Coordination Concepts for Ramp Metering Control in a Freeway Network

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Abstract: The steadily increasing numbers and lengths of traffic jams on freeways have led to the application of Dynamic Traffic Management (DTM) measures all over the world. Ramp metering control has proven to be one of the most efficient means to reduce freeway congestion. Currently, it is expected that integrated and coordinated application of DTM measures will further improve its impact.

This paper studies a coordinated ramp metering control algorithm called HERO/RWS. This algorithm has been developed for the current Dutch ramp metering systems and it will be applied on the Amsterdam A10 freeway network in the near future. The aim of this algorithm is to postpone congestion on freeways by effectively using ramp storage space from upstream on-ramps. VISSIM-based microscopic simulation results show that the HERO/RWS coordinated control outperforms non-coordinated ramp metering control. Parameter settings have been optimized for the specific A10-west network through a robustness study. In addition, the concept of coordination between ramp meter and upstream intersection traffic controllers is developed. The feasibility of this idea has been proven by a simulation study.

Keywords: HERO/RWS ramp metering coordination algorithm, upstream intersection coordination, Amsterdam A10 beltway, microscopic simulation.

1. INTRODUCTION

The steadily increasing numbers and lengths of traffic jams on freeways are a source of inconveniences for road users and for the society, as is reflected by increasing total travel times, economic losses, environmental pollution, and reduced traffic safety. Part of the problem is believed to be caused by an underutilization of the existing infrastructure. In other words, better utilization of the network can be a solution to manage congestion better, next to *increasing* the capacity by expansion of infrastructure and *reducing* traffic demand by pricing. Ramp metering is amongst the most efficient measures to improve the problem mentioned above (Papageorgiou and Papamichail, 2007). At present, Dynamic Traffic Management (DTM) tends to focus on the integrated and coordinated deployment of measures. So an integrated control strategy on a network-wide level is needed.

The ring-road A10 around the city of Amsterdam is one of the busiest urban freeways in the Netherlands. Several consecutive on-ramps have been equipped with ramp metering controllers since 1989 (Middelham and Taale, 2006). In the near future, the remaining on-ramps along the A10 will also be equipped with ramp metering controllers. In order to further exploit the effect of local control, a coordinated ramp metering control algorithm, the HERO/RWS algorithm (HERO refers to HEuristic Ramp metering coOrdination; RWS is the commissioning organization), has been developed for the current Dutch ramp metering systems and it will be applied to the whole A10 network in the near future (Cappendijk, 2007). This algorithm has been based on the HERO algorithm (Papamichail and Papageorgiou, 2007), but it has been adapted to the Dutch situation. Furthermore, a new concept for better utilization of ramp metering has been developed. This idea relies on coordinating the ramp meter with the related upstream urban traffic intersection controller.

The effects of installing the proposed HERO/RWS algorithm, however, are still unclear to the government. So, correctly identifying and analyzing the effects and consequences is crucial to develop and implement a coordination control scheme to enhance the performance in the whole Amsterdam freeway network. Microscopic simulation is expected to provide a more detailed description of the traffic flow operations. In the study described in this paper, simulations have been performed using VISSIM (a microscopic traffic model with the capability of connecting external control interfaces) to investigate the algorithm. Additionally, the robustness of the HERO/RWS algorithm has been studied.

The province of North-Holland and the municipality of Amsterdam have developed a management philosophy for the freeway network (Cappendijk, 2007). The main aim in the philosophy is to keep the A10 ring-road free of congestion. This leads to a control strategy of reducing the inflows of the underlying urban network, increasing the outflows to the underlying urban network and buffering the traffic on freeways leading towards the A10. In our project, we also looked to what extent the HERO/RWS algorithm meets these requirements.

The next section will provide a brief state-of-the-art on ramp metering and its coordination. Then, the details of the HERO/RWS algorithm and the concept of the upstream intersection coordination are described, followed by a brief description of the methodology and the case study on the A10-West network to assess the HERO/RWS. Then, VISSIM-based simulation results are presented. Moreover, the concept of the upstream intersection coordination is introduced together with some discussion. The conclusions and further research in this field are given in the last section.

2. STATE-OF-THE-ART

In this section, more details of the literature study are given on local control and coordinated control, respectively.

2.1 Local Ramp Metering Control

The aim of local ramp metering control is to reduce the inflow from the on-ramp to the freeway in order to postpone congestion on the freeway since this would lead to a capacity drop (free flow capacity is higher than the queue discharge rate). Apart from shorter travel times on the freeway, secondary blocking of upstream off-ramps is prevented. For *individual ramp metering control*, the most popular strategies are the Demand Capacity (DC) strategy, ALINEA and variations of these concepts.

The DC strategy (Masher et al., 1975) is a *feed-forward* control, comparing primarily the incoming freeway flow to an assumed pre-specified capacity value. Such a pre-fixed capacity value may lead to further efficiency degradation due to the fact that in reality the capacity is stochastic (Papageorgiou and Papamichail, 2007). ALINEA control (Papageorgiou et al., 1991) is a *feedback* strategy in which the inflow is determined as proportional to the difference between the ideal occupancy and the observed occupancy.

In the Netherlands, the RWS strategy is used in field applications (Middelham and Taale, 2006). This strategy is a variation of the DC strategy. Real-time traffic data in the Netherlands are measured with double inductive loops. Control activation and deactivation are based on speed and flow thresholds (e.g. 70/80 km/h, 1650/1500 veh/h/lane). When the speed on the freeway upstream or downstream of the on-ramp drops, the metering will reduce the inflow from the on-ramp to a minimum. When the queue on the on-ramp becomes too large, the access from the on-ramp is set to a maximum.

There are some 35 locations in the Netherlands using the RWS ramp metering control (Taale, 2003). Stanescu (2008) has investigated whether a value of capacity based on current conditions would improve the impact of the RWS algorithm and obtained positive improvement. Due to the limited storage space of a single on-ramp, the local control does not address the problem of optimal coordinated utilization of the overall infrastructure, nor does it guarantee an even distribution of queues over the ramps. Hence, a coordination strategy is needed.

2.2 Coordinated Ramp Metering Control

An alternative would be to reduce the flow on the freeway by activating an upstream controller, the so-called *coordinated ramp metering control*. This will spread the extra waiting time over multiple on-ramps, thus causing equity in the network. The literature offers a number of different coordinated control strategies, some of which are in operational use, mainly in the USA, some in Australia (Papageorgiou and Papamichail, 2007). These strategies may be subdivided into optimal control strategies (Papageorgiou and Kotsialos, 2002), hierarchical control strategies (Kotsialos et al. 2005) and rule-based strategies.

Rule-based algorithms apply appropriate heuristic rules to the input data in order to approximate optimal settings for each individual ramp metering system. Contrary to the other two strategies, these strategies are actually implemented and operated. The HERO algorithm, as one of various rule-based strategies, is regarded as the most promising approach for large-scale field application of coordinated ramp metering (Papageorgiou and Papamichail, 2007). The HERO algorithm incorporates local ALINEA regulators. When the queue of an on-ramp becomes larger than a predetermined threshold, then the burden of decreasing this queue is assigned to upstream on-ramps. This algorithm has been shown to reach the efficiency of more complex, model based control schemes (Papageorgiou and Papamichail, 2007; Papamichail and Papageorgiou, 2007).

3. INTRODUCTION TO HERO/RWS

By implementation of hierarchical coordinated strategy using the optimal control tool "AMOC", Kotsialos et al. (2005) have reported positive simulation results on the ring-road A10. However, to implement the control strategy in AMOC in practice is very complex and not yet operational. So, the Dutch ministry of transport developed a ramp metering coordination strategy (HERO/RWS algorithm) for the Dutch freeway network (Cappendijk, 2007). This algorithm creates a variant version of the standard HERO algorithm which uses ALINEA regulators, instead incorporating local RWS controllers. Nevertheless, the basic concepts of HERO (Papamichail and Papageorgiou, 2007) and HERO/RWS are similar, namely rule-based control strategy.

In the HERO/RWS algorithm, individual ramp metering (RM) systems operate isolated as long as no need exists for coordination. When the queue on a certain on-ramp (referred to as "*master*" in the ensuing) exceeds some predefined threshold length, HERO/RWS starts gradually recruiting upstream ramp metering controllers (so-called "*slaves*") to support the metering task of the master. The reason for recruiting slave ramps is to enlarge the useable storage space that would otherwise be limited to the storage space available at the master ramp only. More specifically, it aims at preventing the queue on the master ramp from spilling back to urban intersections as well as limiting inflow onto the freeway. The underlying principle of this algorithm is to postpone the occurrence of congestion on freeways based on more storage space on the successive on-ramps, leading to higher freeway outflow and lower total travel times both on freeway and urban networks.

To facilitate the coordination control, a CVMS (Central Traffic Signal Control Management System) controller is used to communicate and coordinate with each local controller. This coordination controller reads data from each ramp metering controller, consisting of RM control status, current ramp queue length and maximum admissible ramp queue lengths. As soon as one of the ramps has a queue longer than the threshold length, the ramp is assigned as master over its upstream ramps, which become slaves (usually 4~6 slaves). The slaves are informed of a minimum queue length to maintain, which is chosen such that queue lengths are approximately equal for master and slaves. This minimum is updated when the master queue further increases due to increasing demand. As soon as the master queue is below the threshold, the cluster of master and slaves is dissolved. The specific control scheme of the HERO/RWS algorithm can be found in (Yuan, 2008).

The features of this control concept are simple, real-time operable and efficient. The HERO/RWS algorithm has been assessed using a microscopic simulation environment for the A10 network. The details of the proposed research methodology and the case study are described in section 4.

4. ASSESSMENT METHODOLOGY

VISSIM is a microscopic simulation tool in which external traffic control algorithms can be implemented and tested via an external interface (Kaal, 2007). In this study, HERO/RWS is tested in VISSIM for the Amsterdam A10-west network. Dynamic assignment procedures are used for traffic distribution and this function is able to model route choice behavior with respect to different control strategies.

For a structured identification of the assessment objectives, the following types of objectives may be considered: technical objectives, impact objectives, user acceptance objectives, socio-economic evaluation, market objectives, and financial objectives (Zhang et al., 1998). For the purpose of this study, we focus on assessment of the impact on traffic system and users. The main actors in this study are the Directorate-General for Public Works and Water Management, the municipality of Amsterdam and the road users. In Table 1, an overview is given of the global assessment questions, the specific assessment questions, and the assessment indicators.

We consider and compare three different scenarios: the null scenario (no RM), scenario 1 (non-coordinated RM) and scenario 2 (RM coordinated by HERO/RWS). Since VISSIM is a stochastic model, ten simulation runs are performed to get an average result, each with different random seeds. This appears to be sufficient to get representative and reliable results (Yuan, 2008).

Table 1. Overview of assessment questions and indicators

Global assessment objective	Specific assessment objective	Assessment indicator
What are the traffic conditions for the complete network?	How long do vehicles in total spent in the network?	Total time spent (TTS) by all vehicles in the network (freeway & urban road)
	What is the effect on route choice?	Total distance travelled in the network
What are the effects for individual vehicles?	What is the effect on average travel time per vehicle?	Average travel time for each vehicle in the network
		Average travel time on the main surveyed stretch (see Fig. 1)
		Mean speeds of segments on the main surveyed stretch
How are the effects distributed over the freeway and the on ramps?	What is the effect of the measure on the considered freeway stretch?	Total throughput of the main surveyed stretch
		Speed contour plot of the related freeway stretch
	What is the effect of the measure on the on ramps?	Average delay time on each on-ramp
		Usage (throughput) of each on-ramp

Another aim of this project is to perform a robustness study to optimize the parameter settings of the HERO/RWS algorithm for real implementation. The parameter groups in the control process are the activation and deactivation thresholds (in relation to relative queue length on the on-ramp (%)) in HERO/RWS and the critical speed (km/h) and flow (veh/h) values for individual controllers. The robustness study therefore focuses on these three parameters. The default values (30/15%, 70/80 km/h, 1650/1500 veh/h/lane) for these parameters are obtained from the settings in the standard ramp metering application or estimated given available literature and expert experience (Cappendijk, 2007). In the study presented here, a total of 12 scenarios (named A to L) are chosen. Scenario A with default settings is considered as reference. In scenarios B through F, HERO/RWS control threshold are changing from 10/5 to 60/30. Scenarios G and H are using 65/75 and 75/80 as speed thresholds respectively. The flow thresholds are varied between 1350/1200 and 1950/1800 in scenarios I to L. In these scenarios, all other parameters are maintained as default. To fully investigate the robustness and applicability of the proposed parameter settings, simulation tests are conducted under various traffic demands. Based on the reference network with proper traffic demand, a less-congested network and an over-congested network are considered in the robustness study.

5. CASE STUDY

A VISSIM model is built to simulate a part of the Amsterdam A10 beltway network, where the existing four ramp meters are located, as shown in Fig. 1. The main research stretch is restricted to the freeway section from S105 to the Coentunnel (see yellow oval in Fig. 1). The main study area from S105 to S101 is divided into four segments, each of which contains one ramp metering controller. The afternoon peak period between 15:30 and 18:00 has been chosen as the simulation period. The first half hour is regarded as warming-up. Fixed-time control is adopted for the urban intersections. The pre-fixed capacity value is assumed to be 2200 veh/h/lane for the ramp metering configuration. Based on the geographic lengths of each on-ramp, the maximum admissible lengths (in number of vehicles) are 36 (S101), 32 (S102), 18 (S104) and 18 (S105), respectively.

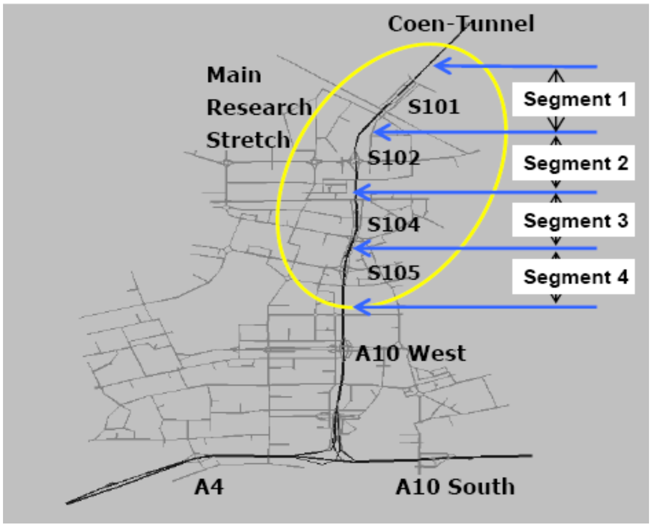


Fig. 1. Simulation model of Amsterdam A10-West.

The simulator has been connected with RWS controllers and the CVMS controller via the VriVissim interface (Kaal, 2007) for traffic signalling control. The data exchange between different controllers has been realized via link cables provided by the control interface based on the Dynamic Data Exchange (DDE) communication technique. Matlab has been used to batch process iterative simulation runs as well as to process the raw-data from simulation. The complete simulation environment is illustrated in more detail in Fig. 2.

Based on empirical data collected by double inductive loop detectors, the calibration and validation of the model have been performed for the main study stretch in order to reproduce a realistic traffic pattern featuring congestion. More details of model assumptions and modelling are described in (Yuan, 2008).

6. HERO/RWS ASSESSMENT

In this section, the simulation results and the scenario comparisons for the HERO/RWS algorithm are presented.

6.1 Impact assessment

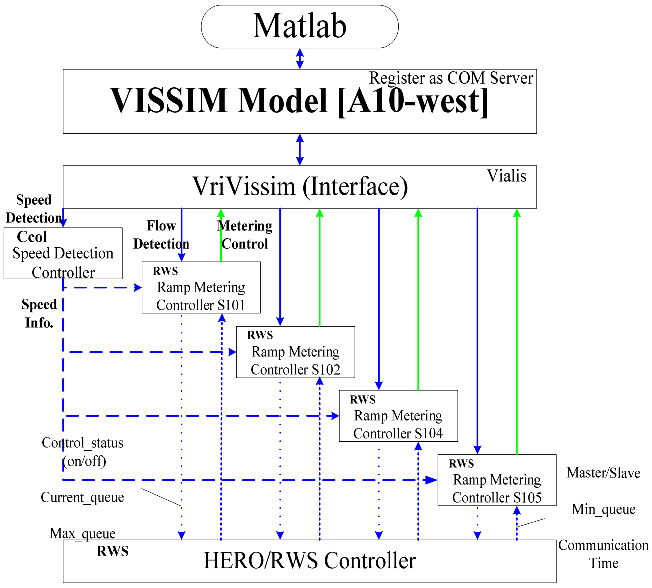


Fig. 2. VISSIM simulation environment (blue lines indicate data streams; green lines indicate control streams).

For the impact assessment, three scenarios have been tested in VISSIM. The integrated results are presented in Table 2. Although the overall performance of HERO/RWS in the network is the best of the three scenarios, the results at the system-level are not statistically significant. However, the changes on the freeway section are significant. In scenario 1 and scenario 2, the average travel time on the freeway decreases by 24.15% (scenario 1) and 25.67% (scenario 2) respectively compared to the reference. The average travel time in scenario 2 is 10 seconds less than that in scenario 1, which is a 2.00% improvement. The coordinated control is the main reason of the positive effect, both for the freeway and for the whole traffic network. Moreover, the mean speeds on the first two segments (S101 and S102) of the freeway are improved. This is the main reason of the decrease in average travel time. In scenario 2, the increase of the mean speed on segment 1 is even higher than 50% compared to the no-control case. This improvement is caused by the fact that the inflows are metered at on-ramps to limit the flow on the freeway.

The speed contour plots derived for the three scenarios illustrate the traffic performance on the freeway, as shown in Fig. 3a, b and c. What is worth mentioning here is that the congestion in scenario 2 occurs later than that in the null scenario and scenario 1, as indicated with vertical lines. As shown in Fig. 3c, during the first half hour from 16:00 to 16:30, the queue's growth rate (shockwave speed) is lower than in the previous two cases. In the congested area, the overall speed indicated in Fig. 3c is also higher than that in Fig. 3b. This is again evidence for the benefits from the HERO/RWS coordinated control, to enlarge storage space to postpone congestion.

Due to the amelioration of traffic conditions, the total throughput of the freeway in the two control cases increases, as presented in Table 2, with 5.49% and 5.69% improvement respectively compared with the null scenario. That means that the outflow of the freeway increases.

The following discussion focuses on urban traffic around the main area related to the so-called *equity*. The term “equity” used here has two meanings. First, it describes the fairness between the freeway traffic and the urban traffic. According to the Amsterdam management philosophy, the priority should be given to freeway traffic. The HERO/RWS strategy turns out to be unfair to the travellers on the urban network: the resulting total delay time for the traffic using the four on-ramps in scenario 2 increases by 2.59% compared to scenario 1. Nevertheless, the new control scheme meets the objective of Amsterdam by reducing delay on the freeway at the expense of inducing more local delay. Second, the equity is required over the on-ramps. In non-coordinated control, it is unfair that huge delays occur at S101. HERO/RWS orders the slave ramp metering to start control earlier than scenario 1. Consequently, the queues formed at upstream on-ramps occur earlier as well. The HERO/RWS algorithm distributes delay in a more balanced way over the on-ramps within a coordination control string, by activating upstream located ramp meters and thus inducing more delay there.

In summary, the HERO/RWS algorithm outperforms the no-control and non-coordinated control networks. It is able to postpone congestion on the freeway at the expense of inducing more unfair local delay. On the other hand, HERO/RWS improves the equity requirement for each on-ramp within a coordination control string.

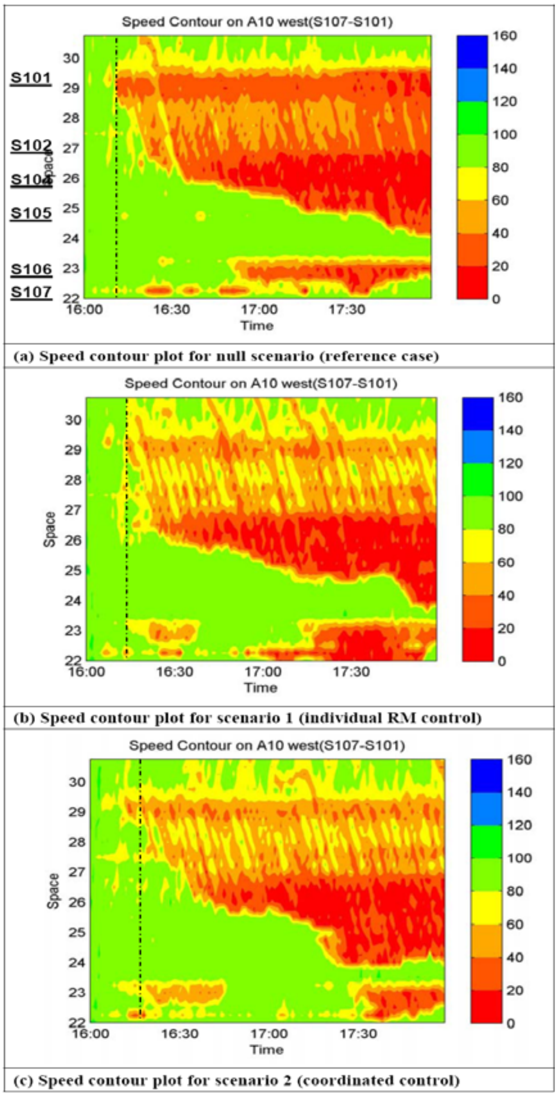
Table 2. Integrated Simulation Results for the Three Scenarios from 10 Simulation Runs.

Simulation Time Period: 16:00-18:00		Null Sce.	Sce. 1		Sce. 2		
		Value	Value	Impr. (%)	Value	Impr. to null sce.	Impr. to sce. 1
TTS [a]		9834.8	9781.2	-0.54	9803.6	-0.32	0.23
Ave.TTN [b]		599.5	594.9	-0.78	588.1	-1.90	-1.13
TDist [c]		5302.7	5317.6	0.28	5388.8	1.62	1.34
Ave.TTM [d]		625.2	474.2	-24.15	464.7	-25.67	-2.00
Throughput [e]		8383	8843	5.49	8859	5.69	0.18
Mean speed [f]	Seg.1	34.5	50.4	46.24	52.1	51.35	3.49
	Seg.2	48.2	618	28.28	63.0	30.75	1.93
	Seg.3	37.9	35.5	-6.44	36.3	-4.27	2.31
	Seg.4	57.0	58.2	2.23	56.9	-0.07	-2.25
ADT [g]	S101	7.6	102.7		105.5		
	S102	0.3	27.4		27.5		
	S104	7.9	31.6		31.6		
	S105	22.2	15.6		8.9		
Starting time (Slave) [h]	S102		43		21		
	S104		38		21		
	S105		75		21		

[a] total time spent (TTS) in the whole network (in 2 hours) (veh*h), [b] average travel time in the network (seconds), [c] total distance travelled in the network (veh*km), [d] average travel time on main study area (seconds), [e] total throughput of the main study area (vehicles), [f] mean speed on each segment (km/h), [g] average delay time per car (seconds), [h] starting control time of slave ramps (minutes).

6.2 Robustness study

The overall results of twelve proposed scenarios with respect to the changed parameters can be found in Yuan (2008). Here, a discussion of the result is presented. First, we discuss the activation/deactivation thresholds for HERO/RWS. Referring to scenarios A to F, it is found that the 50%/25% combination in scenario E outperforms the other parameters under the less congested traffic network and the normal demand network. Obviously, lower threshold values result in earlier control activation of the upstream slave controllers. Although the new combination (50%/25%) is higher than the default value, it is able to make efficient use of the upstream storage space by ordering higher minimum desired queue lengths at slave on-ramps while it does not activate the slave controllers too late. However, in over-congested networks, the performance based on this setting is not as good as expected. So this setting is not robust, as the related system is not able to cope with variation in traffic demand.



(a) Speed contour plot for null scenario (reference case)
(b) Speed contour plot for scenario 1 (individual RM control)
(c) Speed contour plot for scenario 2 (coordinated control)

Fig. 3. Graphical results for the three scenarios.

In scenario G and scenario H, the traffic situation on the freeway does not seem to be sensitive to the speed switch values. However, in the over-congested network, the system with a 75/80 km/h setting in scenario H outperforms the reference scenario. Similar to the property of thresholds for HERO/RWS, higher speed thresholds, resulting in much earlier control activations, are beneficial in overloaded networks.

The last four scenarios study the flow thresholds. It is found that the system with the 1800/1650 veh/h setting performs best, also in the over-congested network. It can thus be concluded that this setting is optimal and a robust choice for the existing surveyed traffic network.

7. UPSTREAM INTERSECTION COORDINATION

7.1 Concept of coordination with upstream intersections

As stated before, one of the main reasons for coordinated ramp metering is the limited ramp storage space. Other than calling for co-operation of upstream ramps to avoid congestion, one can also call for storage space from urban upstream intersections. This idea has been derived from the traffic management philosophy presented above.

The basic control strategy for this coordination is that once the congestion occurs on the on-ramp, the upstream urban intersection controllers would use another pre-defined control scheme, in which the green times of the streams towards the on-ramp would be shortened in order to limit the inflow for the on-ramp and buffer the traffic towards the freeway. These green times are determined dynamically depending on the queue lengths on on-ramps.

In the Netherlands, vehicle-actuated control programs are used for urban intersections (Van Katwijk, 2007). Inductive loop detectors are used to get information about the actual traffic situation in order to generate real-time traffic control schemes. On-ramp congestion information can also be detected by detectors and sent to local intersection traffic controllers to realize the coordination.

7.2 Discussion

In order to test this concept, on-ramp S102 coordinated with its nearest upstream intersection is simulated as an example (more upstream intersections could be coordinated under this concept). The similar data exchange principle as presented in Fig.2 applies to this kind of coordination. The coordination between ramp meter and its upstream intersection controller works well in VISSIM. The effect of this coordination is clear.

When isolated control both for on-ramp and the related urban intersection is chosen, the congestion occurs on the on-ramp S102. Once the coordination with the upstream intersection is activated, the congestion on the on-ramp disappears. Instead, urban queues form at the intersection and local traffic is buffered. This coordination is feasible in terms of the traffic management objective in the target area.

However, the overall waiting time formed at the urban intersection is much higher than the time spent by the same vehicle group at the on-ramp. This leads to much higher travel times for urban traffic. One reason is that the pre-defined intersection control scheme used in the on-ramp congestion state needs to be configured and calibrated to realise a local optimum. Meanwhile, it should be kept in mind that DTM measures have a large impact on the whole transport system. So this effect is acceptable only if a clear policy is in place that gives priority to freeway fluidity over urban congestion.

8. CONCLUSIONS AND RECOMMENDATIONS

The VISSIM simulations performed in this study show that HERO/RWS coordination control offers potential improvement over individual ramp metering control, in accordance with the control objectives established for this region. Although it may induce more delay on the urban network compared to the individual ramp metering, it turns out to provide less congestion, higher mean speeds and lower travel time spent on the freeway. Furthermore, the HERO/RWS algorithm distributes the delay in a more balanced way over consecutive on-ramps.

Based on the given traffic information, parameters within the HERO/RWS control scheme have been optimized for the specific traffic network of the A10 west. Although this will give a good indication of the robustness of the parameters, the parameters will need to be further tested and tuned when the algorithm is implemented in reality.

Further improvements on coordinated ramp metering can be obtained, apart from extending the number of ramps involved, but especially from the application of the ALINEA algorithm in the individual ramp metering systems. The *feed-forward* RWS controllers that were applied in the case study, in order to reflect the actual situation on the Dutch freeways, have a number of disadvantages that are likely to influence the coordination results in a negative way.

The coordination concepts for ramp metering control presented in this paper have two aspects. To avoid congestion on the freeway is not only using more space on upstream on-ramps but also on the urban network. The coordination between ramp meters and upstream urban intersection controllers does provide more flexibility to buffer traffic flow towards to freeway network at the expense of urban traffic delay. More detailed analyses and further developments about the intersection control scheme in congested state are needed to reach a local optimum.

In VISSIM the route choice model is based on experienced travel time, while in reality, route choice depends on many factors, such as personal preference, experience or comfort. Further research is needed on the effect of the HERO/RWS algorithm and upstream intersection coordination on route choice behaviour as well as departure time choice. It would be helpful for road management authorities to include other additional DTM measures in a coordinated way, such as route guidance.

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