 16945 | 11.6 | 13945 | 3000 | 19945 | 6.8 | 12.6 | 407.1 | 112.9 | 50 | 236 |
| **Relative values** | | | | | | | | | | | | | | | |
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| PP-INTRA 5 | 100 | 101 | 110 | 115 | 98 | 149 | 98 | 99 | 98 | 108 | 121 | 126 | 43 | 167 | 131 |
| PP-INTRA 10 | 100 | 101 | 106 | 107 | 98 | 136 | 98 | 96 | 98 | 106 | 109 | 117 | 35 | 120 | 94 |
| PP-INTRA 15 | 97 | 101 | 111 | 118 | 97 | 152 | 99 | 87 | 95 | 106 | 136 | 125 | 52 | 135 | 94 |
| PP-INTRA 20 | 94 | 102 | 111 | 113 | 94 | 143 | 99 | 78 | 91 | 105 | 145 | 117 | 59 | 98 | 93 |

## Table D.12. Impact assessment of inter-distance between platoons at off-ramps

| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Absolute values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 4718.8 | 98.8 | 7 | 314.8 | 17990 | 8.1 | 14123 | 3867 | 21857 | 6.5 | 8.7 | 348.8 | 190.6 | 51 | 254 |
| PP-INTER 50 | Not reached | Meaningless | 6 | 150.9 | 19113 | 0.3 | 14898 | 4215 | 23328 | 5.8 | 7 | 189.9 | 13.2 | 14 | 14 |
| PP-INTER 100 | 4977.6 | 98.1 | 6.4 | 210.7 | 18603 | 3.5 | 14517 | 4086 | 22689 | 6.1 | 7.3 | 260.5 | 34.1 | 22 | 76 |
| PP-INTER 150 | 4714.1 | 99.3 | 7.4 | 336.9 | 17623 | 11 | 13904 | 3719 | 21342 | 6.9 | 9.5 | 409 | 67.2 | 61 | 239 |
| PP-INTER 200 | 4508.6 | 100.1 | 8 | 367.8 | 17241 | 12 | 13954 | 3287 | 20528 | 6.9 | 12.5 | 431.7 | 96.7 | 71 | 319 |
| PP-INTER 250 | 4369.3 | 100.5 | 8.2 | 402.7 | 16781 | 13.4 | 13886 | 2895 | 19676 | 7.1 | 13.6 | 465.3 | 102.6 | 110 | 364 |
| **Relative values** | | | | | | | | | | | | | | | |
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| PP-INTER 50 | N.A | N.A | 86 | 48 | 106 | 4 | 105 | 109 | 107 | 89 | 80 | 54 | 7 | 27 | 6 |
| PP-INTER 100 | 105 | 99 | 91 | 67 | 103 | 43 | 103 | 106 | 104 | 94 | 84 | 75 | 18 | 43 | 30 |
| PP-INTER 150 | 100 | 101 | 106 | 107 | 98 | 136 | 98 | 96 | 98 | 106 | 109 | 117 | 35 | 120 | 94 |
| PP-INTER 200 | 96 | 101 | 114 | 117 | 96 | 148 | 99 | 85 | 94 | 106 | 144 | 124 | 51 | 139 | 126 |
| PP-INTER 250 | 93 | 102 | 117 | 128 | 93 | 165 | 98 | 75 | 90 | 109 | 156 | 133 | 54 | 216 | 143 |

## Table D.13. Impact assessment of desired speed of platoons at off-ramps

| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Absolute values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 4718.8 | 98.8 | 7 | 314.8 | 17990 | 8.1 | 14123 | 3867 | 21857 | 6.5 | 8.7 | 348.8 | 190.6 | 51 | 254 |
| PP-S 55 | 4195.4 | 92 | 8.9 | 510.3 | 16143 | 18.5 | 13339 | 2804 | 18947 | 7.8 | 14.1 | 599 | 88.4 | 145 | 639 |
| PP-S 70 | 4562.3 | 95.7 | 8 | 382.9 | 17373 | 12.2 | 13967 | 3406 | 20779 | 7 | 11.9 | 456.1 | 82.9 | 78 | 304 |
| PP-S 85 | 4714.1 | 99.3 | 7.4 | 336.9 | 17623 | 11 | 13904 | 3719 | 21342 | 6.9 | 9.5 | 409 | 67.2 | 61 | 239 |
| **Relative values** | | | | | | | | | | | | | | | |
| | | | | | | | Veh_Count | | | average travel time | | average # accel./decel. | | Total time (sec.) with: | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| PP-S 55 | 89 | 93 | 127 | 162 | 90 | 228 | 94 | 73 | 87 | 120 | 162 | 172 | 46 | 284 | 252 |
| PP-S 70 | 97 | 97 | 114 | 122 | 97 | 151 | 99 | 88 | 95 | 108 | 137 | 131 | 43 | 153 | 120 |
| PP-S 85 | 100 | 101 | 106 | 107 | 98 | 136 | 98 | 96 | 98 | 106 | 109 | 117 | 35 | 120 | 94 |

## Table D.14. Impact assessment of the maximum acceleration and decleration rates of trucks in platoons at off-ramps

| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Veh_Count Car | Veh_Count Truck (Ordinary/ACT) | Veh_Count PCU | average travel time Car | average travel time Truck (Ordinary/ACT) | average # accel./decel. Car | average # accel./decel. Truck (Ordinary/ACT) | Total time (sec.) with: TTC<1.5 s | Total time (sec.) with: 1.5 s < TTC<3 s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Absolute values** | | | | | | | | | | | | | | | |
| RR | 4718.8 | 98.8 | 7 | 314.8 | 17990 | 8.1 | 14123 | 3867 | 21857 | 6.5 | 8.7 | 348.8 | 190.6 | 51 | 254 |
| PP-Accel. (-1/1) | 4612.4 | 99.1 | 7.2 | 380.3 | 17600 | 12.3 | 13543 | 4057 | 21657 | 7.2 | 7.1 | 480.3 | 46.4 | 700 | 1070 |
| PP-Accel. (-2/2) | 4714.1 | 99.3 | 7.4 | 336.9 | 17623 | 11 | 13904 | 3719 | 21342 | 6.9 | 9.5 | 409 | 67.2 | 61 | 239 |
| PP-Accel. (-4/4) | 4687.6 | 99.1 | 7.9 | 370.6 | 17785 | 12.4 | 14052 | 3733 | 21518 | 7 | 11.4 | 443.8 | 94.8 | 66 | 276 |
| **Relative values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| PP-Accel. (-1/1) | 98 | 100 | 103 | 121 | 98 | 152 | 96 | 105 | 99 | 111 | 82 | 138 | 24 | 1373 | 421 |
| PP-Accel. (-2/2) | 100 | 101 | 106 | 107 | 98 | 136 | 98 | 96 | 98 | 106 | 109 | 117 | 35 | 120 | 94 |
| PP-Accel. (-4/4) | 99 | 100 | 113 | 118 | 99 | 153 | 99 | 97 | 98 | 108 | 131 | 127 | 50 | 129 | 109 |

## Table D.15. Impact assessment of traffic signal control on the performance of platooning strategies at on-ramps

| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Veh_Count Car | Veh_Count Truck (Ordinary/ACT) | Veh_Count PCU | average travel time Car | average travel time Truck (Ordinary/ACT) | average # accel./decel. Car | average # accel./decel. Truck (Ordinary/ACT) | Total time (sec.) with: TTC<1.5 s | Total time (sec.) with: 1.5 s < TTC<3 s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Absolute values** | | | | | | | | | | | | | | | |
| R | 5434.2 | 94.5 | 6.8 | 335.6 | 20626 | 4.9 | 16759 | 3867 | 24493 | 6.4 | 8.3 | 380.2 | 141.8 | 92 | 359 |
| P-COM I | 5596 | 94.6 | 6.6 | 283.4 | 21240 | 3 | 17199 | 4041 | 25281 | 6.2 | 8.2 | 339.6 | 43.9 | 187 | 323 |
| OPTION 1 | 5148.3 | 96.2 | 7.3 | 332.5 | 19944 | 3.5 | 17040 | 2904 | 22848 | 6.5 | 12.5 | 366.1 | 135.2 | 70 | 472 |
| OPTION 2 | 5182.7 | 95.6 | 7.3 | 323.3 | 20112 | 2.7 | 17091 | 3021 | 23133 | 6.5 | 11.8 | 361.7 | 106.2 | 134 | 843 |
| OPTION 3 | 5187.2 | 96.8 | 7.2 | 267.9 | 20121 | 1.2 | 16577 | 3544 | 23665 | 6.4 | 10.7 | 302.7 | 105.2 | 223 | 1507 |
| OPTION 4 | 5142 | 95.6 | 7.4 | 342.3 | 19920 | 3.8 | 17168 | 2752 | 22672 | 6.5 | 12.8 | 376.4 | 129.6 | 128 | 363 |
| **Relative values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| R | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| P-COM I | 103 | 100 | 97 | 84 | 103 | 61 | 103 | 104 | 103 | 97 | 99 | 89 | 31 | 203 | 90 |
| OPTION 1 | 95 | 102 | 107 | 99 | 97 | 71 | 102 | 75 | 93 | 102 | 151 | 96 | 95 | 76 | 131 |
| OPTION 2 | 95 | 101 | 107 | 96 | 98 | 55 | 102 | 78 | 94 | 102 | 142 | 95 | 75 | 146 | 235 |
| OPTION 3 | 95 | 102 | 106 | 80 | 98 | 24 | 99 | 92 | 97 | 100 | 129 | 80 | 74 | 242 | 420 |
| OPTION 4 | 95 | 101 | 109 | 102 | 97 | 78 | 102 | 71 | 93 | 102 | 154 | 99 | 91 | 139 | 101 |

## Table D.16. Impact assessment of traffic signal control on the performance of platooning strategies at off-ramps

| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Veh_Count Car | Veh_Count Truck (Ordinary/ACT) | Veh_Count PCU | average travel time Car | average travel time Truck (Ordinary/ACT) | average # accel./decel. Car | average # accel./decel. Truck (Ordinary/ACT) | Total time (sec.) with: TTC<1.5 s | Total time (sec.) with: 1.5 s < TTC<3 s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Absolute values** | | | | | | | | | | | | | | | |
| RR | 4718.8 | 98.8 | 7 | 314.8 | 17990 | 8.1 | 14123 | 3867 | 21857 | 6.5 | 8.7 | 348.8 | 190.6 | 51 | 254 |
| PP-COM I | 5577 | 96.6 | 6.3 | 191.2 | 18811 | 1.3 | 14779 | 4032 | 22843 | 5.9 | 7.6 | 230.3 | 48 | 23 | 80 |
| OPTION 1 | 4109.1 | 98.7 | 9.3 | 505.2 | 16022 | 13.9 | 12402 | 3620 | 19642 | 8.2 | 12.9 | 580.1 | 248.5 | 256 | 2101 |
| OPTION 2 | 4094.3 | 98.7 | 8.7 | 450.8 | 16048 | 11.3 | 12336 | 3712 | 19760 | 7.9 | 11.2 | 529.4 | 189.6 | 425 | 2549 |
| OPTION 3 | 4086.4 | 98.8 | 8.6 | 438.1 | 16021 | 10.9 | 12307 | 3714 | 19735 | 7.8 | 11.1 | 514 | 186.6 | 403 | 2295 |
| OPTION 4 | 4112.6 | 98.9 | 9.3 | 496.4 | 16041 | 13.9 | 12414 | 3627 | 19668 | 8.2 | 13 | 567.4 | 253.5 | 358 | 2596 |
| **Relative values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| PP-COM I | 118 | 98 | 90 | 61 | 105 | 16 | 105 | 104 | 105 | 91 | 87 | 66 | 25 | 45 | 31 |
| OPTION 1 | 87 | 100 | 133 | 160 | 89 | 172 | 88 | 94 | 90 | 126 | 148 | 166 | 130 | 502 | 827 |
| OPTION 2 | 87 | 100 | 124 | 143 | 89 | 140 | 87 | 96 | 90 | 122 | 129 | 152 | 99 | 833 | 1004 |
| OPTION 3 | 87 | 100 | 123 | 139 | 89 | 135 | 87 | 96 | 90 | 120 | 128 | 147 | 98 | 790 | 904 |
| OPTION 4 | 87 | 100 | 133 | 158 | 89 | 172 | 88 | 94 | 90 | 126 | 149 | 163 | 133 | 702 | 1022 |

## Table D.17. The impact of the creation of an extra lane on the performance of The platooning strategies at off-ramps with traffic signal control

| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Veh_Count Car | Veh_Count Truck (Ordinary/ACT) | Veh_Count PCU | average travel time Car | average travel time Truck (Ordinary/ACT) | average # accel./decel. Car | average # accel./decel. Truck (Ordinary/ACT) | Total time (sec.) with: TTC<1.5 s | Total time (sec.) with: 1.5 s < TTC<3 s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Absolute values** | | | | | | | | | | | | | | | |
| RR | 4718.8 | 98.8 | 7 | 314.8 | 17990 | 8.1 | 14123 | 3867 | 21857 | 6.5 | 8.7 | 348.8 | 190.6 | 51 | 254 |
| PP-COM I | 5577 | 96.6 | 6.3 | 191.2 | 18811 | 1.3 | 14779 | 4032 | 22843 | 5.9 | 7.6 | 230.3 | 48 | 23 | 80 |
| OPTION 1- extra lane | 4908 | 98.4 | 8 | 335 | 18062 | 2.2 | 14700 | 3362 | 21424 | 6.8 | 13.7 | 340.8 | 309.9 | 182 | 1599 |
| OPTION 2- extra lane | 4955 | 97.9 | 8 | 326.2 | 18142 | 3 | 14520 | 3622 | 21764 | 6.9 | 12.3 | 352.3 | 221.3 | 263 | 2492 |
| OPTION 3- extra lane | 4874.3 | 98 | 8 | 360.4 | 17934 | 5.1 | 14281 | 3653 | 21587 | 7.1 | 11.8 | 400.4 | 203.8 | 237 | 2038 |
| OPTION 4- extra lane | 4859.1 | 98.8 | 8 | 316.7 | 17986 | 2 | 14608 | 3378 | 21364 | 6.7 | 13.9 | 322.3 | 292.8 | 164 | 1823 |
| **Relative values** | | | | | | | | | | | | | | | |
| scenario | capacity | speed at capacity | average travel time | average # accel./decel. | Total passing veh. | Congestion indicator (km-hour) | Car | Truck (Ordinary/ACT) | PCU | Car | Truck (Ordinary/ACT) | Car | Truck (Ordinary/ACT) | TTC<1.5 s | 1.5 s < TTC<3 s |
| RR | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| PP-COM I | 118 | 98 | 90 | 61 | 105 | 16 | 105 | 104 | 105 | 91 | 87 | 66 | 25 | 45 | 31 |
| OPTION 1- extra lane | 104 | 100 | 114 | 106 | 100 | 27 | 104 | 87 | 98 | 105 | 157 | 98 | 163 | 357 | 630 |
| OPTION 2- extra lane | 105 | 99 | 114 | 104 | 101 | 37 | 103 | 94 | 100 | 106 | 141 | 101 | 116 | 516 | 981 |
| OPTION 3- extra lane | 103 | 99 | 114 | 114 | 100 | 63 | 101 | 94 | 99 | 109 | 136 | 115 | 107 | 465 | 802 |
| OPTION 4- extra lane | 103 | 100 | 114 | 101 | 100 | 25 | 103 | 87 | 98 | 103 | 160 | 92 | 154 | 322 | 718 |

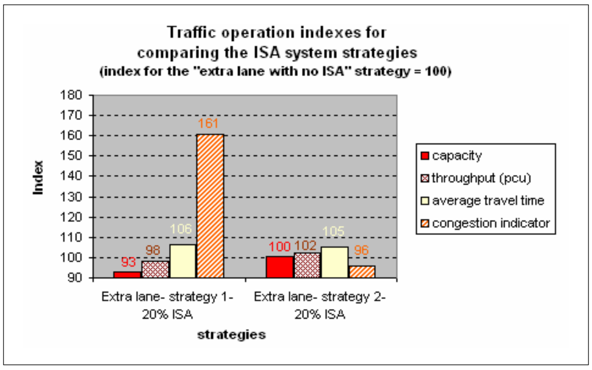



**Figure D.1. The impact of the implementation of the ISA system on the traffic operation performance of platooning scenarios at signalised off-ramps (including an extra lane for cars leaving the mainline)**

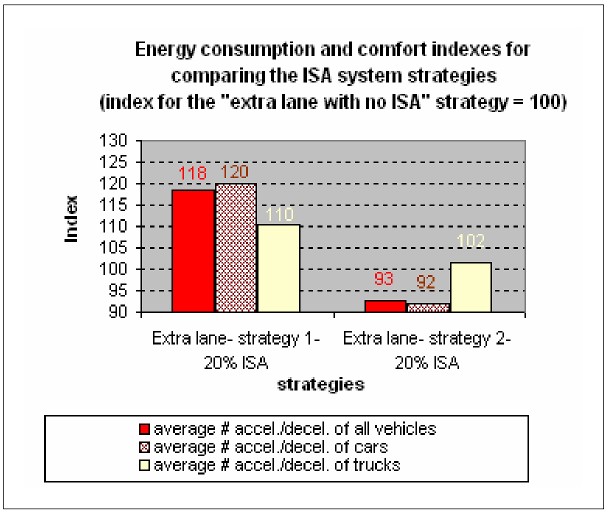



**Figure D.2. The impact of the implementation of the ISA system on the traffic comfort indicators of platooning scenarios at signalised off-ramps (including an extra lane for cars leaving the mainline)**

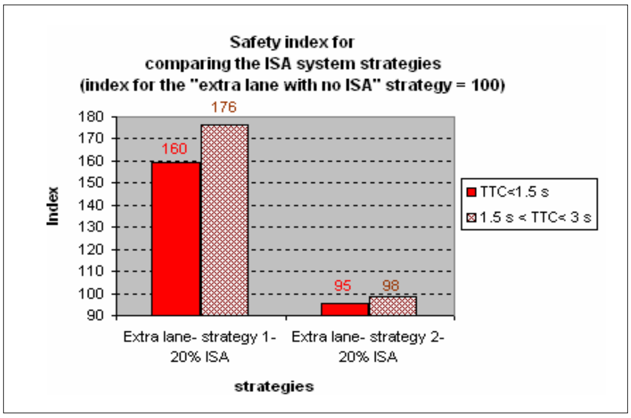



**Figure D.3. The impact of the implementation of the ISA system on the TTC values of platooning scenarios at signalised off-ramps (including an extra lane for cars leaving the mainline)**

# Appendix E
# An example of the GAMS Formulation for the Flow Control Optimization Model

## The input of one of the models in the GAMS formulation

```
$Title: An optimization model for controlling the mixed traffic flow of ACTs and MDVs at merging areas

sets
m       Number of segments on the DFL         /1*5/
mm      Number of segments on the on-ramp   /1*3/
t       Time instant                        / 0,900 (*10) /;

alias (t,at,bt) ;

parameter    DACTD(t)   Equivalent demand of ACTs on the DFL at time instant t (vph) ;
                        DACTD(t)= 870$(ord(t) le 44)+ 700$(ord(t) gt 44);
parameter    DACTR(t)   Equivalent demand of ACTs on the on-ramp at time instant t (vph) ;
                        DACTR(t)= 130$(ord(t) le 44)+ 100$(ord(t) gt 44);
parameter    DMDVD(t)   Equivalent demand of MDVs on the right lane of the motorway at time instant t (vph) ;
                        DMDVD(t)= 1740$(ord(t) le 44)+ 1400$(ord(t) gt 44);
parameter    DMDVR(t)   Equivalent demand of MDVs on the on-ramp at time instant t (vph);
                        DMDVR(t)= 520$(ord(t) le 44)+ 420$(ord(t) gt 44) ;
parameters

L(m)            Length of segments of the DFL (km)
                / 1 0.5, 2 0.5, 3 0.5, 4 0.5, 5  0.5/
LL(mm)          Length of segments of the on-ramp (km)
                / 1 .5, 2 .5, 3 .5 /
LbA(m)          Length of the buffer area located on segment "m" of the DFL for ACTs (km)
                / 1  0.5, 2  0.5, 3  0.5, 4  0.5, 5  0.5 /
LLbA(mm)        Length of the buffer area located on segment "mm" of the on-ramp for ACTs (km)
```

/ 1 0.5, 2 0.5, 3 0.5 /
LLbM(mm) Length of the buffer area located on segment "mm" of the on-ramp for MDVs (km)
/ 1 0.5, 2 0.5, 3 0.5 /
NLA(m) Number of parking lanes created in the buffer area which is located on segment "m" of the DFL for ACTs
/ 1 0, 2 2, 3 0, 4 0, 5 0 /
NNLA(mm) Number of parking lanes in the buffer area which is located on segment "mm" of the on-ramp for ACTs
/ 1 0, 2 2, 3 0 /
NNLM(mm) Number of parking lanes in the buffer area which is located on segment "mm" of the on-ramp for MDVs
/ 1 0, 2 2, 3 0 /
kiA(m) Initial density of ACTs on segment m of the DFL
/ 1 1, 2 1, 3 1, 4 1, 5 1 /
kkiA(mm) Initial density of ACTs on segment mm of the on-ramp
/ 1 1, 2 1, 3 1 /
kiM(m) Initial density of MDVs on segment m of the mainline
/ 1 1, 2 1, 3 1, 4 1, 5 1 /
kkiM(mm) Initial density of MDVs on segment mm of the on-ramp
/ 1 1, 2 1, 3 1 /
kbiA(m) Initial density of ACTs in the buffer 'm' of the DFL
/ 1 0, 2 0, 3 0, 4 0, 5 0 /
kkbiA(mm) Initial density of ACTs in the buffer 'mm' of the on-ramp
/ 1 0, 2 0, 3 0 /
kkbiM(mm) Initial density of MDVs in the buffer 'mm' of the on-ramp
/ 1 0, 2 0, 3 0 /

**Scalars**

| | | |
|---|---|---|
| dt | Time interval(seconds) | / 10/ |
| TP | Total time period(seconds) | / 900 / |
| VfA | Free flow speed of the ACTs | / 88/ |
| VfM | Free flow speed of the MDVs | / 120/ |
| KmaxA | Maximum density of ACTs | / 60/ |
| KmaxM | Maximum density of MDVs | / 120/ |
| KcrAD | Critical density of ACTs on the DFL | / 18/ |
| KcrAR | Critical density of ACTs on the on-ramp | / 18/ |
| KcrM | Critical density of MDVs | / 60/ |
| tow | Time constant for relaxation term (seconds) | / 20.4/ |
| beta1 | Reduction factor for measuring capacity at the on-ramp for the flow of ACTs | / 0.75/ |
| beta2 | Reduction factor for measuring capacity at the on-ramp for the flow of MDVs | / 0.65 / |
| GAMMA | Reduction factor indicating non-applicable places in a buffer area for parking of vehicles | / 0.8/ |
| LA | Average length of an ACT (m) | / 15 / |
| LM | Average length of a MDV (m) | / 5 / |

**Scalars** nsDFL, nsRAMP, NumTIME "Number of segments on the DFL, Number of segments of the on-ramp, Number of time intervals";
NSdfl=smax(m,ord(m)) ;
NSramp=smax(mm,ord(mm));
NumTime=smax(t,ord(t));

**scalars** LenDFL, LenRAMP, LenBA, LenBAA, LenBMM "Length of the DFL, Length of the on-ramp, Length of the mainline buffer, Length of the on-ramp buffer for ACTs, Length of the on-ramp buffer for MDVs";
LenDFL=NSdfl*l("1");
LenRAMP=NSramp*ll("1");
LenBA=1*LbA("2");
LenBAA=1*LLbA("2");
LenBMM=1*LLbM("2");

**parameter** viA(m) ;
viA(m)= VfA*exp(-0.5*power((kiA(m)/KcrAD),2)) ;
**parameter** vbiA(m) ;
vbiA(m)= 0.1 ;
**parameter** vviA(mm) ;
vviA(mm)= VfA*exp(-0.5*power((kkiA(mm)/KcrAR),2)) ;
**parameter** vvbiA(mm) ;
vvbiA(mm)= 0.1 ;
**parameter** viM(m) ;
viM(m)= VfM*exp(-0.5*power((kiM(m)/KcrM),2)) ;
**parameter** vviM(mm) ;
vviM(mm)= VfM*exp(-0.5*power((kkiM(mm)/KcrM),2)) ;
**parameter** vvbiM(mm) ;

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      vvbiM(mm)= 0.1 ;

parameter  qiA(m) ;
      qiA(m)= kiA(m)*viA(m);
parameter  siA(m) ;
      siA(m)= kbiA(m)*vbiA(m);
parameter  qqiA(mm) ;
      qqiA(mm)= kkiA(mm)*vviA(mm);
parameter  ssiA(mm) ;
      ssiA(mm)= kkbiA(mm)*vvbiA(mm);
parameter  qiM(m) ;
      qiM(m)= kiM(m)*viM(m);
parameter  qqiM(mm) ;
      qqiM(mm)= kkiM(mm)*vviM(mm);
parameter  ssiM(mm) ;
      ssiM(mm)= kkbiM(mm)*vvbiM(mm);

Variables
vA(m,t)             speed of ACTs in segment m of the DFL at time instant t
vbA(m,t)            speed of ACTs in the buffer m of the DFL at time instant t
vvA(mm,t)           speed of ACTs in segment mm of the on-ramp at time instant t
vvbA(mm,t)          speed of ACTs in the buffer mm of the on-ramp at time instant t
vM(m,t)             speed of MDVs in segment m of the mainline at time instant t
vvM(mm,t)           speed of MDVs in segment mm of the on-ramp at time instant t
vvbM(mm,t)          speed of MDVs in the buffer mm of the on-ramp at time instant t
kA(m,t)             density of ACTs in segment m of the DFL at time instant t
kbA(m,t)            density of ACTs in the buffer m of the DFL at time instant t
kkA(mm,t)           density of ACTs in segment mm of the on-ramp at time instant t
kkbA(mm,t)          density of ACTs in the buffer mm of the on-ramp at time instant t
kM(m,t)             density of MDVs in segment m of the on-ramp at time instant t
kbM(m,t)            density of MDVs in the buffer m of the on-ramp at time instant t
kkM(mm,t)           density of MDVs in segment mm of the on-ramp at time instant t
kkbM(mm,t)          density of MDVs in the buffer mm of the on-ramp at time instant t
veA(m,t)            equilibrium speed of ACTs in segment m of the DFL while density kA at time instant t
vebA(m,t)           equilibrium speed of ACTs in the buffer m of the DFL while density kbA at time instant t
vveA(mm,t)          equilibrium speed of ACTs in segment mm of the on-ramp while density kkA at time instant t
vvebA(mm,t)         equilibrium speed of ACTs in thr buffer mm of the on-ramp while density kkbA at time instant t
veM(m,t)            equilibrium speed of MDVs in segment m of the mainline while density kM at time instant t
vveM(mm,t)          equilibrium speed of MDVs in segment mm of the on-ramp while density kkM at time instant t
vvebM(mm,t)         equilibrium speed of MDVs in the buffer mm of the on-ramp while density kkbM at time instant t
qA(m,t)             traffic flow of ACTs in segment m of the DFL at time instant t
qqA(mm,t)           traffic flow of ACTs in segment mm of the on-ramp at time instant t
qM(m,t)             traffic flow of MDVs in segment m of the mainline at time instant t
qqM(mm,t)           traffic flow of MDVs in segment mm of the on-ramp at time instant t
rA(m,t)             input flow of ACTs to the buffer area located on segment m of the DFL at time instant t
rrA(mm,t)           input flow of ACTs to the buffer area located on segment mm of the on-ramp at time instant t
rrM(mm,t)           input traffic flow of MDVs to the on-ramp's buffer assigned to the MDVs at time instant t
alphaA(m,t)         share of directed flow of ACTs to the parking area in buffer m at time instant t
alphaAA(mm,t)       share of directed flow of ACTs to the parking area in buffer mm of the on-ramp at time instant t
alphaMM(mm,t)       share of directed flow of MDVs to the parking area in buffer mm of the on-ramp at time instant t
sA(m,t)             input traffic flow of ACTs to segment m of the DFL at time instant t
ssA(mm,t)           input traffic flow of ACTs to segment mm of the on-ramp at time instant t
ssM(mm,t)           output traffic flow of MDVs from on-ramp buffer of MDVs on the segment "mm" at time instant t
IoutbA(m,t)         output flow of ACTs from parking area of buffer m on the DFL at time instant t
IoutbbA(mm,t)       output flow of ACTs from parking area of buffer mm on the on-ramp at time instant t
IoutbbM(mm,t)       output flow of MDVs from parking area of buffer mm on the on-ramp at time instant t
ATT                 average travel time per vehicle (ACT+MDV)in the layout  ;

positive variables  vA,vM,vvA,vvM,kA,kM,kkA,kkM,veA,veM,vveA,vveM,qA,qM,qqA,qqM,rA,rrA,rM,rrM,sA,ssA,sM,ssM  ;
positive variables  vbA,vvbA,vvbM,kbA,kkbA,kkbM,vebA,vvebA,vvebM  ;
positive variables  IoutbA,IoutbbA,IoutbbM,alphaA,alphaAA,alphaMM  ;

equations

attime               Objective function
densityDA(m,t)       Conservation of flow of ACTs in the segment m of the DFL
densityDbA(m,t)      Conservation of flow of ACTs in the buffer m of the DFL
densityDM(m,t)       Conservation of flow of MDVs in the segment m of the mainline
densityRA(mm,t)      Conservation of flow of ACTs in the segment mm of the on-ramp
```

| | |
|---|---|
| densityRbA(mm,t) | Conservation of flow of ACTs in the buffer mm of the on-ramp |
| densityRM(mm,t) | Conservation of flow of MDVs in the segment mm of the on-ramp |
| densityRbM(mm,t) | Conservation of flow of MDVs in the buffer mm of the on-ramp |
| maxdenDA(m,t) | Maximum allowable density of ACTs in the segment m of the DFL |
| maxdenDbA(m,t) | Maximum allowable density of ACTs in the buffer m of the DFL |
| maxdenDM(m,t) | Maximum allowable density of MDVs in the segment m of the mainline |
| maxdenRA(mm,t) | Maximum allowable density of ACTs in the segment mm of the on-ramp |
| maxdenRbA(mm,t) | Maximum allowable density of ACTs in the buffer mm of the on-ramp |
| maxdenRM(mm,t) | Maximum allowable density of MDVs in the segment mm of the on-ramp |
| maxdenRbM(mm,t) | Maximum allowable density of MDVs in the buffer mm of the on-ramp |
| spdenDA(m,t) | Speed-density relation in the segment m of the DFL at time instant t |
| spdenDbA(m,t) | Speed-density relation in the buffer m of the DFL at time instant t |
| spdenDM(m,t) | Speed-density relation for MDVs in the segment m of the mainline at time instant t |
| spdenRA(mm,t) | Speed-density relation for ACTs in the segment mm of the on-ramp at time instant t |
| spdenRbA(mm,t) | Speed-density relation for ACTs in the buffer mm of the on-ramp at time instant t |
| spdenRM(mm,t) | Speed-density relation for MDVs in the segment mm of the on-ramp at time instant t |
| spdenRbM(mm,t) | Speed-density relation for MDVs in the buffer mm of the on-ramp at time instant t |
| speedDA(m,t) | Speed of ACTs in the segment m of the DFL at time instant t |
| speedDbA(m,t) | Speed of ACTs in the buffer m of the DFL at time instant t |
| speedDM(m,t) | Speed of MDVs in the segment m of the mainline at time instant t |
| speedRA(mm,t) | Speed of ACTs in the segment mm of the on-ramp at time instant t |
| speedRbA(mm,t) | Speed of ACTs in the buffer mm of the on-ramp at time instant t |
| speedRM(mm,t) | Speed of MDVs in the segment mm of the on-ramp at time instant t |
| speedRbM(mm,t) | Speed of MDVs in the buffer mm of the on-ramp at time instant t |
| maxspDA(m,t) | Maximum allowable speed of ACTs in the segment m of the DFL at time instant t |
| maxspDbA(m,t) | Maximum allowable speed of ACTs in the buffer m of the DFL at time instant t |
| maxspDM(m,t) | Maximum allowable speed of MDVs in the segment m of the mainline at time instant t |
| maxspRA(mm,t) | Maximum allowable speed of ACTs in the segment mm of the on-ramp at time instant t |
| maxspRbA(mm,t) | Maximum allowable speed of ACTs in the buffer mm of the on-ramp at time instant t |
| maxspRM(mm,t) | Maximum allowable speed of MDVs in the segment mm of the on-ramp at time instant t |
| maxspRbM(mm,t) | Maximum allowable speed of MDVs in the buffer mm of the on-ramp at time instant t |
| flowDA(m,t) | Output flow of ACTs from the segment m of the DFL at time instant t |
| flowDbA(m,t) | Output flow of ACTs from the buffer m of the DFL at time instant t |
| flowDM(m,t) | Output flow of MDVs from the segment m of the mainline at time instant t |
| flowRA(mm,t) | Output flow of ACTs from the segment mm of the on-ramp at time instant t |
| flowRbA(mm,t) | Output flow of ACTs from the buffer mm of the on-ramp at time instant t |
| flowRM(mm,t) | Output flow of ACTs from the segment mm of the on-ramp at time instant t |
| flowRbM(mm,t) | Output flow of ACTs from the buffer mm of the on-ramp at time instant t |
| maxflowDA(m,t) | Maximum allowable flow of ACTs in the segment m of the DFL at time instant t |
| maxflowDbA(m,t) | Maximum allowable flow of ACTs in the buffer m of the DFL at time instant t |
| maxflowDM(m,t) | Maximum allowable flow of MDVs in the segment m of the mainline at time instant t |
| maxflowRA(mm,t) | Maximum allowable flow of ACTs in the segment mm of the on-ramp at time instant t |
| maxflowRbA(mm,t) | Maximum allowable flow of ACTs in the buffer mm of the on-ramp at time instant t |
| maxflowRM(mm,t) | Maximum allowable flow of MDVs in the segment mm of the on-ramp at time instant t |
| maxflowRbM(mm,t) | Maximum allowable flow of MDVs in the buffer mm of the on-ramp at time instant t |
| safemergedMA(t) | Ensuring the safe merge conditions |
| INVconsDA(m,t) | Inventory control of stored ACTs in the buffer area m of the DFL at time instant t |
| INVconsRA(mm,t) | Inventory control of stored ACTs in the buffer area mm of the on-ramp at time instant t |
| INVconsRM(mm,t) | Inventory control of stored MDVs in the buffer area mm of the on-ramp at time instant t |
| MaxrA(m,t) | Maximum allowable input flow to the mainline buffers for ACTs |
| MaxrrA(mm,t) | Maximum allowable input flow to the on-ramp buffers for ACTs |
| MaxrrM(mm,t) | Maximum allowable input flow to the on-ramp buffers for MDVs |
| DISparDA(m) | Discharge of parking area of ACTs in the buffer m of the DFL |
| DISparRA(mm) | Discharge of parking area of ACTs in the buffer mm of the on-ramp |
| DISparRM(mm) | Discharge of parking area of MDVs in the buffer mm of the on-ramp |
| DISbufDA(m) | Discharge of the buffer of ACTs on the segment m of the DFL |
| DISbufRA(mm) | Discharge of the buffer of ACTs on the segment mm of the on-ramp |
| DISbufRM(mm) | Discharge of the buffer of MDVs on the segment mm of the on-ramp |
| CapbufDA(m,t) | Capacity of the buffer area m on the DFL for ACTs |
| CapbufRA(mm,t) | Capacity of the buffer area mm on the on-ramp for ACTs |
| CapbufRM(mm,t) | Capacity of the buffer area mm on the on-ramp for MDVs |
| yesnobufferDA(m,t) | Existing of a buffer in the segment m of the DFL for ACTs |
| yesnobufferRA(mm,t) | Existing of a buffer in the segment mm of the on-ramp for ACTs |
| yesnobufferRM(mm,t) | Existing of a buffer in the segment mm of the on-ramp for MDVs |
| Dispers1(m,t) | Share of directed ACTs to the parking area in the buffer m on the DFL at time instant t |
| Dispers3(mm,t) | Share of directed ACTs to the parking area in the buffer mm on the on-ramp at time instant t |
| Dispers4(mm,t) | Share of directed MDVs to the parking area in the buffer mm on the on-ramp at time instant t ; |

```
attime          ..    ATT=e=(( (sum (m,sum(t,kA(m,t)*l (m))))/{LenDFL*1000  / {[sum(m,sum (t,vA(m,t))) / (NSdfl*
                      NumTime)] *dt*1000/3600}} * ((((LenDFL)/( (sum(m,sum(t,vA(m,t))))/(NSdfl*NumTime) ))*3600))
                      +
                      (sum(m,sum (t,kbA(m,t)*lbA(m))))/{ LenBA*1000 / {[sum(m,sum (t,vbA(m,t))) /(1*NumTime)]
                      *dt*1000/3600}} * ((((LenBA)/ ( (sum(m,sum(t,vbA(m,t))))/(1*NumTime)  ))*3600))
                      +
                       (sum(m,sum(t,kM(m,t)*l (m))))/{ LenDFL*1000/ {[sum(m,sum(t,vM(m,t)))/ (NSdfl*NumTime)]
                      *dt*1000/3600}} * ((((LenDFL)/ ( (sum(m,sum(t,vM(m,t))))/(NSdfl*NumTime)  ))*3600))
                      +
                      (sum(mm,sum(t,kkA(mm,t)*ll(mm))))/{ LenRAMP*1000 / {[sum(mm,sum(t,vvA(mm,t)))/ (NSramp*
                      NumTime)]*dt*1000/3600}} *  ((((LenRAMP)/ ( (sum(mm,sum (t,vvA(mm,t))))/ (NSramp*NumTime)
                      ))*3600))
                      +
                      (sum(mm,sum(t,kkbA(mm,t)*llbA(mm))))/{ LenBAA*1000 / {[sum(mm,sum(t,vvbA(mm,t)))/
                      (1*NumTime)]*dt*1000/3600}} * ((((LenBAA)/( (sum(mm,sum(t,vvbA(mm,t))))/ (1*NumTime)
                      ))*3600))
                      +
                      (sum(mm,sum(t,kkM(mm,t)*ll(mm))))/{ LenRAMP*1000 / {[sum(mm,sum(t,vvM(mm,t)))/
                      (NSramp*NumTime)]*dt*1000/3600}} *((((LenRAMP)/ ( (sum (mm,sum(t,vvM(mm,t))))/
                      (NSramp*NumTime) ))*3600))
                      +
                      (sum(mm,sum(t,kkbM(mm,t)*llbM(mm))))/{ LenBMM*1000 / {[sum(mm,sum(t,vvbM(mm,t)))/
                      (1*NumTime)]*dt*1000/3600}} * ((((LenBMM)/ ( (sum(mm,sum(t,vvbM(mm,t)))) /(1*NumTime)
                      ))*3600)) )
                      +
                      ( (sum(m,sum(t,(sum(at$(ord(at) le ord(t)),((1-alphaA(m,at))*rA(m,at)-IoutbA(m,at))*(dt/3600)*dt)))))
                      +
                      (sum(mm,sum(t,(sum(at$(ord (at) le ord(t)),((1-alphaAA(mm,at))*rrA(mm,at)-IoutbbA(mm,at ))*
                      (dt/3600)*dt)))))
                      +
                      (sum(mm,sum(t,(sum(at$(ord(at) le ord(t)),((1-alphaMM(mm,at))*rrM(mm,at)-IoutbbM(mm,at))*
                      (dt/3600)*dt)))))) )
                      /
                      ((sum(m,sum(t,kA(m,t)*l(m))))/{ LenDFL*1000/ {[sum(m,sum (t,vA(m,t)))/(NSdfl *NumTime)] *
                      dt*1000/3600}}
                      +
                      (sum(mm,sum(t,kkA(mm,t)*ll(mm))))/{ LenRAMP*1000 / {[sum(mm,sum(t,vvA(mm,t)))/
                      (NSramp*NumTime)] *dt*1000/3600}}
                      +
                      (sum(m,sum(t,kM(m,t)*l(m))))/{ LenDFL*1000 / {[sum(m,sum(t,vM(m,t)))/ (NSdfl*NumTime)]
                      *dt*1000/3600}}
                      +
                      (sum(mm,sum(t,kkM(mm,t)*ll(mm))))/{ LenRAMP*1000 / {[sum(mm,sum(t,vvM(mm,t)))/
                      (NSramp*NumTime)]*dt*1000/3600}} )  ;

densityDA(m,t)    ..  kA(m,t) =e= kiA(m) $ (ORD(t) eq 1)+   (kA(m,t-1)+(dt/(L(m)*3600))*((qA(m-1,t-1) $ (ord(m) ne 1)+
                          DACTD(t-1) $ (ord(m) eq 1))-qA(m,t-1)-rA(m,t-1)+sA(m,t-1)+(qqA("3",t-1) $ (ord(m) eq
                          3)+ 0 $ (ord(m)ne 3)))) $ (ORD(t) ne 1);

densityDbA(m,t)   ..  kbA(m,t) =e= 0 $ ((ord(m) ne 2) )+          (kbiA(m) $ (ORD(t) eq 1)+ (kbA(m,t-1)+ (dt/ (LbA(m) *
                          3600 ))*(alphaA(m,t-1)*rA(m,t-1)-sA(m,t-1)+IoutbA(m,t-1) )) $ (ORD(t) ne 1)) $
                          ((ord(m) eq 2));

densityDM(m,t)    ..  kM(m,t) =e= kiM(m) $ (ORD(t) eq 1)+(kM(m,t-1)+(dt/(L(m)*3600))*((qM(m-1,t-1) $ (ord(m) ne 1)+
                          DMDVD(t-1) $ (ord(m) eq 1))-qM(m,t-1)+(qqM("3",t-1) $ (ord(m) eq 3)+ 0 $ (ord(m)ne
                          3))))$(ORD(t) ne 1);

densityRA(mm,t)   ..  kkA(mm,t) =e=  kkiA(mm) $ (ORD(t) eq 1)+(kkA(mm,t-1)+(dt/(LL(mm)*3600))*((qqA(mm-1,t-1) $
                          (ord(mm)ne 1)+ DACTR(t-1) $ (ord(mm) eq 1))-qqA(mm,t-1)-rrA(mm,t-1)+ssA(mm,t-
                          1))) $ (ORD(t) ne 1);

densityRbA(mm,t)  ..  kkbA(mm,t) =e= 0 $ (ord(mm) ne 2)+ kkbiA(mm)$(ORD(t) eq 1)+ ((kkbA(mm,t-1)+ (dt/ (LlbA (mm) *
                          3600))*(alphaAA(mm,t-1)*rrA(mm,t-1)-ssA(mm,t-1)+IoutbbA(mm,t-1) )) $ (ORD(t) ne
                          1)) $ (ord(mm) eq 2);

densityRM(mm,t)   ..  kkM(mm,t) =e= kkiM(mm) $ (ORD(t) eq 1)+(kkM(mm,t-1)+(dt/(LL(mm)*3600))*((qqM(mm-1,t-1) $
                          (ord(mm)ne 1)+DMDVR(t-1) $ (ord(mm) eq 1))-qqM(mm,t-1)-rrM(mm,t-1)+ssM(mm,t-
                          1))) $ (ORD(t) ne 1);
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```
densityRbM(mm,t)   ..   kkbM(mm,t) =e= 0 $ (ord(mm) ne 2)+ ( kkbiM(mm) $ (ORD(t) eq 1)+(kkbM(mm,t-1)+
                          (dt/ (LLbM(mm)*3600))*(alphaMM(mm,t-1)*rrM(mm,t-1)-ssM(mm,t-1)+
                          IoutbbM(mm,t-1))) $ (ORD(t) ne 1))$ (ord(mm) eq 2);

maxdenDA(m,t)      ..   kA(m,t) =l= KmaxA  ;
maxdenDbA(m,t)     ..   kbA(m,t) =l= KmaxA ;
maxdenDM(m,t)      ..   kM(m,t) =l= KmaxM  ;
maxdenRA(mm,t)     ..   kkA(mm,t) =l= KmaxA ;
maxdenRbA(mm,t)    ..   kkbA(mm,t) =l= KmaxA ;
maxdenRM(mm,t)     ..   kkM(mm,t) =l= KmaxM ;
maxdenRbM(mm,t)    ..   kkbM(mm,t) =l=KmaxM ;

spdenDA(m,t)       ..   veA(m,t) =e= VfA*exp(-0.5*power((kA(m,t)/KcrAD),2)) ;
spdenDbA(m,t)      ..   vebA(m,t) =e= VfA*exp(-0.5*power((kbA(m,t)/KcrAD),2)) ;
spdenDM(m,t)       ..   veM(m,t) =e= VfM*exp(-0.5*power((kM(m,t)/KcrM),2)) ;
spdenRA(mm,t)      ..   vveA(mm,t) =e= VfA*exp(-0.5*power((kkA(mm,t)/KcrAR),2)) ;
spdenRbA(mm,t)     ..   vvebA(mm,t) =e= VfA*exp(-0.5*power((kkbA(mm,t)/KcrAR),2)) ;
spdenRM(mm,t)      ..   vveM(mm,t) =e= VfM*exp(-0.5*power((kkM(mm,t)/KcrM),2)) ;
spdenRbM(mm,t)     ..   vvebM(mm,t) =e= VfM*exp(-0.5*power((kkbM(mm,t)/KcrM),2)) ;

speedDA(m,t)       ..   vA(m,t) =e= viA(m) $ (ORD(t) eq 1)+(vA(m,t-1)+(dt/tow)*(veA(m,t-1)-vA(m,t-1))+(dt/(L(m)* 3600))
                          *vA(m,t-1)*((vA(m-1,t-1)-vA(m,t-1))$(ord(m) ne 1) +0$(ord(m) eq 1)))$(ORD(t) ne 1) ;

speedDbA(m,t)      ..   vbA(m,t) =e= vbiA(m)$(ORD(t) eq 1)+(vbA(m,t-1)+(dt/tow)*(vebA(m,t-1)-vbA(m,t-1))+
                          (dt/(LbA(m)*3600))*vbA(m,t-1)*((vbA(m-1,t-1)-vbA(m,t-1))$(ord(m) ne 1)
                          +0$(ord(m) eq 1) ))$(ORD(t) ne 1);

speedDM(m,t)       ..   vM(m,t) =e= viM(m)$(ORD(t) eq 1)+(vM(m,t-1)+(dt/tow)*(veM(m,t-1)-vM(m,t-1))+
                          (dt/(L(m)*3600))*vM( m,t-1)*((vM(m-1,t-1)-vM(m,t-1))$(ord(m) ne 1)
                          +0$(ord(m) eq 1)))$(ORD(t) ne 1) ;

speedRA(mm,t)      ..   vvA(mm,t) =e= vviA(mm)$(ORD(t) eq 1)+(vvA(mm,t-1)+(dt/tow)*(vveA(mm,t-1)-vvA(mm,t-1))+
                          (dt/(LL(mm)*3600))*vvA(mm,t-1)*((vvA(mm-1,t-1)-vvA(mm,t-1))$(ord(mm) ne 1)
                          +0$(ord(mm) eq 1)))$(ORD(t) ne 1) ;

speedRbA(mm,t)     ..   vvbA(mm,t) =e= vvbiA(mm)$(ORD(t) eq 1)+(vvbA(mm,t-1)+(dt/tow)*(vvebA(mm,t-1)-vvbA(mm,t-
                          1))+(dt/(LLbA(mm)*3600))*vvbA(mm,t-1)*((vvbA(mm-1,t-1)-vvbA(mm,t-1))$(ord(mm)
                          ne 1) +0$(ord(mm) eq 1)))$(ORD(t) ne 1) ;

speedRM(mm,t)      ..   vvM(mm,t) =e= vviM(mm)$(ORD(t) eq 1)+(vvM(mm,t-1)+(dt/tow)*(vveM(mm,t-1)-vvM(mm,t-1))+
                          (dt/(LL(mm)*3600))*vvM(mm,t-1)*((vvM(mm-1,t-1)-vvM(mm,t-1))$(ord(mm) ne 1)
                          +0$(ord(mm) eq 1)))$(ORD(t) ne 1) ;

speedRbM(mm,t)     ..   vvbM(mm,t) =e= vvbiM(mm)$(ORD(t) eq 1)+(vvbM(mm,t-1)+(dt/tow)*(vvebM(mm,t-1)-vvbM(mm,t-
                          1))+(dt/(LLbM(mm)*3600))*vvbM(mm,t-1)*((vvbM(mm-1,t-1)-vvbM(mm,t-
                          1))$(ord(mm) ne 1) +0$(ord(mm) eq 1)))$(ORD(t) ne 1);

maxspDA(m,t)       ..   vA(m,t) =l= VfA ;
maxspDbA(m,t)      ..   vbA(m,t) =l= VfA ;
maxspDM(m,t)       ..   vM(m,t) =l= VfM ;
maxspRA(mm,t)      ..   vvA(mm,t) =l= VfA ;
maxspRbA(mm,t)     ..   vvbA(mm,t) =l= VfA ;
maxspRM(mm,t)      ..   vvM(mm,t) =l= VfM ;
maxspRbM(mm,t)     ..   vvbM(mm,t) =l= VfM ;

flowDA(m,t)        ..   qA(m,t) =e= kA(m,t)*vA(m,t) ;
flowDbA(m,t)       ..   sA(m,t) =e= 0$(ord(m) ne 2 )+(kbA(m,t)*vbA(m,t))$(ord(m) eq 2 ) ;
flowDM(m,t)        ..   qM(m,t) =e= kM(m,t)*vM(m,t) ;
flowRA(mm,t)       ..   qqA(mm,t) =e= kkA(mm,t)*vvA(mm,t) ;
flowRbA(mm,t)      ..   ssA(mm,t) =e= 0$(ord(mm) ne 2)+(kkbA(mm,t)*vvbA(mm,t))$(ord(mm) eq 2) ;
flowRM(mm,t)       ..   qqM(mm,t) =e= kkM(mm,t)*vvM(mm,t) ;
```

```
flowRbM(mm,t)       ..    ssM(mm,t) =e= 0$(ord(mm) ne 2)+(kkbM(mm,t)*vvbM(mm,t))$(ord(mm) eq 2) ;

maxflowDA(m,t)       ..    qA(m,t) =l=  KcrAD*VfA*exp(-0.5);
maxflowDbA(m,t)      ..    sA(m,t) =l= KcrAD*VfA*exp(-0.5);
maxflowDM(m,t)       ..    qM(m,t) =l= KcrM*VfM*exp(-0.5);
maxflowRA(mm,t)      ..    qqA(mm,t) =l= KcrAR*VfA*exp(-0.5);
maxflowRbA(mm,t)     ..    ssA(mm,t) =l= KcrAR*VfA*exp(-0.5);
maxflowRM(mm,t)      ..    qqM(mm,t) =l= KcrM*VfM*exp(-0.5) ;
maxflowRbM(mm,t)     ..    ssM(mm,t) =l= KcrM*VfM*exp(-0.5) ;

safemergedMA(t)      ..    qA("3",t)+qqM("3",t) =l= beta1*DACTD(t)+beta2*DMDVR(t) ;

INVconsDA(m,t)       ..    IoutbA(m,t) =l= 0 $ ((ord(m) ne 2) )+(sum (at $ (ord(at) lt ord(t)),((1-alphaA(m,at))*rA(m,at)-IoutbA
                                  (m,at )))) $ ((ord(m) eq 2));

INVconsRA(mm,t)      ..    IoutbbA(mm,t) =l= 0 $ (ord(mm) ne 2)+(sum(at $ (ord(at) lt ord(t)),((1-alphaAA(mm,at))*rrA(mm,at)-
                                  IoutbbA(mm,at)))) $ (ord(mm) eq 2);

INVconsRM(mm,t)      ..    IoutbbM(mm,t) =l= 0 $ (ord(mm) ne 2)+(sum(at $ (ord(at) lt ord(t)),((1-alphaMM(mm,at))*rrM(mm,at)
                                  -IoutbbM(mm,at))))  $ (ord(mm) eq 2);

MaxrA(m,t)           ..    rA(m,t) =l= qA(m-1,t)$(ord(m) ne 1)+DACTD(t)$(ord(m) eq 1) ;
MaxrrA(mm,t)         ..    rrA(mm,t) =l= qqA(mm-1,t)$(ord(mm) ne 1)+DACTR(t)$(ord(mm) eq 1) ;
MaxrrM(mm,t)         ..    rrM(mm,t) =l= qqM(mm-1,t)$(ord(mm) ne 1)+DMDVR(t)$(ord(mm) eq 1) ;

DISparDA(m)          ..    sum(t,IoutbA(m,t)) =e= sum (t,(1-alphaA(m,t))*rA(m,t)) ;
DISparRA(mm)         ..    sum(t,IoutbbA(mm,t)) =e= sum (t,(1-alphaAA(mm,t))*rrA(mm,t)) ;
DISparRM(mm)         ..    sum(t,IoutbbM(mm,t)) =e= sum (t,(1-alphaMM(mm,t))*rrM(mm,t)) ;

DISbufDA(m)          ..    sum(t,sA(m,t)) =e= sum (t,rA(m,t)) ;
DISbufRA(mm)         ..    sum(t,ssA(mm,t)) =e= sum (t,rrA(mm,t)) ;
DISbufRM(mm)         ..    sum(t,ssM(mm,t)) =e= sum (t,rrM(mm,t)) ;

CapbufDA(m,t)        ..    sum(at$(ord(at) le ord(t)),(((1-alphaA(m,at))*rA(m,at)-IoutbA(m,at))*dt/3600)) =l=
                                        LbA(m)*1000*NLA(m)*GAMMA/LA ;

CapbufRA(mm,t)       ..    sum(at$(ord(at) le ord(t)),(((1-alphaAA(mm,at))*rrA(mm,at)-IoutbbA(mm,at))*dt/3600)) =l=
                                        LLbA(mm)*1000*NNLA(mm)*GAMMA/LA ;

CapbufRM(mm,t)       ..    sum(at$(ord(at) le ord(t)),(((1-alphaMM(mm,at))*rrM(mm,at)-IoutbbM(mm,at))*dt/3600)) =l=
                                        LLbM(mm)*1000*NNLM(mm)*GAMMA/LM ;

yesnobufferDA(m,t)   ..    rA(m,t)$( (ORD(m) ne 2) or (ord(t) eq 1)) =e= 0;
yesnobufferRA(mm,t)  ..    rrA(mm,t)$( (ORD(mm) ne 2) or (ord(t) eq 1)) =e= 0;
yesnobufferRM(mm,t)  ..    rrM(mm,t)$( (ORD(mm) ne 2) or (ord(t) eq 1)) =e= 0;

Dispers1(m,t)        ..    alphaA(m,t)  =l= 0$((ord(m) ne 2))+  1 $((ord(m) eq 2))  ;
Dispers3(mm,t)       ..    alphaAA(mm,t) =l= 0$(ord(mm) ne 2)+  1 $(ord(mm) eq 2)  ;
Dispers4(mm,t)       ..    alphaMM(mm,t) =l= 0$(ord(mm) ne 2)+  1 $(ord(mm) eq 2)  ;

model New /all/;
option limrow = 0, limcol = 0 ;
option solprint=off ;
option iterlim = 100000;
option reslim = 100000 ;

kA.l(m,t)=7.2 ;  kM.l(m,t)=12.5 ;  kkA.l(mm,t)=1.1 ;  kkM.l(mm,t)=3.3 ;
kbA.l(m,t)=1 ;  kkbA.l(mm,t)=0 ;  kkbM.l(mm,t)=0 ;
veA.l(m,t)=81 ;  veM.l(m,t)=110 ;  vveA.l(mm,t)=87.8 ;  vveM.l(mm,t)=119 ;
vebA.l(m,t)=88 ;  vvebA.l(mm,t)=87 ;  vvebM.l(mm,t)=120 ;
vA.l(m,t)=81 ;  vM.l(m,t)=110 ;  vvA.l(mm,t)=87.8 ;  vvM.l(mm,t)=119 ;
```

```
vbA.l(m,t)=70 ;  vvbA.l(mm,t)=72 ;   vvbM.l(mm,t)=90 ;
qA.l(m,t)=600 ;   qM.l(m,t)=1400 ;  qqA.l(mm,t)=100 ;   qqM.l(mm,t)=400 ;
rA.up(m,t)=800 ;  rrA.up(mm,t)=160 ;   rrM.up(mm,t)=640 ;
IoutbA.l(m,t)=0 ; IoutbbA.l(mm,t)=0 ; IoutbbM.l(mm,t)=0 ;
vA.lo(m,t)=.01 ;  kA.lo(m,t)=.1 ;
vM.lo(m,t)=.01 ;  kM.lo(m,t)=.1 ;
vvA.lo(mm,t)=.01 ; kkA.lo(mm,t)=.1 ;
vvM.lo(mm,t)=.01 ; kkM.lo(mm,t)=.1 ;

vbA.lo(m,t)=.1 ;
vvbA.lo(mm,t)=.1 ;
vvbM.lo(mm,t)=.1 ;

New.optfile=1;
option nlp=conopt3;
solve New using nlp minimizing ATT ;

display kA.l, kM.l,kkA.l,kkM.l,kbA.l, kkbA.l,kkbM.l,veA.l,veM.l, vveA.l,vveM.l,vebA.l,vvebA.l,vvebM.l ;
display vA.l,vM.l,vvA.l, vvM.l,vbA.l,vvbA.l, vvbM.l,qA.l,qM.l,qqA.l,qqM.l, rA.l,sA.l,rrA.l,ssA.l,rrM.l,ssM.l;
display IoutbA.l,IoutbbA.l,IoutbbM.l,alphaA.l,alphaAA.l,alphaMM.l;
display ATT.l ;

parameters IinbA(m,t), IinbbA(mm,t), IinbbM(mm,t) ;

IinbA(m,t)=(1-alphaA.l(m,t))*rA.l(m,t) ;
IinbbA(mm,t)=(1-alphaAA.l(mm,t))*rrA.l(mm,t) ;
IinbbM(mm,t)=(1-alphaMM.l(mm,t))*rrM.l(mm,t) ;

display IinbA,IinbbA,IinbbM ;

parameter vmeanAD(m); parameter vmeanAR(mm); parameter vmeanMD(m); parameter vmeanMR(mm);
parameter vaveAD(t); parameter vaveAR(t); parameter vaveMD(t); parameter vaveMR(t);
parameter vaveADFL; parameter vaveARAMP;parameter vaveMDFL; parameter vaveMRAMP;

VmeanAD(m)=sum(t$(ord(t) ne 1),vA.l(m,t))/smax(t,ord(t)) ;
VmeanAR(mm)=sum(t$(ord(t) ne 1),vvA.l(mm,t))/smax(t,ord(t)) ;
VmeanMD(m)=sum(t$(ord(t) ne 1),vM.l(m,t))/smax(t,ord(t)) ;
VmeanMR(mm)=sum(t$(ord(t) ne 1),vvM.l(mm,t))/smax(t,ord(t)) ;

VaveAD(t)=sum(m,vA.l(m,t))$(ord(t) ne 1)/smax(m,ord(m)) ;
VaveAR(t)=sum(mm,vvA.l(mm,t))$(ord(t) ne 1)/smax(mm,ord(mm)) ;
VaveMD(t)=sum(m,vM.l(m,t))$(ord(t) ne 1)/smax(m,ord(m)) ;
VaveMR(t)=sum(mm,vvM.l(mm,t))$(ord(t) ne 1)/smax(mm,ord(mm)) ;

VaveADFL=SUM(t$(ord(t) ne 1),VaveAD(t))/smax(t,ord(t));
VaveARAMP=SUM(t$(ord(t) ne 1),VaveAR(t))/smax(t,ord(t));
VaveMDFL=SUM(t$(ord(t) ne 1),VaveMD(t))/smax(t,ord(t));
VaveMRAMP=SUM(t$(ord(t) ne 1),VaveMR(t))/smax(t,ord(t));

display vmeanAD,vmeanAR, vmeanMD,vmeanMR,  vaveAD,vaveAR,vaveMD,vaveMR,  vaveADFL, vaveARAMP,
vaveMDFL,vaveMRAMP ;

parameters ARTdflA, ARTdflM,ARTrampA,ARTrampM;

ARTdflA= ((((LenDFL)/( (sum(m,sum(t,vA.l(m,t))))/(NSdfl*NumTime)  ))*3600));
ARTdflM= ((((LenDFL)/( (sum(m,sum(t,vM.l(m,t))))/(NSdfl*NumTime)  ))*3600)) ;
ARTrampA=((((LenRAMP)/( (sum(mm,sum(t,vvA.l(mm,t))))/(NSramp*NumTime)  ))*3600));
ARTrampM=((((LenRAMP)/( (sum(mm,sum(t,vvM.l(mm,t))))/(NSramp*NumTime)  ))*3600)) ;

display ARTdflA, ARTdflM,ARTrampA,ARTrampM;


parameter ART Average running time of a vehicle on the roadway;

ART =  (((sum(m,sum(t,kA.l(m,t)*l(m))))/{ LenDFL*1000 / {[sum(m,sum(t,vA.l(m,t)))/(NSdfl*NumTime)]*dt*1000/3600}} *
         ((((LenDFL)/( (sum(m,sum(t,vA.l(m,t))))/(NSdfl*NumTime)  ))*3600))
        +
         (sum(m,sum(t,kM.l(m,t)*l(m))))/{ LenDFL*1000 / {[sum(m,sum(t,vM.l(m,t)))/(NSdfl*NumTime)]*dt*1000/3600}} *
         ((((LenDFL)/( (sum(m,sum(t,vM.l(m,t))))/(NSdfl*NumTime)  ))*3600))
```

```
+
(sum(mm,sum(t,kkA.l(mm,t)*ll(mm))))/{ LenRAMP*1000 / {[sum(mm,sum(t,vvA.l(mm,t)))/ (NSramp*NumTime)] *
dt*1000/3600}} * ((((LenRAMP)/ ( (sum(mm,sum (t,vvA.l(mm,t) ))) /(NSramp*NumTime)  ))*3600))
+
(sum(mm,sum(t,kkM.l(mm,t)*ll(mm))))/{ LenRAMP*1000 / {[sum(mm,sum(t,vvM.l(mm,t)))/(NSramp*NumTime)] *
dt*1000/3600}} * ((((LenRAMP)/( (sum(mm,sum(t,vvM.l(mm,t))))/(NSramp*NumTime)  ))*3600))   )
/
((sum(m,sum(t,kA.l(m,t)*l(m))))/{ LenDFL*1000 / {[sum(m,sum(t,vA.l(m,t)))/(NSdfl*NumTime)]*dt*1000/3600}}
+
(sum(mm,sum(t,kkA.l(mm,t)*ll(mm))))/{ LenRAMP*1000 / {[sum(mm,sum(t,vvA.l(mm,t)))/ (NSramp*NumTime )] *
dt*1000/3600}}
+
(sum(m,sum(t,kM.l(m,t)*l(m))))/{ LenDFL*1000 / {[sum(m,sum(t,vM.l(m,t)))/(NSdfl*NumTime)]*dt*1000/3600}}
+
(sum(mm,sum(t,kkM.l(mm,t)*ll(mm))))/{ LenRAMP*1000 / {[sum(mm,sum(t,vvM.l(mm,t)))/(NSramp* NumTime)] *
dt*1000/3600}}  ));
```

```
parameter ARTB Average running time of a vehicle in the dynamic part of a buffer area;

ARTB = ( (sum(m,sum(t,kbA.l(m,t)*lbA(m))))/{ LenBA*1000 / {[sum(m,sum(t,vbA.l(m,t)))/(1*NumTime)]*dt*1000/3600}} *
        ((((LenBA)/( (sum(m,sum(t,vbA.l(m,t))))/(1*NumTime)  ))*3600))
+
(sum(mm,sum(t,kkbA.l(mm,t)*llbA(mm))))/{ LenBAA*1000 / {[sum(mm,sum(t,vvbA.l(mm,t)))/(1*NumTime)]*dt*
1000/3600}} * ((((LenBAA)/( (sum(mm,sum(t,vvbA.l(mm,t))))/(1*NumTime)  ))*3600))
+
(sum(mm,sum(t,kkbM.l(mm,t)*llbM(mm))))/{ LenBMM*1000 / {[sum(mm,sum(t,vvbM.l(mm,t)))/(1*NumTime)]*dt*
1000/3600}} * ((((LenBMM)/( (sum(mm,sum(t,vvbM.l(mm,t))))/(1*NumTime)  ))*3600))  )
/
(   (sum(m,sum(t,kA.l(m,t)*l(m))))/{ LenDFL*1000      / {[sum(m,sum(t,vA.l(m,t)))/(NSdfl*NumTime)]*dt*1000/3600}}
+
(sum(mm,sum(t,kkA.l(mm,t)*ll(mm))))/{ LenRAMP*1000 / {[sum(mm,sum(t,vvA.l(mm,t)))/(NSramp*NumTime)]
*dt*1000/3600}}
+
(sum(m,sum(t,kM.l(m,t)*l(m))))/{ LenDFL*1000 / {[sum(m,sum(t,vM.l(m,t)))/(NSdfl*NumTime)]*dt*1000/3600}}
+
(sum(mm,sum(t,kkM.l(mm,t)*ll(mm))))/{ LenRAMP*1000 / {[sum(mm,sum(t,vvM.l(mm,t)))/(NSramp*NumTime)]*dt*
1000/3600}} );
```

```
parameter AWTB Average waiting time of a vehicle in the buffer area;

AWTB = ( (sum(m,sum(t,(sum(at$(ord(at) le ord(t)),((1-alphaA.l(m,at))*rA.l(m,at)-IoutbA.l(m,at))*(dt/3600)*dt)))))        +
        (sum(mm,sum(t,(sum(at$(ord(at) le ord(t)),((1-alphaAA.l(mm,at))*rrA.l(mm,at)-IoutbbA.l(mm,at))*(dt/3600)*dt))))) +
        (sum(mm,sum(t,(sum(at$(ord(at) le ord(t)),((1-alphaMM.l(mm,at))*rrM.l(mm,at)-IoutbbM.l(mm,at))*(dt/3600)*dt))))) )
        /
        ((sum(m,sum(t,kA.l(m,t)*l(m))))/{ LenDFL*1000 / {[sum(m,sum(t,vA.l(m,t)))/(NSdfl*NumTime)]*dt*1000/3600}}
        +
        (sum(mm,sum(t,kkA.l(mm,t)*ll(mm))))/{ LenRAMP*1000 / {[sum(mm,sum(t,vvA.l(mm,t)))/(NSramp*NumTime)] *
        dt*1000/3600}}
        +
        (sum(m,sum(t,kM.l(m,t)*l(m))))/{ LenDFL*1000 / {[sum(m,sum(t,vM.l(m,t)))/(NSdfl*NumTime)]*dt*1000/3600}}
        +
        (sum(mm,sum(t,kkM.l(mm,t)*ll(mm))))/{ LenRAMP*1000 / {[sum(mm,sum(t,vvM.l(mm,t)))/(NSramp*NumTime)]*
        dt*1000/3600}} )  ;

display ART, ARTB, AWTB ;


parameters sumrA2,sumrrA2,sumrrM2,sumIinbA2,sumIinbbA2,sumIinbbM2  Total input flow to the buffer areas during time "t";

sumrA2=(sum(t,rA.l("2",t)))*dt/3600 ;
sumrrA2=(sum(t,rrA.l("2",t)))*dt/3600 ;
sumrrM2=(sum(t,rrM.l("2",t)))*dt/3600 ;

sumIinbA2=(sum(t,IinbA("2",t)))*dt/3600 ;
sumIinbbA2=(sum(t,IinbbA("2",t)))*dt/3600 ;
sumIinbbM2=(sum(t,IinbbM("2",t)))*dt/3600 ;

display sumrA2,sumrrA2,sumrrM2,sumIinbA2,sumIinbbA2,sumIinbbM2;
```

```
parameter INVbA2(t)  Inventory of flow in buffer area #2 on the DFL for ACTs;
parameter INVbbA2(t) Inventory of flow in buffer area #2 on the on-ramp for ACTs;
parameter INVbbM2(t) Inventory of flow in buffer area #2 on the on-ramp for MDVs;

INVbA2(t) =(sum(at$(ord(at) lt ord(t)),((1-alphaA.l("2",at))*rA.l("2",at)-IoutbA.l("2",at))))   ;
INVbbA2(t)=(sum(at$(ord(at) lt ord(t)),((1-alphaAA.l("2",at))*rrA.l("2",at)-IoutbbA.l("2",at)))) ;
INVbbM2(t)=(sum(at$(ord(at) lt ord(t)),((1-alphaMM.l("2",at))*rrM.l("2",at)-IoutbbM.l("2",at)))) ;

display INVbA2,INVbbA2,INVbbM2 ;


parameter sINVbA2  surface under inv-t graph of buffer area #2 on the DFL for ACTs  ;
parameter sINVbbA2 surface under inv-t graph of buffer area #2 on the on-ramp for ACTs;
parameter sINVbbM2 surface under inv-t graph of buffer area #2 on the on-ramp for MDVs;

sINVbA2 =sum(t,INVbA2(t))*dt/3600   ;
sINVbbA2 =sum(t,INVbbA2(t))*dt/3600   ;
sINVbbM2 =sum(t,INVbbM2(t))*dt/3600   ;

display sINVbA2,sINVbbA2,sINVbbM2 ;


parameters cumIinbA2(t), cumIoutbA2(t), cumIinbbA2(t), cumIoutbbA2(t), cumIinbbM2(t),  cumIoutbbM2(t)  the cumulative
           flow of stored vehicles in the parking area of buffre areas;

cumIinbA2(t)=sum(at$(ord(at) le ord(t)),IinbA("2",at));
cumIoutbA2(t)=sum(at$(ord(at) le ord(t)),IoutbA.l("2",at));
cumIinbbA2(t)=sum(at$(ord(at) le ord(t)),IinbbA("2",at));
cumIoutbbA2(t)=sum(at$(ord(at) le ord(t)),IoutbbA.l("2",at));
cumIinbbM2(t)=sum(at$(ord(at) le ord(t)),IinbbM("2",at));
cumIoutbbM2(t)=sum(at$(ord(at) le ord(t)),IoutbbM.l("2",at));

display cumIinbA2, cumIoutbA2, cumIinbbA2, cumIoutbbA2, cumIinbbM2, cumIoutbbM2  ;
```

# Appendix F
# Estimation of Speed-Density Relation for ACTs and MDVs

In order to estimate the speed-density relation for ACTs and MDVs, a simulation is conducted in which three detectors are located on different locations on the road layout (see figure F.1).

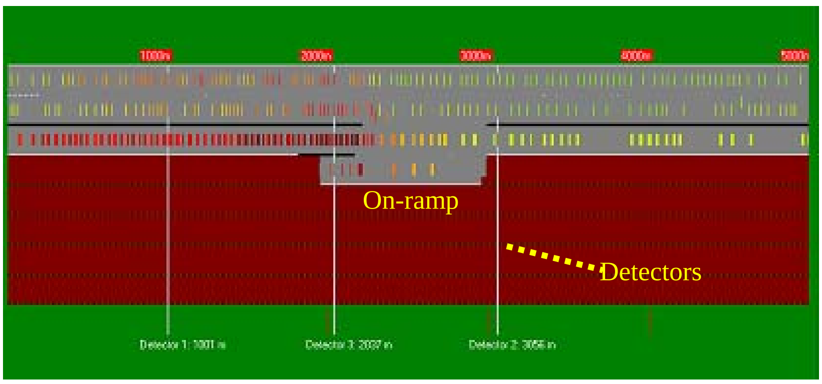



**Figure F.1. A schematic layout about the road layout and the location of detectors**

It is assumed that an exponential equation, like what was described in the equation (5.2) of chapter 5 can represents the speed-density relation for ACTs (on the DFL ) and MDVs (on the mainline), separately. The free flow speed of ACTs and MDVs is assumed to be equal to 88 km/h and 120 km/h, respectively. Taking into account an average length of 14 m and 5 m for ACTs and cars, respectively, and also a minimum safe distance of 3 m between vehicles in the congested situation, a jam density of 60 truck/km and 125 car/km can be considered for ACTs and MDVs, respectively. Thus, the main aim is to look for the best estimation of $k_{cr}$ which can fit the equation 5.2 to simulation results (e.g. speed and density data collected by the three detectors on the road layout). Figure F.2 and indicates that the best fit for ACTs happen in case of a value of 18 and 60 for $k_{cr}$ of ACTs and MDVs respectively.

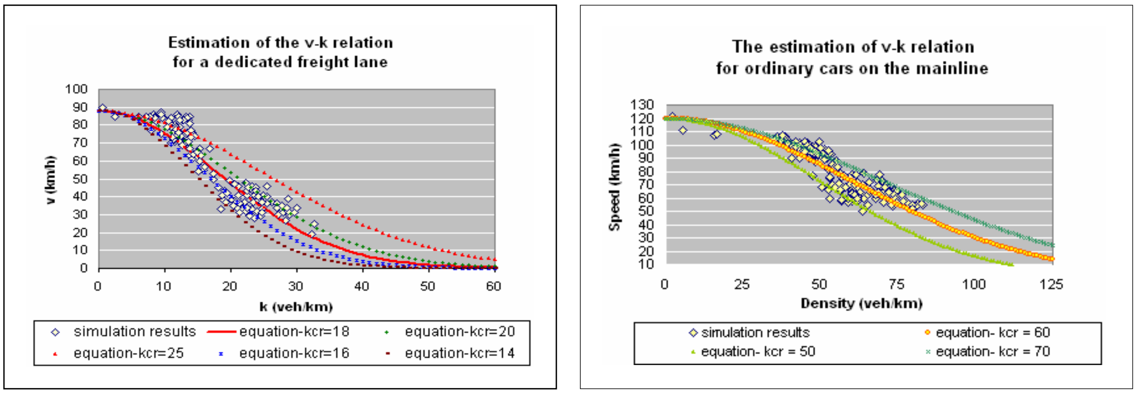



**Figure F.2. Estimation of speed-density relation for ACTs and MDVs**

# Appendix G
# Optimization Results for Buffer Areas

## A summary of results of the optimization models for all the objective functions described in chapter 7

*(1) Minimization of the average travel time of vehicles*

**Table G.1. Time-related indicators**

| Option | Time related indicators (sec.) | | | |
|---|---|---|---|---|
| | Average running time on the roadway | Average running time in buffer areas | Average waiting time in buffer areas | Average travel time per vehicle |
| Option 1 (ref.) | 90.1 | 1 | 1.8 | 92.9 |
| Option 2 | 90.1 | 1.2 | 2.3 | 93.6 |
| Option 3 | 90.1 | 1.1 | 2.9 | 94.1 |
| Option 4 | 90.1 | 1.2 | 2.3 | 93.6 |

**Table G.2. Number of vehicles stored in the buffer areas**

| Option | Number of vehicles stored in buffer areas | | |
|---|---|---|---|
| | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs |
| Option 1 (ref.) | 11 | 32 | 103 |
| Option 2 | 5 | 64 | 119 |
| Option 3 | 6 | 87 | 144 |
| Option 4 | 9 | 67 | 105 |

**Table G.3. The total input flow to buffer areas (veh/h)**

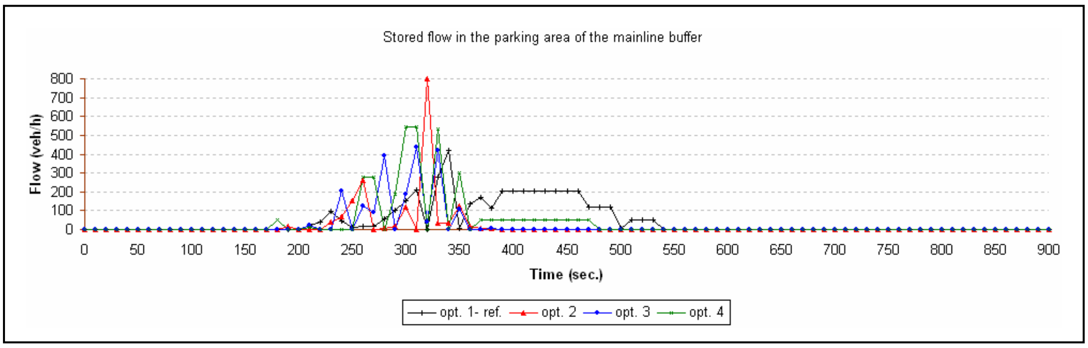
| Option | Total input flow to buffer areas (veh/h) | | | | | |
|---|---|---|---|---|---|---|
| | The dynamic part | | | The static part | | |
| | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs |
| Option 1 (ref.) | 1601 | 1934 | 14820 | 1435 | 1924 | 12357 |
| Option 2 | 2549 | 2478 | 16725 | 1595 | 2473 | 16705 |
| Option 3 | 2002 | 2280 | 16241 | 2001 | 2280 | 15838 |
| Option 4 | 2486 | 2694 | 16068 | 1967 | 2691 | 14969 |

**Table G.4. Entrance/exit gate utilization of the dynamic part of buffer areas**

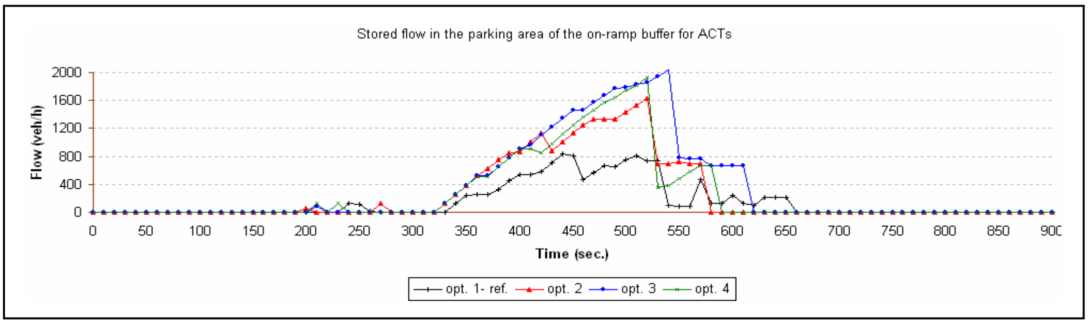
| Option | Gate utilization of the dynamic part of buffer areas (%) | | | | | |
|---|---|---|---|---|---|---|
| | The mainline buffer | | The on-ramp buffer for ACTs | | The on-ramp buffer for MDVs | |
| | In | Out | In | Out | In | Out |
| Option 1 (ref.) | 22 | 38 | 22 | 32 | 49 | 59 |
| Option 2 | 13 | 26 | 27 | 40 | 46 | 54 |
| Option 3 | 12 | 24 | 26 | 32 | 45 | 56 |
| Option 4 | 11 | 34 | 26 | 36 | 48 | 54 |

**Table G.5. Entrance/exit gate utilization of the static part of buffer areas**

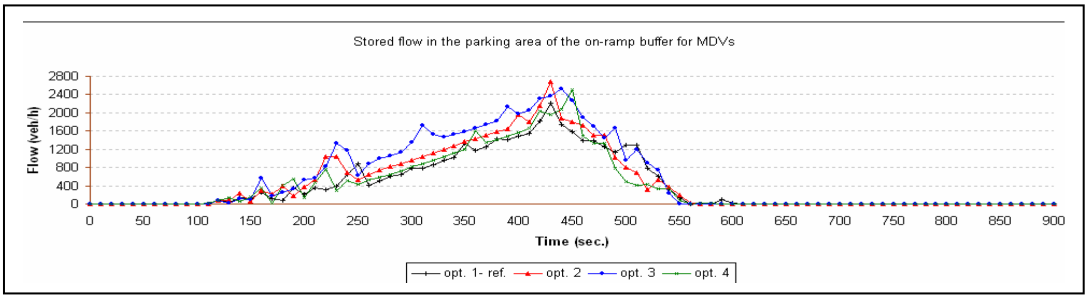
| Option | Gate utilization of the static part of buffer areas (%) | | | | | |
|---|---|---|---|---|---|---|
| | The mainline buffer | | The on-ramp buffer for ACTs | | The on-ramp buffer for MDVs | |
| | In | Out | In | Out | In | Out |
| Option 1 (ref.) | 20 | 14 | 22 | 14 | 47 | 46 |
| Option 2 | 12 | 14 | 27 | 11 | 46 | 47 |
| Option 3 | 12 | 12 | 26 | 9 | 45 | 45 |
| Option 4 | 11 | 10 | 26 | 7 | 47 | 42 |




(a) The mainline buffer

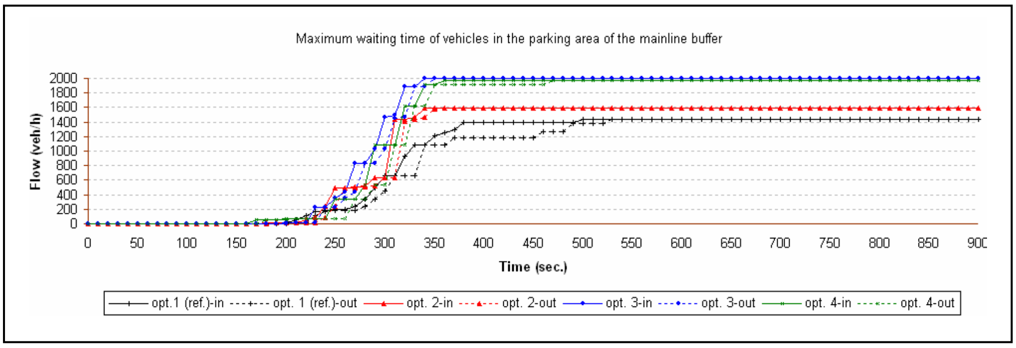



(b) The on-ramp buffer for ACTs

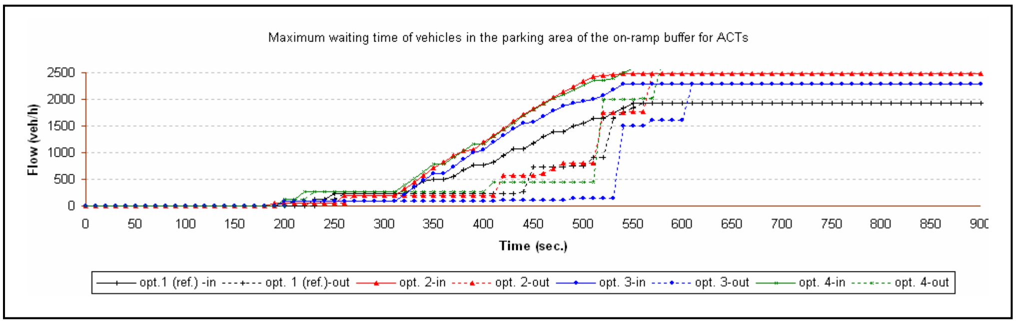



(c) The on-ramp buffer for MDVs

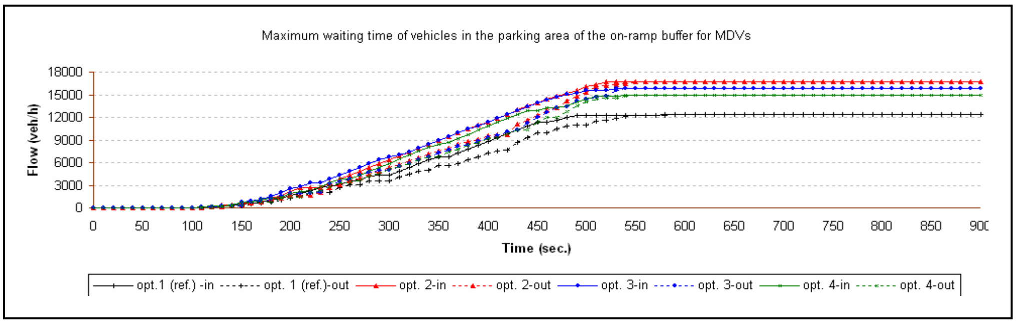
**Figure G.1. Flow inventory in buffer areas**




(a) The mainline buffer




(b) The on-ramp buffer for ACTs




(c) The on-ramp buffer for MDVs

**Figure G.2. The cumulative input-output flow of buffer areas**

## *(2) Minimization of total travel time of vehicles*

### Table G.6. Time-related indicators

| Option | Time related indicators (sec.) | | | |
|---|---|---|---|---|
| | Average running time on the roadway | Average running time in buffer areas | Average waiting time in buffer areas | Average travel time per vehicle |
| Option 1 (ref.) | 90.2 | 1.1 | 1.7 | 93 |
| Option 2 | 90.1 | 1 | 3.3 | 94.4 |
| Option 3 | 90.1 | 1.2 | 2.7 | 94 |
| Option 4 | 90.1 | 1.1 | 2.3 | 93.5 |

### Table G.7. Number of vehicles stored in the buffer areas

| Option | Number of vehicles stored in buffer areas | | |
|---|---|---|---|
| | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs |
| Option 1 (ref.) | 6 | 34 | 100 |
| Option 2 | 0 | 127 | 135 |
| Option 3 | 60 | 4 | 151 |
| Option 4 | 9 | 80 | 95 |

### Table G.8. The total input flow to buffer areas (veh/h)

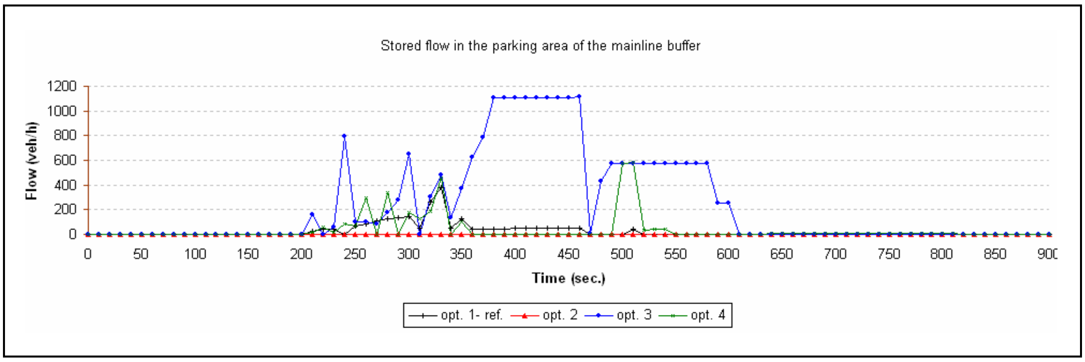
| Option | Total input flow to buffer areas (veh/h) | | | | | |
|---|---|---|---|---|---|---|
| | The dynamic part | | | The static part | | |
| | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs |
| Option 1 (ref.) | 1495 | 2400 | 15304 | 1373 | 2400 | 12871 |
| Option 2 | 0 | 3227 | 15437 | 0 | 3223 | 14406 |
| Option 3 | 4292 | 1347 | 15429 | 4287 | 1235 | 14990 |
| Option 4 | 2587 | 2359 | 14371 | 2563 | 2305 | 13268 |

### Table G.9. Entrance/exit gate utilization of the dynamic part of buffer areas

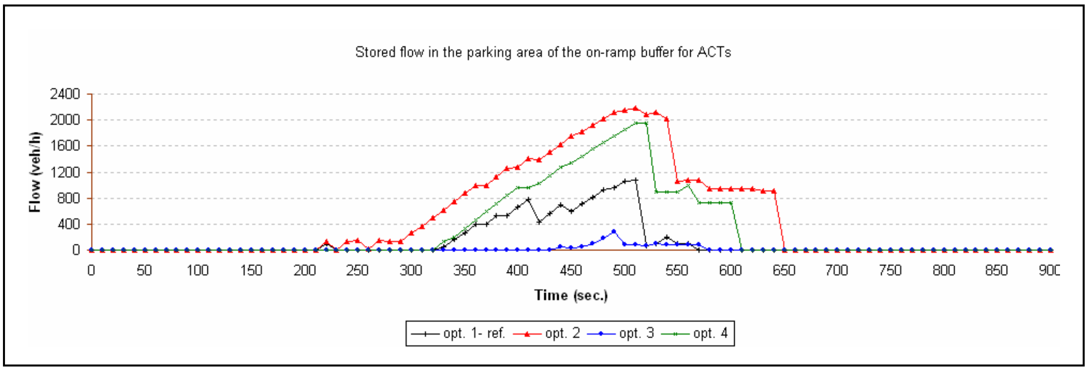
| Option | Gate utilization of the dynamic part of buffer areas (%) | | | | | |
|---|---|---|---|---|---|---|
| | The mainline buffer | | The on-ramp buffer for ACTs | | The on-ramp buffer for MDVs | |
| | In | Out | In | Out | In | Out |
| Option 1 (ref.) | 20 | 35 | 24 | 31 | 49 | 58 |
| Option 2 | 0 | 0 | 35 | 52 | 46 | 54 |
| Option 3 | 21 | 46 | 21 | 26 | 45 | 58 |
| Option 4 | 20 | 36 | 23 | 34 | 47 | 52 |

### Table G.10. Entrance/exit gate utilization of the static part of buffer areas

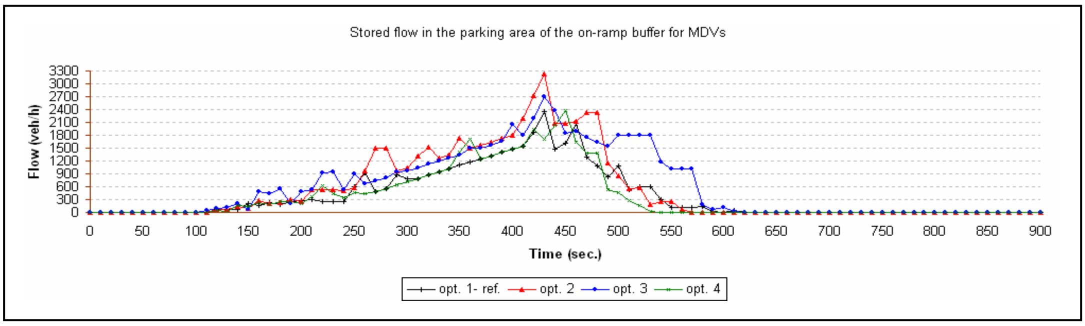
| Option | Gate utilization of the static part of buffer areas (%) | | | | | |
|---|---|---|---|---|---|---|
| | The mainline buffer | | The on-ramp buffer for ACTs | | The on-ramp buffer for MDVs | |
| | In | Out | In | Out | In | Out |
| Option 1 (ref.) | 20 | 16 | 24 | 10 | 46 | 42 |
| Option 2 | 0 | 0 | 35 | 20 | 45 | 41 |
| Option 3 | 21 | 14 | 20 | 18 | 45 | 48 |
| Option 4 | 20 | 16 | 23 | 5 | 46 | 41 |




(a) The mainline buffer

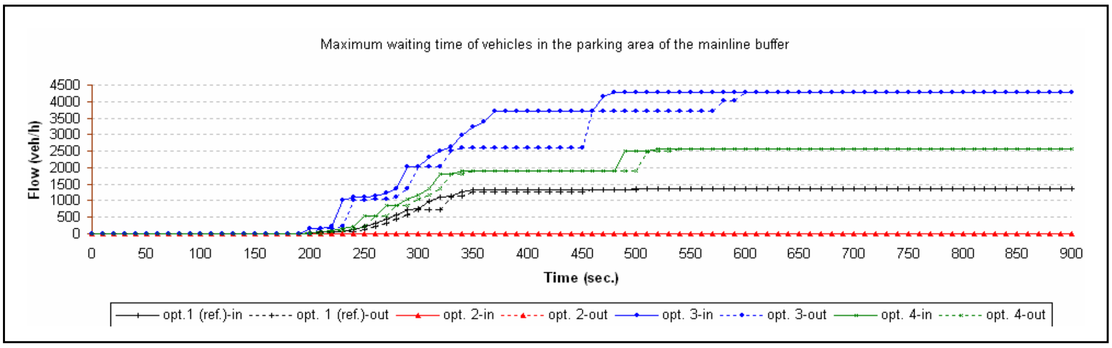



(b) The on-ramp buffer for ACTs

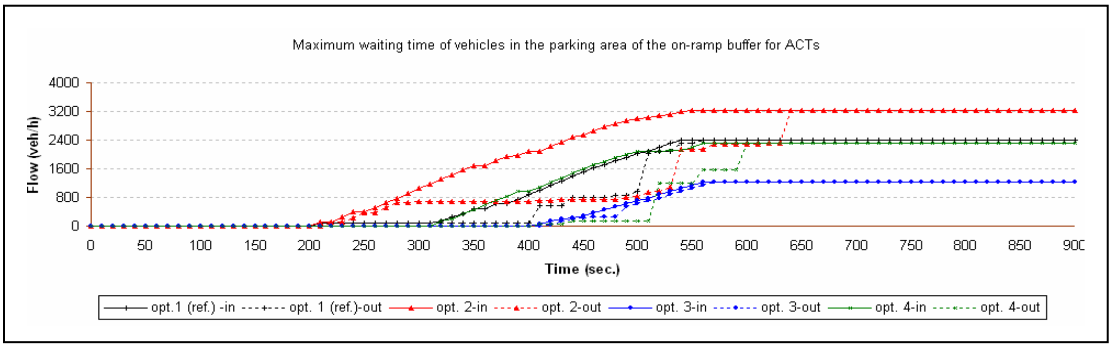



(c) The on-ramp buffer for MDVs

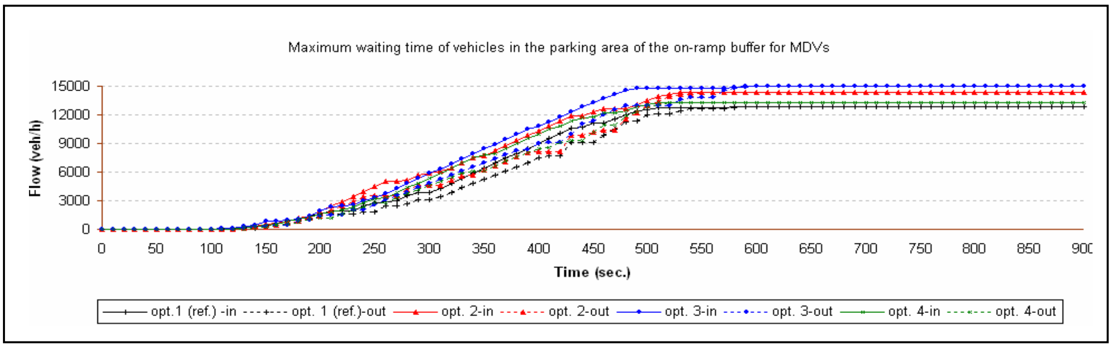
**Figure G.3. Flow inventory in buffer areas**




(a) The mainline buffer




(b) The on-ramp buffer for ACTs




(c) The on-ramp buffer for MDVs

**Figure G.4. The cumulative input-output flow of buffer areas**

### *(3) Maximization of throughput at the merging area*

**Table G.11. Time-related indicators**

| Option | Time related indicators (sec.) | | | |
|---|---|---|---|---|
| | Average running time on the roadway | Average running time in buffer areas | Average waiting time in buffer areas | Average travel time per vehicle |
| Option 1 (ref.) | 90.1 | 1.1 | 2.3 | 93.5 |
| Option 2 | 90.1 | 1.2 | 2.4 | 93.7 |
| Option 3 | 90.1 | 1.2 | 2.4 | 93.7 |

**Table G.12. Number of vehicles stored in the buffer areas**

| Option | Number of vehicles stored in buffer areas | | |
|---|---|---|---|
| | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs |
| Option 1 (ref.) | 10 | 54 | 118 |
| Option 2 | 6 | 52 | 135 |
| Option 3 | 6 | 67 | 121 |

**Table G.13. The total input flow to buffer areas (veh/h)**

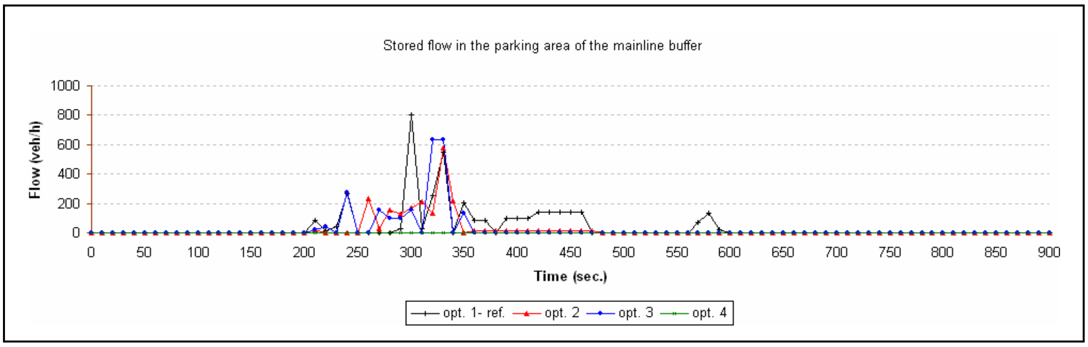
| Option | Total input flow to buffer areas (veh/h) | | | | | |
|---|---|---|---|---|---|---|
| | The dynamic part | | | The static part | | |
| | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs |
| Option 1 (ref.) | 2518 | 2378 | 15407 | 2330 | 2378 | 15311 |
| Option 2 | 1737 | 2467 | 17343 | 1558 | 2415 | 16547 |
| Option 3 | 2161 | 2428 | 16108 | 1563 | 2428 | 15046 |

**Table G.14. Entrance/exit gate utilization of the dynamic part of buffer areas**

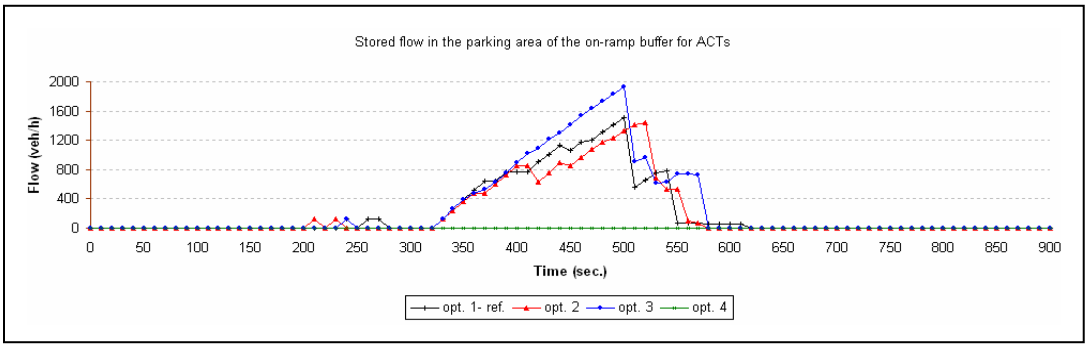
| Option | Gate utilization of the dynamic part of buffer areas (%) | | | | | |
|---|---|---|---|---|---|---|
| | The mainline buffer | | The on-ramp buffer for ACTs | | The on-ramp buffer for MDVs | |
| | In | Out | In | Out | In | Out |
| Option 1 (ref.) | 15 | 46 | 24 | 40 | 43 | 56 |
| Option 2 | 14 | 31 | 27 | 45 | 49 | 55 |
| Option 3 | 14 | 25 | 33 | 37 | 46 | 57 |

**Table G.15. Entrance/exit gate utilization of the static part of buffer areas**

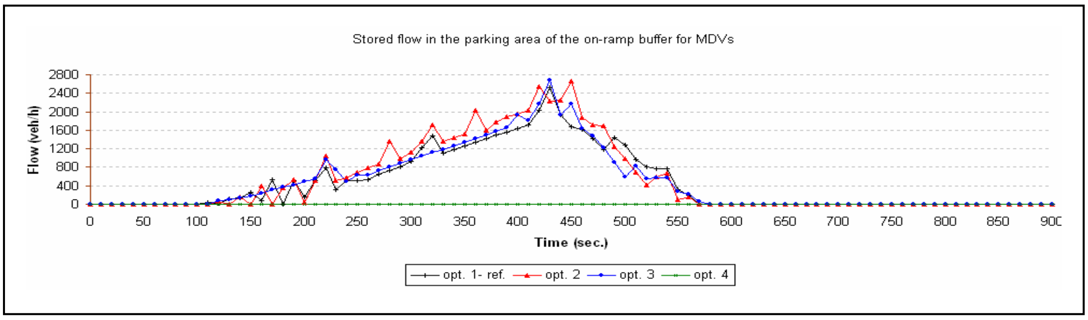
| Option | Gate utilization of the static part of buffer areas (%) | | | | | |
|---|---|---|---|---|---|---|
| | The mainline buffer | | The on-ramp buffer for ACTs | | The on-ramp buffer for MDVs | |
| | In | Out | In | Out | In | Out |
| Option 1 (ref.) | 14 | 15 | 24 | 12 | 42 | 48 |
| Option 2 | 14 | 15 | 27 | 11 | 46 | 43 |
| Option 3 | 12 | 12 | 33 | 13 | 45 | 49 |




(a) The mainline buffer

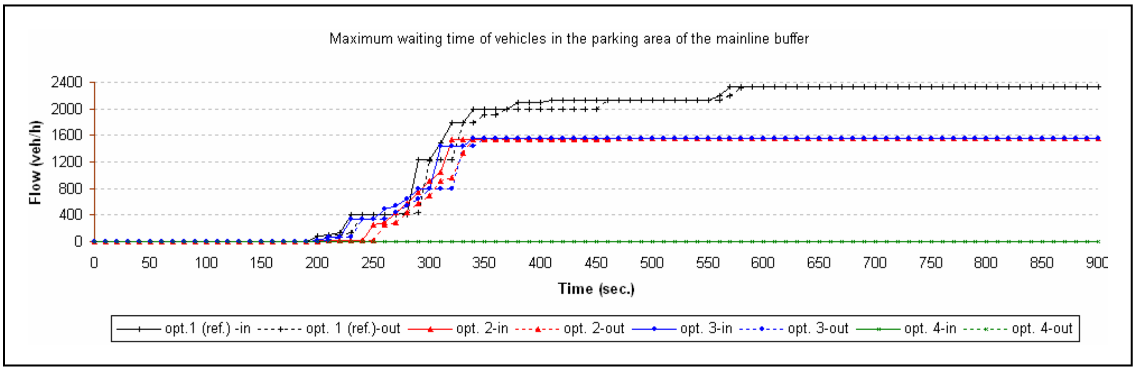



(b) The on-ramp buffer for ACTs

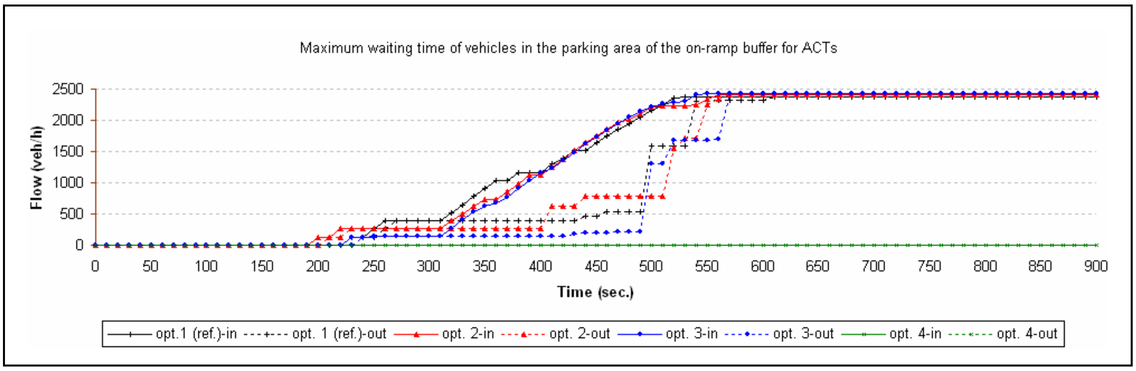



(c) The on-ramp buffer for MDVs

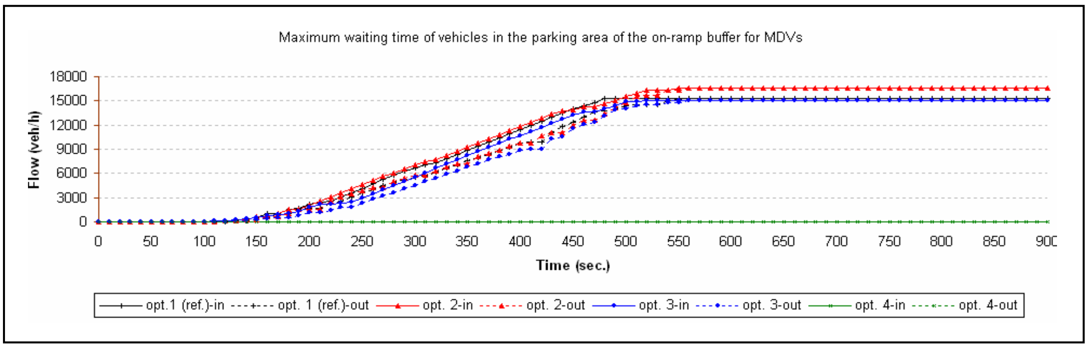
**Figure G.5. Flow inventory in buffer areas**




(a) The mainline buffer




(b) The on-ramp buffer for ACTs




(c) The on-ramp buffer for MDVs

**Figure G.6. The cumulative input-output flow of buffer areas**

*(4) Maximization of safety*

**Table G.16. Time-related indicators**

| Option | Time related indicators (sec.) | | | |
|---|---|---|---|---|
| | Average running time on the roadway | Average running time in buffer areas | Average waiting time in buffer areas | Average travel time per vehicle |
| Option 1 (ref.) | 90.1 | 1.2 | 2.8 | 94.1 |
| Option 2 | 90 | 1.2 | 3.2 | 94.4 |
| Option 3 | 90 | 1.5 | 3.4 | 94.9 |
| Option 4 | 90.1 | 1.2 | 5.3 | 96.6 |

**Table G.17. Number of vehicles stored in the buffer areas**

| Option | Number of vehicles stored in buffer areas | | |
|---|---|---|---|
| | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs |
| Option 1 (ref.) | 15 | 80 | 132 |
| Option 2 | 47 | 84 | 124 |
| Option 3 | 50 | 58 | 169 |
| Option 4 | 10 | 48 | 365 |

**Table G.18. The total input flow to buffer areas (veh/h)**

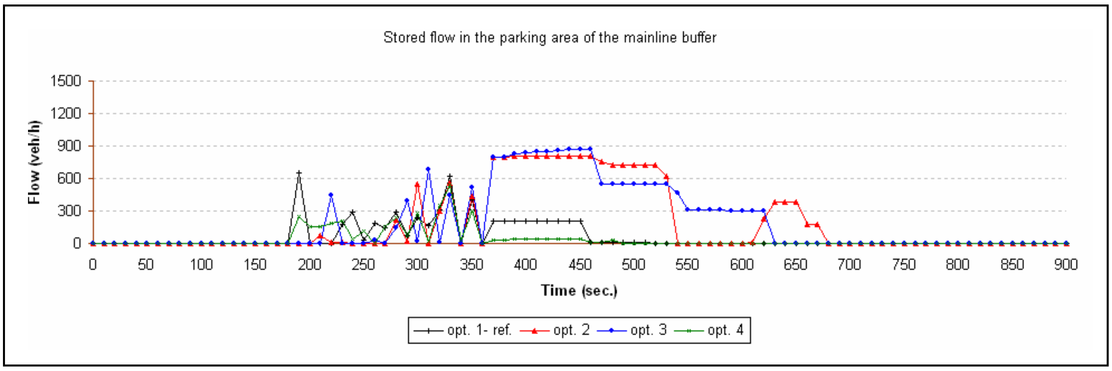
| Option | Total input flow to buffer areas (veh/h) | | | | | |
|---|---|---|---|---|---|---|
| | The dynamic part | | | The static part | | |
| | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs |
| Option 1 (ref.) | 3171 | 2670 | 16005 | 3171 | 2670 | 14587 |
| Option 2 | 3778 | 2436 | 14862 | 3455 | 2436 | 13900 |
| Option 3 | 4604 | 2896 | 17700 | 3543 | 2877 | 16486 |
| Option 4 | 2922 | 2290 | 15176 | 1885 | 2290 | 14800 |

**Table G.19. Entrance/exit gate utilization of the dynamic part of buffer areas**

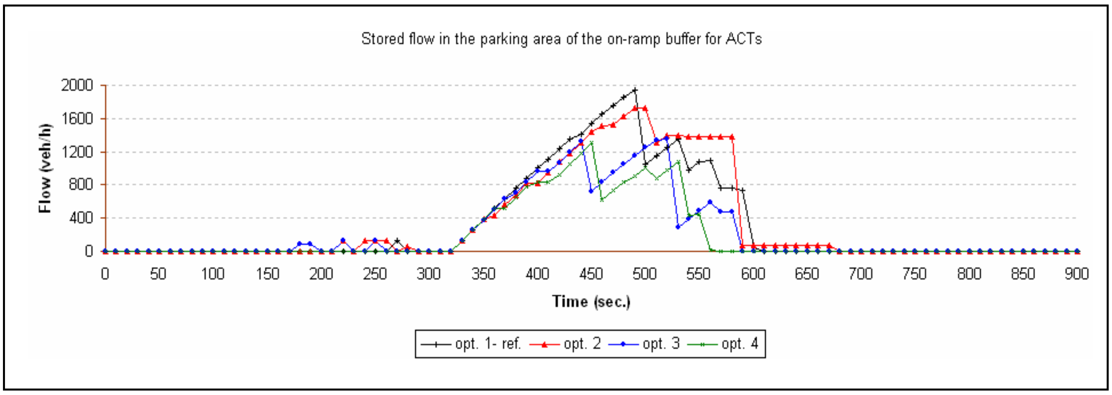
| Option | Gate utilization of the dynamic part of buffer areas (%) | | | | | |
|---|---|---|---|---|---|---|
| | The mainline buffer | | The on-ramp buffer for ACTs | | The on-ramp buffer for MDVs | |
| | In | Out | In | Out | In | Out |
| Option 1 (ref.) | 15 | 42 | 32 | 40 | 46 | 56 |
| Option 2 | 18 | 58 | 31 | 48 | 44 | 56 |
| Option 3 | 23 | 52 | 30 | 51 | 49 | 60 |
| Option 4 | 23 | 40 | 25 | 25 | 46 | 77 |

**Table G.20. Entrance/exit gate utilization of the static part of buffer areas**

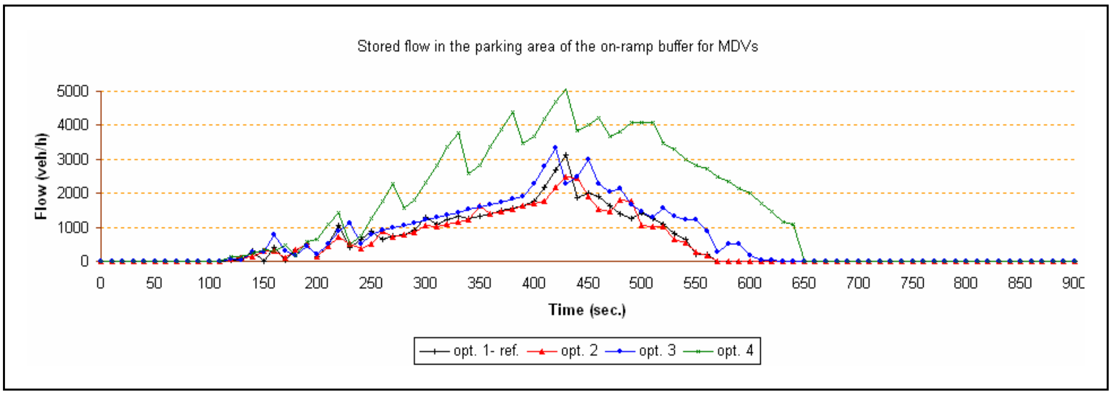
| Option | Gate utilization of the static part of buffer areas (%) | | | | | |
|---|---|---|---|---|---|---|
| | The mainline buffer | | The on-ramp buffer for ACTs | | The on-ramp buffer for MDVs | |
| | In | Out | In | Out | In | Out |
| Option 1 (ref.) | 15 | 13 | 32 | 11 | 46 | 46 |
| Option 2 | 18 | 19 | 31 | 16 | 44 | 43 |
| Option 3 | 20 | 13 | 30 | 13 | 49 | 43 |
| Option 4 | 21 | 18 | 25 | 7 | 46 | 53 |




(a) The mainline buffer

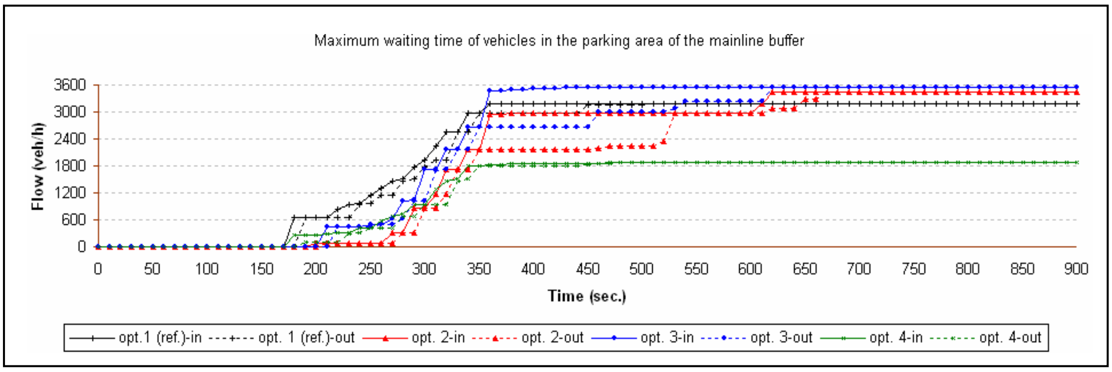



(b) The on-ramp buffer for ACTs

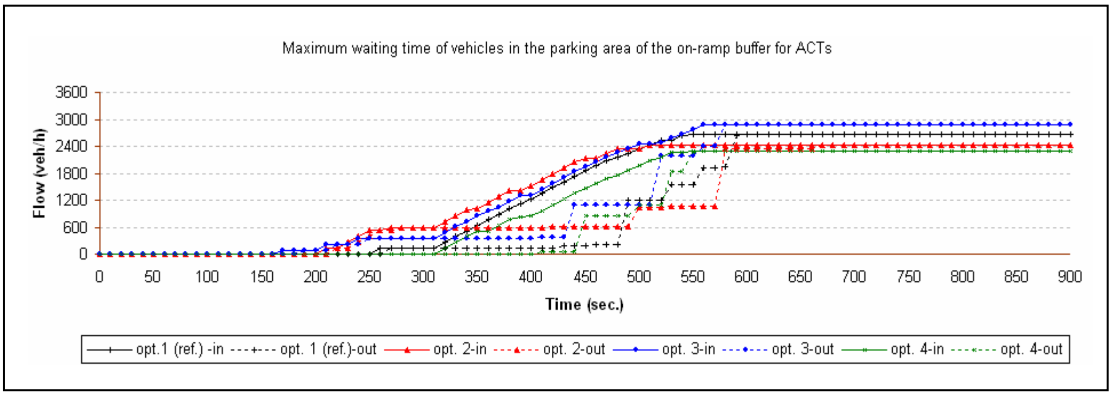



(c) The on-ramp buffer for MDVs

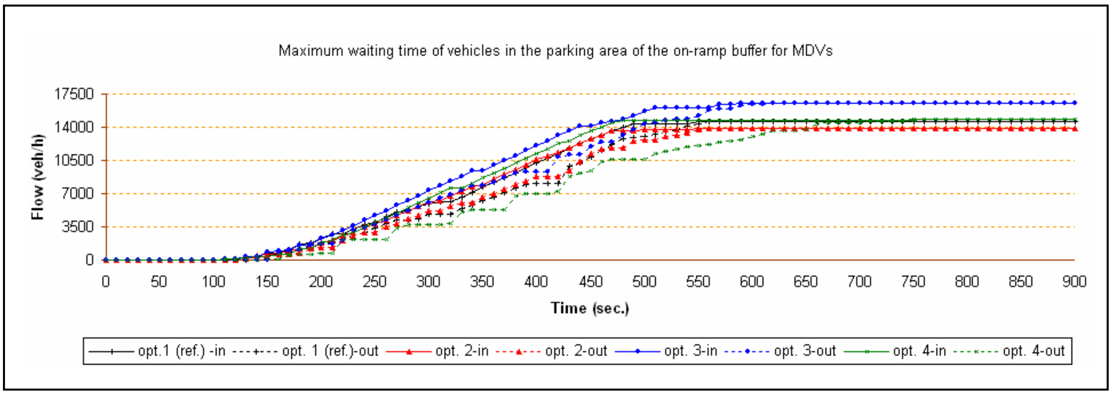
**Figure G.7. Flow inventory in buffer areas**




(a) The mainline buffer




(b) The on-ramp buffer for ACTs




(c) The on-ramp buffer for MDVs

**Figure G.8. The cumulative input-output flow of buffer areas**

### *(5) Minimization of fuel consumption*

**Table G.21. Time-related indicators**

| Option | Time related indicators (sec.) | | | |
|---|---|---|---|---|
| | Average running time on the roadway | Average running time in buffer areas | Average waiting time in buffer areas | Average travel time per vehicle |
| Option 1 (ref.) | 90.1 | 1.2 | 2.4 | 93.7 |
| Option 2 | 90.1 | 1.2 | 2.3 | 93.6 |
| Option 3 | 90.1 | 1.4 | 2.6 | 94.1 |
| Option 4 | 90.1 | 1.2 | 2.7 | 94 |

**Table G.22. Number of vehicles stored in the buffer areas**

| Option | Number of vehicles stored in buffer areas | | |
|---|---|---|---|
| | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs |
| Option 1 (ref.) | 10 | 62 | 120 |
| Option 2 | 9 | 60 | 116 |
| Option 3 | 23 | 67 | 122 |
| Option 4 | 5 | 76 | 139 |

**Table G.23. The total input flow to buffer areas (veh/h)**

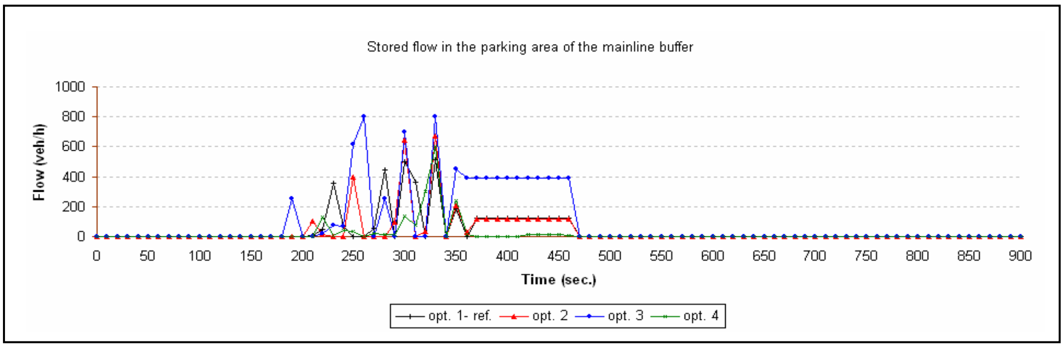
| Option | Total input flow to buffer areas (veh/h) | | | | | |
|---|---|---|---|---|---|---|
| | The dynamic part | | | The static part | | |
| | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs | The mainline buffer | The on-ramp buffer for ACTs | The on-ramp buffer for MDVs |
| Option 1 (ref.) | 2466 | 2106 | 16836 | 2365 | 2106 | 16672 |
| Option 2 | 3415 | 2256 | 16093 | 2331 | 2256 | 14183 |
| Option 3 | 4484 | 2313 | 16865 | 4021 | 2313 | 16339 |
| Option 4 | 2228 | 2381 | 16351 | 1280 | 2321 | 15527 |

**Table G.24. Entrance/exit gate utilization of the dynamic part of buffer areas**

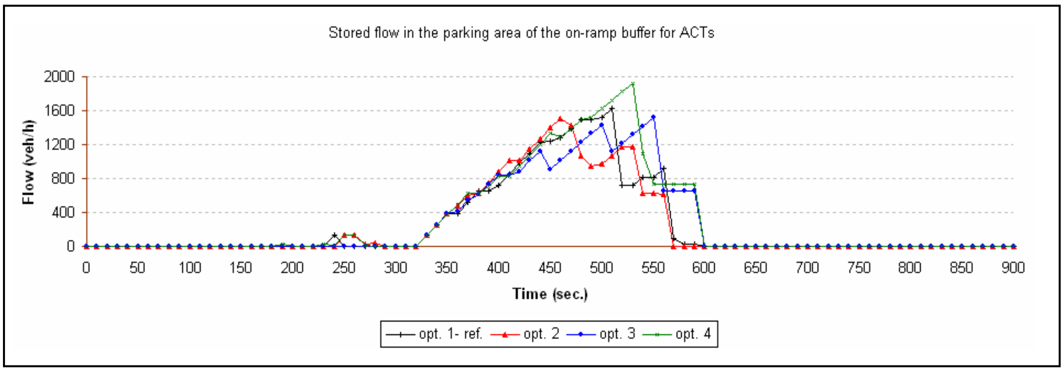
| Option | Gate utilization of the dynamic part of buffer areas (%) | | | | | |
|---|---|---|---|---|---|---|
| | The mainline buffer | | The on-ramp buffer for ACTs | | The on-ramp buffer for MDVs | |
| | In | Out | In | Out | In | Out |
| Option 1 (ref.) | 13 | 35 | 27 | 32 | 46 | 62 |
| Option 2 | 12 | 35 | 26 | 35 | 44 | 57 |
| Option 3 | 12 | 35 | 24 | 30 | 47 | 58 |
| Option 4 | 15 | 33 | 33 | 48 | 48 | 58 |

**Table G.25. Entrance/exit gate utilization of the static part of buffer areas**

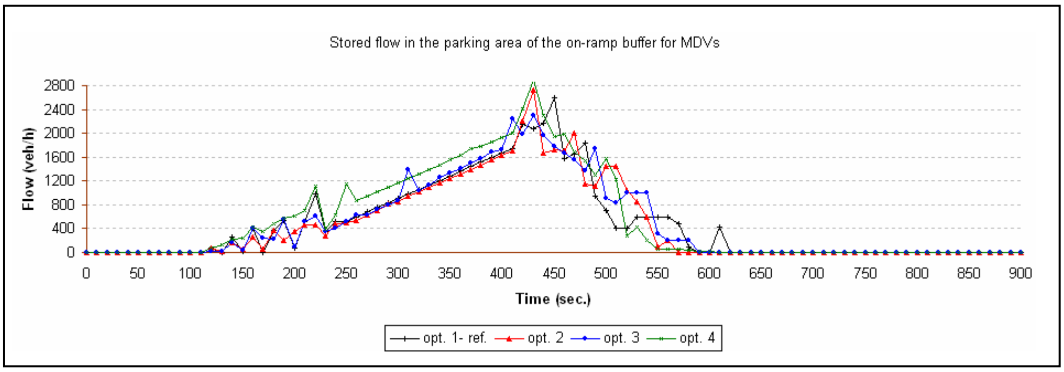
| Option | Gate utilization of the static part of buffer areas (%) | | | | | |
|---|---|---|---|---|---|---|
| | The mainline buffer | | The on-ramp buffer for ACTs | | The on-ramp buffer for MDVs | |
| | In | Out | In | Out | In | Out |
| Option 1 (ref.) | 12 | 12 | 27 | 9 | 46 | 48 |
| Option 2 | 12 | 12 | 26 | 14 | 40 | 41 |
| Option 3 | 11 | 12 | 24 | 9 | 46 | 42 |
| Option 4 | 15 | 22 | 33 | 18 | 48 | 48 |




(a) The mainline buffer

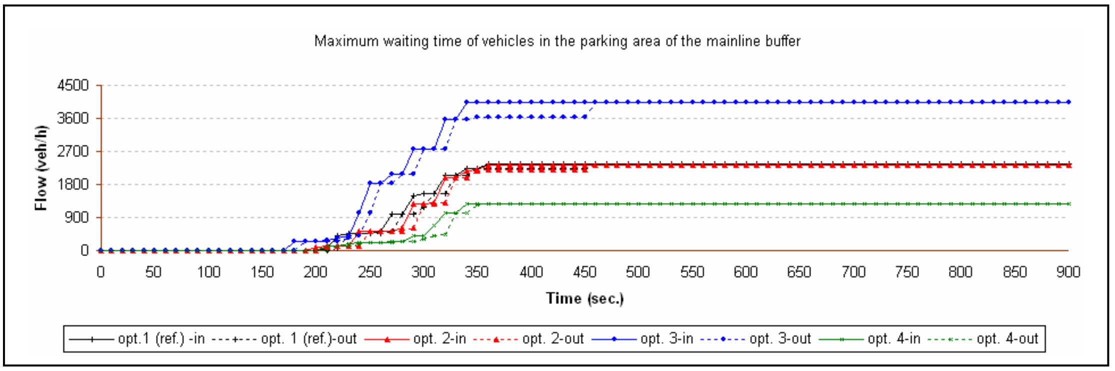



(b) The on-ramp buffer for ACTs

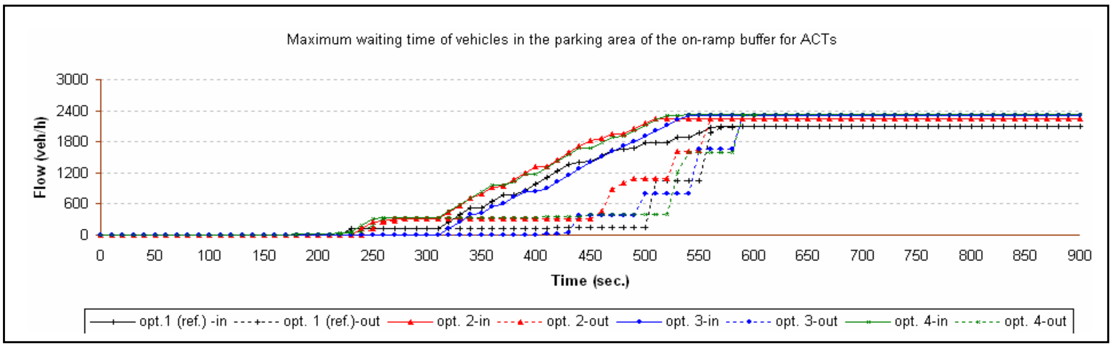



(c) The on-ramp buffer for MDVs

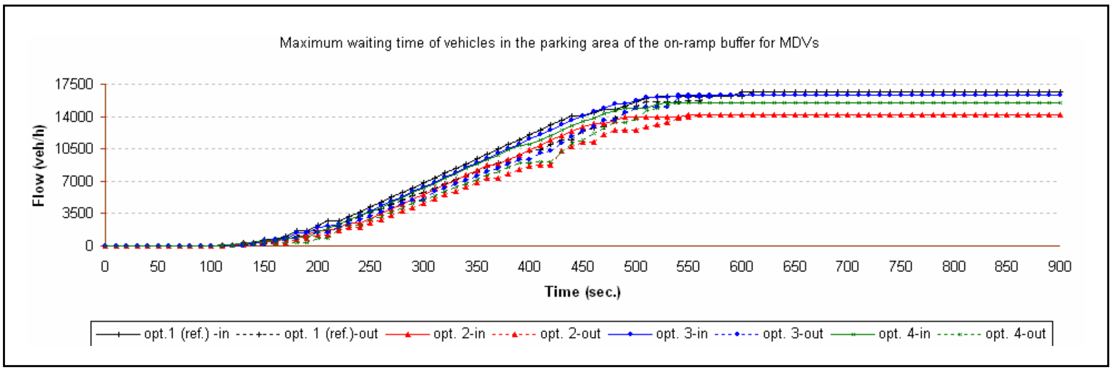
**Figure G.9. Flow inventory in buffer areas**




(a) The mainline buffer




(b) The on-ramp buffer for ACTs




(c) The on-ramp buffer for MDVs

**Figure G.10. The cumulative input-output flow of buffer areas**

# Summary

The growing traffic congestion on motorways is characterized, commonly, in the public opinion as a waste of time and money that should preferably be eliminated by means of increasing the road capacity. However, the required high investment (for building the motorways and the acquisition of its right-of-way) and also the negative environmental impact can be considered as major opposite factors for developing Dutch motorways. Apart from time and environmental losses, traffic jams cause considerable reliability problems in the road system. It might endanger the pivot point function of the Netherlands in European goods distribution. Therefore, it is required to look for a set of means which might improve the efficiency of existing motorways for the goods transport. The proposed mean(s) should not lead to an unacceptable level of service for the operation of other user groups of motorways.

One of the options available to decrease congestion is the proper use of new transport technologies such as the operation of Fully Automated Vehicles instead of ordinary vehicles. In fact, Automated control has the potential to remove the human error from the driving process and provide a higher level of efficiency. Benefits of vehicle automation may be more wide reaching with attitudes toward driving moving away from an aggressive approach to an understanding of the benefits of co-operative systems.

In this research study we assess the impact of the operation of Automatically Controlled Trucks (ACTs) driving on Dedicated Freight Lanes (DFLs) in major parts of existing

motorways. The introduction of DFL would segregate the flow of ACTs from ordinary cars and might facilitate the co-operative operation of ACTs. Since, the main aim is to avoid constructing new road infrastructures like new lanes on major segments or flyovers at bottlenecks like on-/off-ramp areas, the flow of ACTs would be hindered by the flow of Manually Driven Vehicles (MDVs) at on-/off-ramp areas, necessarily. To deal with such an issue, the chosen approach of this research is to use optimization methods to minimize the hindrance of flow of ACTs by MDVs and vice versa. Since the completely segregated network for automated freight transport will not be available in the next decade, for safety reasons, the driver of an ACT remains on-board to take over the control of truck during emergency conditions.

Hence, this contribution can be characterized from other similar researches in the field of AHS from the following points of view:

a) it has focused on using the existing infrastructure (motorways) for the operation of automatically controlled trucks;
b) it has concentrated on crucial time and space situations like focusing on peak hours and bottlenecks, among which the maximum level of hindrance between user groups would be expected;
c) it has introduced the wide application of optimization methods in developing control strategies at bottlenecks.

The key questions that are addressed in this research study are as follows:

(1) what are the main benefits of the operation of ACTs?
(2) which design and control requirements should be designed for?
(3) which impacts on other user groups of roads will be expected?
(4) how it would be possible to minimize the negative impacts on other user groups (ordinary vehicles)?

**Chapter 2** gives an overview of the state-of-the-art of AHS with focus on truck automation. It has addressed PATH and CHAUFFEUR as two major research projects focusing on AHS concepts. While the first research program has considered trucks as a part of the integrated AHS concept, the second research study has focused on the operation of automatically controlled trucks (Tow-Bar trucks which are electronically coupled). The review of literature indicates that the application of dedicated lanes for automated trucks is essential. This chapter also refers to general benefits of trucks automation like the potential safety improvements, the closer longitudinal separations between trucks enabled via platooning of trucks, and the possibility for increasing the efficiency of roads during night hours for the freight transport. In this chapter, the main difference between the traffic flow theory of automated vehicles and non-automated vehicles is also argued. It is explained that a theory of AHS traffic flow will tend to be *prescriptive* since the vehicles are under automatic control. While, in non-automated vehicles the driver determines the vehicle's headway, its speed, its movement during a merge. Therefore, non-automated traffic flow theory is more *descriptive*, by contrast. Based on this benefit of operation of automated vehicles, this chapter has addressed the possible extensions of the application of optimization algorithms in the design of road layouts and traffic flow control of automated vehicles.

To treat the second key question, in **Chapter 3** we have addressed two major elements for the operation of ACTs. The first element is to assign a lane of the existing motorways to the operation of ACTs. Such a dedicated freight lane prevents a mix of ACTs and MDVs on motorway links and minimizes the hindrance of flow of ACTs by MDVs, ensures traffic safety and simplifies the operation of ACTs in platoons, and saves investment costs for the construction of additional lanes for the operation of ACTs. However, the reduction of the number of lanes for other vehicles than trucks would reduce the remaining capacity of the motorway and lead to even more congestion if the access at on-ramps is not controlled by additional means. To provide an adequate answer for the third key question it should be emphasized that the principal results of the analysis indicate that in case of a high share of trucks in the traffic flow (e.g. >20%) the creation of a dedicated freight lane at the shoulder lane of existing motorways is the most efficient option. The location of DFL on the median lane only might be considered in case of dedicated on-/off-ramps, e.g. by means of fly-overs.

The second element, named *buffer area*, is a complementary (new) means for the operation of ACTs. A buffer area provides the opportunity for regulating the flow of ACTs upstream of on-/off-ramps (by platooning and splitting the flow of ACTs). Buffer areas for ACTs may be situated close the DFL on the mainline just upstream on-/off-ramps on the mainline or at on-ramp. The application of ordinary buffer areas for MDVs at on-ramps also would be beneficial. The buffer areas for ACTs facilitate the synchronization of the speed and density of ACTs while approaching to on-/ off-ramp areas, the switch of the control mode of ACTs from manual to automatic and vice versa, and dynamic traffic management of operation of ACTs and MDVs nearby on-/off-ramps.

**Chapter 4** describes the concept of truck platooning as one of the main control strategies when automatically controlled trucks are operating on motorways. The results of simulations indicate that at on-/off-ramps, due to the hindrance of flow of platoons of trucks by crossing cars, a platooning scenario does not lead to a higher traffic performance, necessarily. The application of additional traffic control measures, like traffic signals control, is defined essential while applying a continuous platooning strategy to ensure safety specially at on-ramps. However, at off-ramps the application of traffic signals control alone is not sufficient. It still might create a very dangerous situation on the mainline, due to stopping vehicles at the back of the traffic signal control at the off-ramp. Therefore, in order to create a safe situation at off-ramp areas, it is recommended to apply an extra lane for cars leaving the mainline flow (in case of existence of the required space) or to implement an appropriate Intelligent Speed Adaptation (ISA) strategy for advanced cars on the mainline. A summary overview of results of simulations indicates the capability of truck automation for improving the performance of existing motorways. However, the benefits mostly are related to comfort and safety, rather than capacity and throughput. Thus, the optimization of flow of ACTs upstream of on-/off-ramps is heavily recommended to minimize the hindrance of flow of ACTs by MDVs. The quasi deterministic state of flow of ACTs aims to promote the application of flow control optimization models n order to provide a higher performance of traffic flow at on-/off-ramps.

Thus, in **chapter 5** we have proposed an optimization-based approach which is applied to optimize the proposed design objective by means of synchronizing the speed and density of ACTs and MDVs at on/off-ramps. The proposed model has taken into account four categories of rules (as constraints of the model) including definition of flow dynamics of ACTs and MDVs on different kinds of road segments (DFL, mainline, on/off-ramp), definition of upper and lower bounds for the decision variables (like density, speed, flow, etc.), description of merging (diverging) capacity at on/off-ramps, and required rules with regard to applying buffer areas. In order to verify the impact of different strategies of system design and control, five categories of objectives are addressed as follows: Minimization of average travel time of vehicles, minimization of total travel time of vehicles, maximization of throughput at merging (or diverging) area, minimization of fuel consumption, and maximization of safety. Then, the required equations were developed.

To provide an adequate answer for the last key question, **chapter 6** determines the impact of the synchronization of speed and density of ACTs in an on-ramp, quantitatively. This chapter also presents a sensitivity analysis of the impact of various elements and parameters of the proposed optimization model like critical density of flow of ACTs, relaxation factor of the speed equation of ACTs, the length of buffer areas, number of lanes in buffer areas, location and number of buffer areas. The findings of this chapter support the expectation that creating buffer areas with an adequate capacity, may lead to a reduction of average travel time of vehicles at merging areas by about 15%. It is also emphasized that the impact of buffer areas heavily depends on three factors: the fluctuation of traffic flow per user groups, the capacity of the merging area, and the capacity of the buffer area. Generally the findings of analysis confirm that a dramatic change in average travel time of the vehicles due to buffer areas can not be expected in cases with a mixed flow of ACTs and MDVs at merging areas.

Finally, **chapter 7** has focused on the impact of the selection of different design objectives of the traffic control system on the function of buffer areas. The findings of the analysis clearly indicates the major role of buffer areas to reach to the proposed design objective. For instance, to minimize the total travel time of vehicles in a mixed flow of ACTs and MDVs at merging areas, buffer areas can help to store some vehicles during a peak interval and then to release the stored vehicles during off-peak time. The results of the model determine how many vehicles can enter to (and similarly exit from) the buffer area within a certain time period. Based on this result, the buffer traffic controller can decide upon the most effective measures like checking or platooning of trucks within a certain time period. The analysis also confirms that giving priority to a specific user group or a specific flow direction results in a lower utilization of buffer areas which are assigned to that specific user group or flow direction.

The comparison of different objective functions in this chapter presents a more complex behavior of buffer areas with respect to objective functions like the maximization of safety or the minimization of fuel consumption, compared to the other proposed objectives. By means of applying these objective functions, it may take a longer time (more than 3 min.) for a buffer traffic controller to store vehicles inside a buffer area.

In brief, the main crucial point in this research thesis has been to focus on an integrated solution which would increase the efficiency of the existing motorways for trucks. The proposed solution, namely the operation of automatically controlled trucks on dedicated freight lanes is designed and developed in such a way to minimize the hindrance of flow of ACTs by ordinary vehicles at on-/off-ramps. However, further work along three lines of research obviously is necessary to overcome remaining questions: cost-benefit and risk analysis for all possible competitive solutions, further developments in the simulation tool used for assessing the impact of platooning scenarios, and further development of the proposed optimization model for traffic control at bottlenecks.

# Samenvatting

De toenemende congestie op autosnelwegen wordt in de publieke opinie beschouwd als een verspilling van tijd en geld, en zou bij voorkeur moeten worden verminderd door de wegcapaciteit te vergroten. Echter, belangrijke factoren die de uitbreiding van het wegennet beperken zijn de vereiste hoge investeringskosten om snelwegen aan te leggen en de bijkomende negatieve effecten op het milieu.

Behalve de negatieve effecten op reistijden en het milieu veroorzaken files een aanzienlijk betrouwbaarheidsprobleem. Dit kan zelfs de belangrijke positie van Nederland als goederendistributieland in gevaar brengen.

Het is daarom noodzakelijk te kijken naar een set van maatregelen die de efficiency van het bestaande autosnelwegennetwerk voor goederentransport kan verbeteren. De voorgestelde maatregelen zouden wel een acceptabel verkeersafwikkelingsniveau voor de andere gebruikersgroepen op de autosnelwegen moeten garanderen.

Een van de mogelijke opties om de congestie te verminderen is het gebruik van nieuwe transport technologieën zoals ‘volledige geautomatiseerde voertuigen’ in plaast van conventionele handmatig bestuurde voertuigen. Geautomatiseerde voertuigbeheersing heeft de potentie om de menselijke factor van het rijden, inclusief de menselijke fouten, te vervangen en om op die manier een hoger efficiency en veiligheidsniveau te bereiken. Voertuiggautomatisering kan ook resulteren in een beter begrip van de voordelen van co-operatieve systemen in plaats van suboptimale individuele voordelen.

In dit onderzoek worden de effecten van Automatische Bestuurde Trucks (ACTs) die rijden op aparte vrachtstroken (DFL's) op delen van het bestaande autosnelwegennetwerk bestudeeerd. De introductie van een DFL zal de trucks van de personeneauto's scheiden, en dit kan ervoor zorgen dat de ACT's co-operatief kunnen verplaatsen. Omdat het doel is om zo min mogelijk nieuwe infrastructuur aan te leggen, zal de stroom van ACT's op bepaalde punten in het netwerk worden gehinderd door de conventionele handmatig bestuurde voertuigen (MDVs). Om met dit probleem om te gaan is gekozen voor een optimalisatie methodiek om de onderlinge hinder tussen deze voertuigtypen te minimaliseren. Een compleet seperaat netwerk voor automatisch vrachtverkeer lijkt de komende decenia niet mogelijk zodat een bestuurder altijd noodzakelijk blijft aan boord van een ACT om te handelen in b.v. het geval van incidenten.

Deze contributie kan worden gekarakteriseerd van andere soortgelijke onderzoeken in het veld van automatische voertuigbesturing door de volgende punten:

a. de bijdrage richt zich op bestaande infrastructuur voor de afwikkeling van automatisch bestuurde trucks;
b. de bijdrage concentreert zich op cruciale momenten en lokaties, zoals het piekuur en knelpunten, waarbij de hinder tussen gebruikersgroepen maximaal is ;
c. de bijdrage introduceert de toepassing van een optimalisatie methodiek voor beheersstrategieën bij knelpunten;

De kernvragen die in het onderzoek worden bestudeerd zijn de volgende:

1. Wat zijn de belangrijkste voordelen van de toepassing van ACT's?
2. Welke ontwerp- en beheerseisen moeten worden toegepast?
3. Welke gevolgen kunnen worden verwacht voor de overige weggebruikers?
4. Hoe is het mogelijk om de negatieve gevolgen voor de overige weggebruikers te minimaliseren?

**Hoofdstuk 2** geeft een overzicht van de state-of-the-art van AHS (Automated Highway Systems) met speciale aandacht voor de automatisering van vrachtverkeer. Hierbij zijn PATH en CHAUFFEUR twee belangrijke onderzoeksprojecten die worden beschreven. Het eerste onderzoeksprogramma beschouwd trucks als onderdeel van een geïntegreerd AHS concept, terwijl het tweede onderzoeksprogramma zich met name heeft gericht op de toepassing van automatische trucks die electronisch zijn gekoppeld. De bestudeerde literatuur laat zien dat de toepassing van speciale stroken voor automatische trucks essentieel is. Het hoofdstuk beschouwd verder de algemene voordelen van geautomatiseerde trucks, zoals de mogelijke veiligheidsverbeteringen, de positieve efficiency effecten door platoon-rijden en de mogelijkheid om de snelwegen tijdens nachtelijke uren te benutten.

In dit hoofdstuk worden ook de belangrijkste verschillen tussen automatische voertuigen en niet-geautomatiseerde voertuigen met betrekking tot de verkeersafwikkelingstheorie beschreven. Een theorie over AHS verkeer zal een voorschrijvende theorie zijn omdat de voertuigen onder automatische control staan. Terwijl bij niet-geautomatiseerde voertuigen de bestuurder zelf de snelheid en volgafstand bepaald; en dus een beschrijvende theorie beter op zijn plaats is. Dit voordeel van geautomatiseerde voertuigen maakt het mogelijk om aanpassingen aan de weginfrastructuur te doen, gecombineerd met de toepassing van optimalisatie algoritmes voor de verkeersafwikkeling.

Om de tweede kernvraag te behandelen, worden in **hoofdstuk 3** twee belangrijke elementen voor de toepassing van ACT's behandeld. Het eerste element is de toekenning van een strook op bestaande autosnelwegen voor gebruik door ACT's. Een dergelijke vrachtstrook zorgt ervoor dat een mix van ACT en MDV niet mogelijk is, minimaliseert de hinder van de ACTs door MDVs, verhoogt de verkeersveiligheid, vereenvoudigt de werking van de ACTs in platoons, en bespaart investeringkosten voor de constructie van extra rijstroken. Echter, de reductie van het aantal rijstroken voor andere voertuigen dan trucks resulteert in een vermindering van de wegcapaciteit voor de overige weggebruikers. Dit kan zelfs tot meer congestie leiden indien de toegang tot invoegingen niet is beheerst door aanvullende verkeersmanagement maatregelen. Om tot een voldoende beantwoording van de derde kernvraag te komen wordt benadrukt dat de resultaten van de analyse aangeven dat in het geval van hoge aandelen vrachtverkeer (> 20%) een vrachtstrook aan de rechterzijde van de rijbaan de meest efficiente oplossing is. De lokatie van een DFL op de meest linkse strook kan alleen worden overwogen wanneer speciale op- en afritten voor het vrachtverkeer beschikbaar zijn; bijvoorbeeld door de aanleg van fly-overs.

Het tweede element, namelijk de bufferruimte, is een aanvullende management maatregel om de afwikkeling van ACTs beter te laten functioneren. Een bufferruimte zorgt voor de mogelijkheid om de stroom van ACTs te reguleren direct bovenstrooms van een op- of afrit (door middel van platoons met ACTs). Deze bufferruimten kunnen dicht bij de DFL worden gesitueerd, net bovenstrooms van de splitsing. Ook kunnen de buffers op de op- en afrit bevinden. De bufferruimten voor ACTs zorgen ervoor dat de snelheden en dichtheden van ACTs worden gesynchroniseerd bij het naderen van de op- en afrit, zorgen ervoor dat de ACTs van handmatige besturing naar automatische besturing kunnen worden omgeschakeld, en vice versa.

**Hoofdstuk 4** beschrijft het concept van vrachtwagen-platoons, als een van de control-strategieën indien de ACTs op de DFL rijden. De simulatieresultaten geven aan dat platoon-rijden niet hoeft te leiden tot een hogere verkeersprestatie, hoofdzakelijk veroorzaakt door de hinder van trucks door auto's nabij op- en afritten. De toepassing van aanvullende verkeersmanagement maatregelen, zoals een verkeerslichtinstallatie, is noodzakelijk bij het platoon-concept om de veiligheid voor zowel auto's als trucks in een platoon, bij het kruisen van de DFL, te garanderen.

Verder blijkt dat bij een afrit een verkeerslichtinstallatie alleen niet voldoende is, aangezien stoppende voertuigen op de hoofdrijbaan bovenstrooms van de afrit tot gevaarlijke situaties kan leiden. Op basis hiervan wordt aanbevolen om een extra strook aan te leggen voor de voertuigen die de hoofdrijbaan willen verlaten. Eventueel kan ook een intelligente snelheidsadaptatie system (ISA) worden toegepast. De simulatieresultaten laten verder zien dat toepassing van geautomatiseerde trucks de mogelijkheid heeft om de prestatie van bestaande autosnelwegen te verbeteren; maar deze voordelen richten zich dan op comfort en veiligheid in plaats van capaciteit en doorstroming.

De optimalisatie van ACTs bovenstrooms op- en afritten is aanbevolen om de hinder tussen MDVs en ACTs te minimaliseren. De quasi deterministische staat van de ACT voertuigenstroom suggereert dat toepassing van een stroom-optimaliseringsmodel kan leiden tot een prestatieverbetering van de afwikkeling nabij op- en afritten.

Vandaar dat in **hoofdstuk 5** een optimaliseringsmethodiek wordt voorgesteld dat ten doel heeft de eerder genoemde problematiek van de afwikkeling bij op- en afritten te optimaliseren door snelheden en dichtheden van ACTs te synchroniseren. Het model kent vier categorieën van regels (de beperkingen), bevat de definitie van de voertuigstroom dynamica van zowel de ACTs als de MDVs op verschillende wegsecties (DFL, hoofdrijbaan,op/afrit), de grenzen van beslissingsvariabelen zoals dichtheid, snelheid en intensiteit, de beschrijving van de invoegcapaciteit, en het functioneren van de bufferruimten.

Vijf categorieën van doelen zijn gedefinieerd om de invloed van verschillende control-strategieën op de systeemprestatie te evalueren: minimalisatie van de gemiddelde reistijd, minimalisatie van de totale reistijd, maximalisatie van de doorstroming, minimalisatie van het brandstofverbruik, en maximalisatie van de veiligheid. De overeenkomstige algoritmes van het model zijn dan in meer detail ontwikkeld.

Om een adequaat antwoord op de laatste kernvraag te krijgen wordt in **hoofdstuk 6** geanalyseerd wat de gevolgen zijn van snelheids- en dichtheidssynchronisatie van ACTs nabij een oprit. Verder wordt een gevoeligheidsanalyse gepresenteerd waarin de verschillende elementen en parameters van het optimalisatiemodel worden gevarieerd. Dit zijn onder meer de kritische dichtheid van de ACT’s, de bufferlengte, lokatie en aantal buffers, en het aantal bufferstroken. De resultaten ondersteunen de verwachting dat de aanleg van bufferruimten met voldoende capaciteit kan leiden tot een reductie van de gemiddelde reistijd (over het beschouwde segment met oprit) met circa 15% . Het wordt benadrukt dat de invloed van bufferruimten met name van drie factoren afhangt: de fluctuaties van de intensiteiten per gebruikersgroep, de capaciteit van de rijbaan met oprit, en de capaciteit van de bufferruimte. In het algemeen kan worden gezegd dat de resultaten bevestigen dat een aanzienlijke verandering in de gemiddelde reistijd niet kan worden verwacht met een mix van ACTs en MDVs op het knelpunt en toepassing van een buffer.

Als laatste wordt in **hoofdstuk 7** ingegaan op de gevolgen van de keuze van verschillende ontwerpdoelen van het verkeersmanagementssysteem op het functioneren van bufferruimten. De resultaten van de analyse geven duidelijk de rol aan van buffers om de voorgestelde ontwerpdoelen te bereiken. Om bijvoorbeeld de totale reistijd van voertuigen in een mix van ACTs en MDVs bij een knelpunt te minimaliseren kan een bufferruimte voertuigen opslaan gedurende een drukke periode, en weer laten gaan tijdens een wat minder drukke periode. De resultaten van het model bepalen hoeveel voertuigen de bufferruimte kunnen betreden binnen een zekere tijdsperiode. Hierop gebaseerd kan de buffer controller beslissen wat de beste, meest effectieve maatregelen zijn, zoals b.v. platooning. De analyse bevestigt verder dat het geven van prioriteit aan een bepaalde gebruikersgroep of aan een bepaalde richting resulteert in een lager gebruik van de bufferruimten die waren toegekend aan die specifieke gebruikersgroep of richting.

De vergelijking van verschillende doelfuncties in dit hoofdstuk laten een complex gedrag zien van bufferruimten ten aanzien van de doelfuncties zoals de maximalisatie van veiligheid of de minimalisatie van brandstofverbruik, vergeleken met de andere doelen. Door het toepassen van deze doelfuncties zal de wachttijd meer dan drie minuten bedragen.

In het kort, het cruciale punt in deze dissertatie is gericht geweest op een integrale oplossing die de efficiency van truckverkeer op bestaande autosnelwegen kan doen toenemen. De voorgestelde aanpak, het gebruik van geautomatiseerde trucks op een speciale vrachtstrook is geanalyseerd, waarbij getracht is om de hinder van de ACTs door MDVs te minimaliseren. Hiertoe is het bufferconcept geïntroduceerd en aangevuld met verkeersmanagementmaatregelen, zodat grote investeringen in fly-overs achterwege kunnen blijven. Hoe dan ook, nader onderzoek zal noodzakelijk blijven om andere vragen te beantwoorden, b.v met betrekking tot kosten en voordelen, de risico’s, de ontwikkeling van het simulatiemodel voor platoon-rijden, en verdere uitbreidingen van het optimalisatiemodel voor afwikkeling bij knelpunten.

# خلاصه


رشد روزافزون راهبندان در آزادراهها, در اذهان عمومی مردم مترادف با اتلاف زمان و هزینه بوده و عقیده عموم بر آن است که از طریق افزایش ظرفیت آزادراهها برای این مشکل بایستی چاره اندیشی شود. اما, سرمایه گذاری هنگفت لازم برای ساخت آزادراههای جدید (و یا تعریض آزاد راههای موجود) و تامین حریم این راهها و همچنین اثرات منفی زیست محیطی ناشی از این توسعه از جمله مهمترین عواملی هستند که مانع توسعه شبکه آزادراهها در کشور هلند میباشند.

علاوه بر مسائل فوق, راهبندان ها سبب بروز مشکلات زیادی در قابلیت اعتماد استفاده کنندگان راهها به سیستم حمل و نقل جاده ای میشوند که این موضوع به نوبه خود میتواند نقش کلیدی هلند در شبکه توزیع کالا در اروپا را با خطر مواجه سازد. بدین ترتیب , توجه به مجموعه ای از ابزار های مدیریت حمل و نقل جاده ای که سبب بهبود کارائی شبکه موجود آزاد راهی کشور برای جابجایی کالا شود ضروری میباشد. این مجموعه ابزارهای مدیریتی بایستی بگونه ای طراحی گردد که حد اقل سطح خدمت ارائه شده به سایر استفاده کنندگان شبکه آزادراهی (بجز کامیون ها) در شرایط موجود کماکان حفظ شود.

یکی از روشهای موجود برای کاهش راهبندان, استفاده مناسبتر از فن آوری های جدید صنعت حمل و نقل همچون حرکت وسایل نقلیه کاملا هوشمند بجای وسایل نقلیه معمولی میباشد. کنترل هوشمند این توانایی بالقوه را دارد که خطا های ناشی از نقش نیروی انسانی در راندن را حذف نماید و بازدهی و ایمنی افزون تری را سبب گردد. منافع ناشی از عملکرد وسایل نقلیه هوشمند به سبب زمینه سازی ارتباط بهتر بین وسایل نقلیه , بجای توجه به منفعت فردی هر یک از رانندگان در روش فعلی , بمراتب قابل توجه تر خواهد بود.

در این تحقیق , اثر عملکرد کامیون های کاملا هوشمند (ACT) بر روی خطوط مخصوص بار در بخشهای مشخصی از شبکه آزاد راهی موجود تعیین خواهد شد. از آنجائیکه هدف اصلی این مطالعه اجتناب از توسعه عمده زیر ساختها میباشد لذا جریان ترافیک کامیون های کاملا هوشمند در محل ورودی و خروجی آزاد راهها بناچار تحت تاثیر جریان ترافیک وسایل نقلیه عادی (MDV) قرار خواهد گرفت. برای حل این موضوع , روش پیشنهادی این تحقیق , استفاده از مدلهای بهینه سازی میباشد بگونه ای که هر یک از دو جریان ترافیک هوشمند و عادی حداقل تاثیرمنفی را بر یکدیگر گذارند.

در این مطالعه, بواسطه حفظ ملاحظات ایمنی, حضور راننده در کامیون هوشمند ضروری فرض شده که در صورت وقوع شرایط اضطراری در مسیر, راننده کنترل کامیون را بدست خواهد گرفت.

این تحقیق از سایر تحقیقات مشابه در زمینه حرکت وسایل نقلیه در محیط های هوشمند (AHS) بواسطه دلایل زیر متمایز میباشد:

الف- تمرکز بر استفاده از زیر ساختهای موجود است,
ب- به زمانهای اوج و مکانهای بحرانی ( گلوگاههای شبکه) اشاره دارد,
پ- روشهای بهینه سازی را برای تدوین روشهای کنترل جریان ترافیک مورد تاکید قرار داده است.

سوالات کلیدی که در این تحقیق بدانها پاسخ داده شده است عبارتند از:

- مزایای اصلی عملکرد کامیونهای کاملا هوشمند چیست؟
- چه نوع ملاحظات طراحی و کنترل جریان ترافیک در حین عملکرد کامیونهای کاملا هوشمند بایستی مورد توجه قرار گیرد؟
- عملکرد کامیونهای کاملا هوشمند چه نوع عوارضی را برای سایر استفاده کنندگان راهها ایجاد خواهد کرد؟
- چگونه میتوان عوارض مورد اشاره در بند فوق را به حداقل رساند؟

# About the Author

Masoud Tabibi was born in 1967 in Qom, Iran. He finished his high school studies in Mathematics and Physics in Qom. In 1985, he passed the national exam test successfully to start his Bachelor of Science in the civil engineering field of knowledge in Tehran University, Iran. After 5 years, he obtained his B.Sc. degree and became a civil engineer. In 1991, he was nominated as the first-rank candidate in the annual national exam in Iran to promote his knowledge in the field of Transport Planning and Traffic Engineering in the the Sharif University of Technology in Tehran, Iran. In 1994, Masoud obtained his M.Sc. degree successfully. During 3 years studying in the university, he also tried to get experiences about working in consulting engineering companies and governmental organizations.

After one-year doing military service in the Iran Air Force, he moved to the Transport and Terminals Organization (TTO), affiliated to the Ministry of Roads and Transport of Iran, to work in this organization to achieve the remaining one-year of his military service, as a civil servant. In TTO, as a member of team of conductors, he accomplished projects like the improvement of methods for traffic counting on Iranian road network and the location of container terminals throughout Iran. He also had contributions in the provision of Iranian guidelines for design of roads (in outside built-up areas) and intersection designs (in built-up areas) for other organizations.

Then, in 1996, Masoud moved to the Ministry of Interior Affairs of Iran and became a member of the secretariat office of the national council for urban traffic. During 2 years working in this office, he switched to urban traffic to get experiences about required traffic measures and means for traffic calming at built-up areas and prioritization of actions.

In 1998, Masoud awarded an abroad scholarship by the Ministry of Science, Research and Technology of Iran (devoted to TTO of Iran) to continue his education. Since June 1999, Masoud joined the Transport and Planning section of the Faculty of Civil Engineering and Geosciences of Delft University of Technology in the Netherlands. He conducted his research work in the framework of the Freight Transport Automation and Multimodality (FTAM), as a member of the TRAIL; The Netherlands Research School for Transport, Infrastructure and Logistics. His work resulted in a number of papers in the national and international conferences and contributions in proceedings and a book.

In parallel to his research work in The Netherlands, as the representative of TTO of Iran in the Netherlands, Masoud organized several training courses for Iranian managers and junior researchers, both in Iran and the Netherlands, and tried to provide a required basis for the sustainable relationship between Iran and the Netherlands in this field. Since transport and traffic engineering can be addressed as a (rather) new field of knowledge in Iran, Masoud’s opinion is that holding professional training courses and workshops for Iranian employees are among the most important needs of Iran. It might lead to such an idea that a sustainable relation with Iran in the field of road transport could be guaranteed by focusing on *transfer of knowledge* as a fundamental requirement, and then working on industrial activities in the transport sector, as a secondary step.

Since road safety for the coming years would be among the major challenges of Iran, the establishment of a (inter-)national road safety academy in Iran is the most important goal of Masoud at this moment. He hopes to be able to play a role in the establishment and organization of such an academy. His opinion is that Iran has a lot of capabilities for showing its capabilities in the international society, however, needs a real willing! And it is not too far …

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