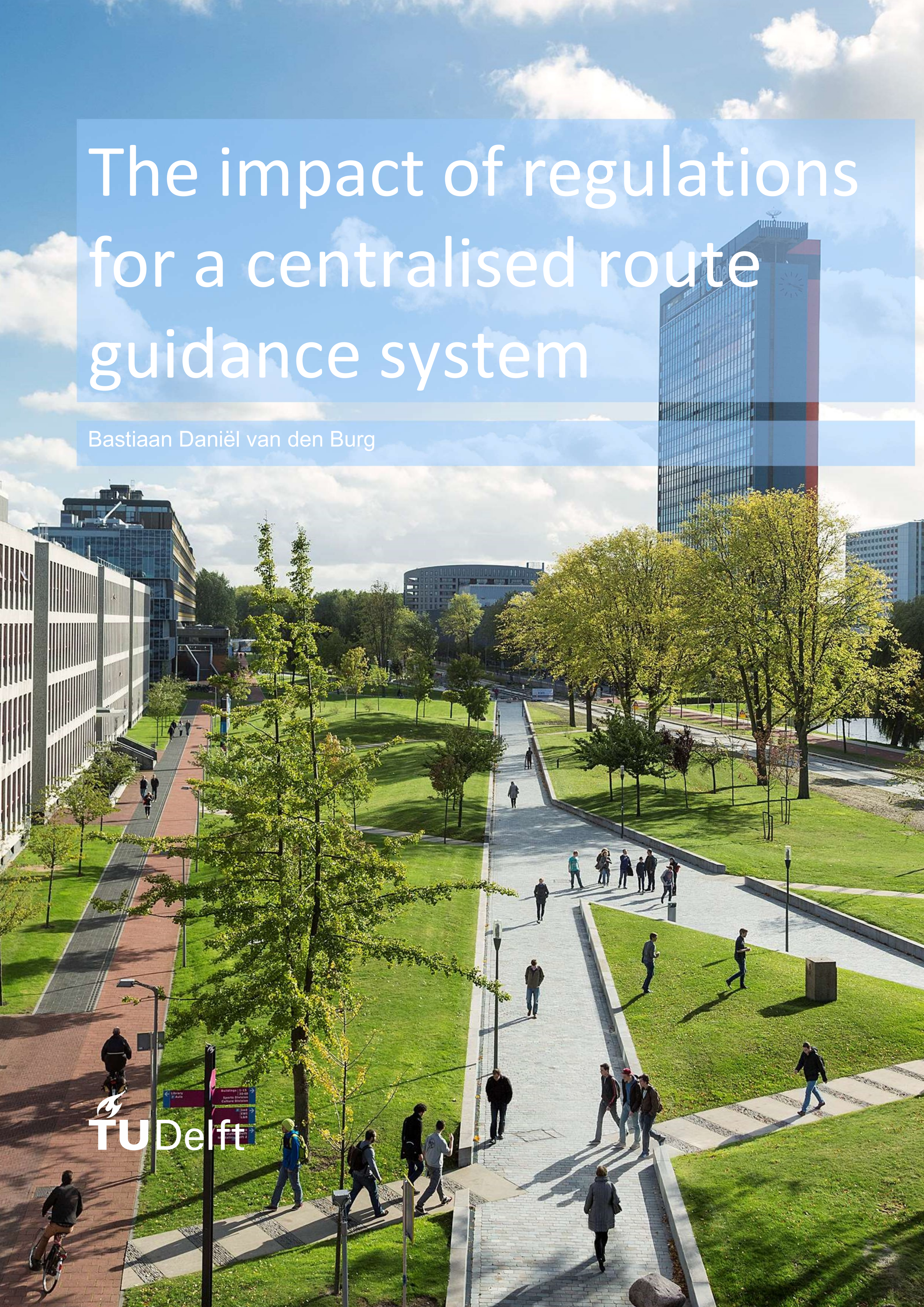

The impact of regulations for a centralised route guidance system

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The impact of regulations for a centralised route guidance system

A simulation study to the effect of a regulated centralised congestion avoiding route guidance system with different penetration rates of automated vehicles on the Milan ring network

By

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Dear reader,

Proudly I present to you my thesis which is written to complete my master’s degree in Transport Infrastructure & Logistics. During my higher professional education, I developed a passion for traffic operations. I gave further shape to this passion during my master's studies, in which this thesis is my final product. With the data-driven era, many new solutions come available to improve traffic operations. With my thesis, I hope to contribute to the discussion about the implementation of a centralised route guidance system to prevent (some of the) future traffic jams. After a period of five years next to my educational job, I am proud of the result and ready to finish my master’s degree. I wish you an informative journey through my thesis and hope you will get some ideas to improve traffic operations.

B.D. van den Burg
Delft, October 2021

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Abstract

This study aims to quantify the impact on the traffic flow performance of different regulation strategies for a centralised route guidance system where road authorities and service providers work together in a coordinated approach. Previous research concentrates on the effect of a centralised route guidance system when every vehicle participates and all vehicles have perfect knowledge of the traffic state. This is not the real case with human drivers and multiple service providers and the impact of cooperation may be limited. This study combines habitual driving behaviour, the effect of the quality of information and a congestion avoiding user optimum algorithm to quantify the impact of a centralised route guidance system. The congestion avoiding user optimum algorithm will add a perceived time penalty to all routes with links above a certain intensity/capacity ratio to avoid choosing the congested route. The cooperation is described by the coordinated approach model of the SOCRATES$^{2.0}$ project. In this model, the cooperation is organised by an intermediary who takes on the management tasks. Because a lack of commitment could be a problem for the success of the system, the services of the intermediary can be regulated with four regulation strategies starting with no regulation to regulation for both service providers and road users. The impact is determined with the dynamic macroscopic traffic model MARPLE. The result shows that without commitment the system does not improve the traffic state. For the maximum potential of the system, it must be fully regulated for both service providers and road users. Although with only the commitment of service providers, there is already a positive impact on the traffic flow and in less complex networks it can already solve all congestion.

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The realisation of this thesis could not have taken place without the expertise and helpfulness of some people around me. I would therefore like to take this opportunity to thank these people for their support. During the graduation period, I had the most regular contact with Simeon Calvert. I would therefore like to thank him for our pleasant sessions in which he always encouraged me to be just a little more critical and to do things better. Besides, our small talks in between were also very nice in a time of lockdowns to make the process a bit more pleasant. The software used, called MARPLE, was developed by my external supervisor Henk Taale. I would like to thank him in particular for the update that was implemented for me and the immediate help when I encountered problems in the system. I would like to thank Jan Anne Annema for our sessions to improve my writing. With his help, I managed to get the report from a toppled bookcase to a logically formed report. However, the number of sessions with Hans van Lint were limited to the official moments. I still want to thank him for his touching remarks and tips which helped me always to take large steps in the progress. For confidence, it was also pleasant to get next to the critical notes, compliments of all the members of the graduation committee which helped a lot in the motivation. During this period of COVID-19 with mainly sitting at home the motivational part was hard. Then I can be blessed with this committee.

Outside the period of writing the thesis, more people have been important in achieving the master's degree. I would also like to express my thanks to these people. Most important my partner Sven Meijer. In the past five years, he has always stood by me and helped take peripheral matters out of my hands so that I could focus on my studies. I was this period not always easy, but I really appreciate the unconditional support, love and the opportunity he has given me. My final thanks go to Ton Heusinkveld. Thanks to him, I started this adventure. He initiated the adventure and opened the door to the teacher's scholarship so that I could get my master's degree. Naming everyone in the acknowledgement would reduce the power of the acknowledgement. But of course, I also thank all teachers who have brought me to this level, my colleagues for their interest in my subject and my family and friends for their mental support. After all, you never achieve success alone.

1 Introduction

1.1 Research Background

Nowadays around 91% of the people have navigation equipment available and 80% of the people who travel for business or who go for a day out use a navigation application (KiM, 2017). Of those people, 35% receives online congestion updates (KiM, 2017) and will be able to change route based on real-time traffic conditions. The percentage of road users with real-time updates will continue to grow with the future of cooperative automated vehicles. Route guidance software will be included in automated vehicles and may automatically be followed up. This means that the information given by the traffic management centres to the road users by Dynamic Route Information Panels (DRIP's) might be less effective to influence the route choice of drivers. With the expectation that in 2035 already 6% of the vehicles is highly automated (Calvert, Schakel, & van Lint, 2017), the possibilities to influence route behaviour starts to shift from road authorities to service providers. These service providers do not work together with the traffic management centre of the government. They base their route advice on real-time data and only consider the travel time of the users of their services (Bilali, Isaax, Amini, & Motamedidehkordi, 2019). Service providers do this by using a user optimum algorithm to guide vehicles through the network. If too many drivers use the user optimum approach this can lead to an inefficient network performance, which will increase the travel time of many travellers (Boyce & Xiong, 2004). With highly automated vehicles, the number of vehicles that drive user optimum will increase. The traffic management centre of road authorities and the service providers might work together to reach common network-wide traffic management goals to prevent inefficient network performances in the future. This could be performed by the concept of the coordinated approach (for smart routing) which has an intermediary implemented to coordinate all actions of all involved actors as described in the so-called SOCRATES cooperation framework (SOCRATES$^{2.0}$, 2020). The SOCRATES$^{2.0}$ project is a European project that is initiated to bring road authorities, service providers and car manufacturers together to improve car mobility. The SOCRATES$^{2.0}$ project suggests, among other things, that this coordinated approach can lead to more optimal use of the network and more satisfied road users. However, how can this approach be implemented, how should it be regulated and what is the impact on the network performance? The biggest conceptual bottleneck according to SOCRATES$^{2.0}$ is the potential lack of political/societal acceptability of this idea (Koller-Matschke, 2018). This concern is justified because a large field study in the region of Amsterdam did not lead to a significant impact on network performance (Wilmink, Jonkers, Snelder, & Klunder, 2017). In addition, most benefits of system optimum routing are obtained by non-participating vehicles which make participating service providers less competitive (Houshmand, Wollenstein-Betech, & Cassandras, 2019). Because the effect and potential of this concept and whether road users would accept this concept are unknown, service providers may not be willing to participate. Regulations may solve the lack of acceptance but are not the preferred alternative of policymakers and may even not be necessary. In conclusion, what kind of policy strategies are possible in a coordinated approach with an intermediary like the SOCRATES$^{2.0}$ project suggests? What is the expected compliance for such a system? What would the impact of regulations for a centralised route guidance system be on the traffic flow performance? And what will be the impact of such a system when there are automated vehicles in the network that will be routed by the service providers?

This research quantifies the impact on the traffic flow performance of different regulation strategies for a centralised route guidance system where road authorities and service providers work together in a coordinated approach. With this result can be determined if the potential lack of acceptability of a coordinated approach for route guidance is an issue for the success of this concept. This is performed with two research methods. A literature study to describe the cooperation model and to identify different regulations. And a simulation to determine the impact of the different regulation strategies.

1.1.1 SOCRATES$^{2.0}$

SOCRATES$^{2.0}$ stands for ‘System of Coordinated Roadside and Automotive Services for Traffic Efficiency and Safety’ (SOCRATES$^{2.0}$, Our-mission, 2021). The SOCRATES$^{2.0}$ project has three main research topics: Smart routing, Actual speed & lane advice, and Local information & hazardous warnings. The SOCRATES$^{2.0}$ project described multiple use cases and conceptual bottlenecks on these topics. This thesis focuses on the topic of Smart routing.

Cooperation framework of Socrates$^{2.0}$

To let road authorities and service providers work together in a coordinated approach for Smart Routing, the Socrates$^{2.0}$ project developed the SOCRATES$^{2.0}$ Cooperation Framework (SOCRATES$^{2.0}$, SOCRATES2.0 Cooperation Framework, 2020). This cooperation framework shows how road authorities and service providers can work together in a coordinated approach with the intervention of an intermediary. Cooperation can take place at three levels. The first, most basic, level comprises simple agreements for sharing public and private traffic data, based on agreed data exchange formats. This level of the cooperation model is named Exchanged data. The second level combines all information to create a common view of the network. In this situation, all actors base their decisions on the same current and predicted traffic situations. This is called the model of Shared view. The last and most advanced model is the model of a coordinated approach. In this concept, all actors will coordinate their actions and services towards communities of travellers. This makes smart routing with a common objective possible. The more advanced the model, the more roles the intermediary will fulfil. All models are presented in Figure 1 and Figure 2 with the needed intermediary roles. Because this study focuses on Smart routing, only the concept of the coordinated approach of the SOCRATES$^{2.0}$ Cooperation Framework is discussed further in this research.

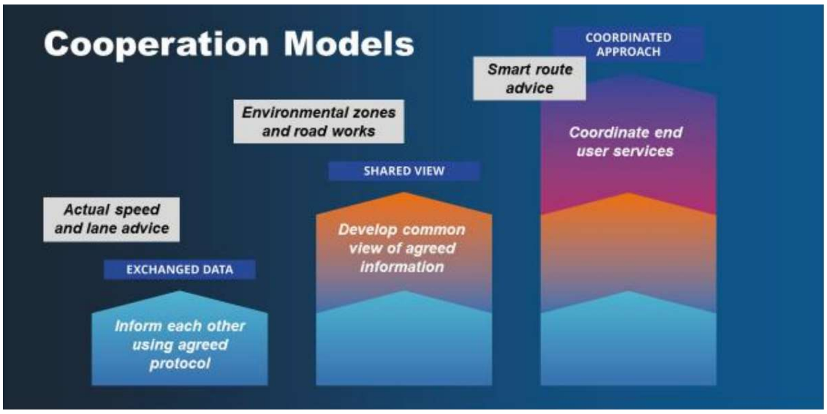


Figure 1 Cooperation Models and intermediaries of the SOCRATES$^{2.0}$ Cooperation Framework (SOCRATES$^{2.0}$, 2020)

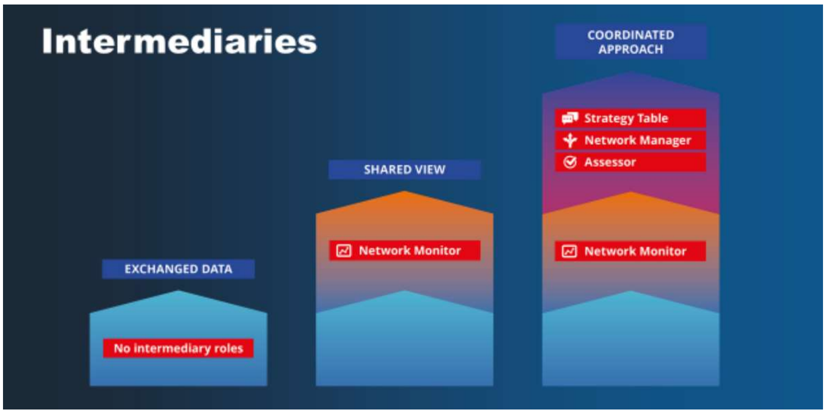


Figure 2 Intermediaries of the SOCRATES$^{2.0}$ Cooperation Framework per cooperation model (SOCRATES$^{2.0}$, 2020)

1.1.2 User and system optimum route guidance

The biggest issue of the presence of personalised route guidance is the dilemma of user optimum versus system optimum. If all road users choose the fastest route for themselves and the demand on a specific route becomes larger than the capacity, congestion will occur. Congestion leads to capacity drops at congested roads which lays between 5% and 30% (Yuan, Laval, Knoop, Jiang, & Hoogendoorn, 2018). These capacity drops lead to network inefficiencies and additional travel time for everyone who passes the jam. Wardrop described this phenomenon as his first principle (Wardrop, 1952). In this principle, all travel times of all used routes between the same origin-destination pair are equal and minimal. This optimum does not lead to a minimal average travel time. The second principle of Wardrop will achieve the minimal average travel time which leads to a system optimum situation. This implies that all users behave cooperatively in choosing their routes to ensure the most efficient network performance.

A study in Chicago shows that a common goal in route choice can decrease the total travel time by 5% while the total travel miles increase by 1,5% (Boyce & Xiong, 2004). An overview in the study of Wilmink et al. in 2017 shows that the theoretical benefits of a system optimum approach can reach up to 30% of the total travel time. This means that current and future user optimum approaches lead to significant inefficiencies in the performance of the network. Fortunately, the study of Wilmink et al. (2017) showed during an experiment with 20.000 participants that 50% of the road users are open to comply with a social routing if the additional travel time is not too big. This means that the potential compliance for a system optimum approach is promising.

1.1.3 Routing policy strategies

The system optimum approach as a route guidance strategy is studied multiple times. All the studies with a cooperative system were done with 100% compliance with the suggested route guidance (El Hamdani & Benamar, 2018; Kuru & Khan, 2020). However, this would not be realistic in the following decades. Automated vehicles will not directly penetrate the entire system, humans might overrule the system (Litman, 2021) and not every human driver uses a route guidance device and can be influenced by route information (Reinolsmann, et al., 2020). There are multiple policy strategies possible of which the impact on the traffic flow is unknown (Bagloee, Tavana, Asadi, & Oliver, 2016). These policy strategies are formed on the level of obligatory or voluntary route guidance for drivers and the cooperation between road authorities and service providers.

1.1.4 Penetration rate automated vehicles

The penetration rate of automated vehicles may play a crucial role in the success of the concept. Not every human driver always uses a navigation system (KiM, 2017) and this concept might only succeed with the involvement of a particular number of participating vehicles. The studies described in the previous paragraph were performed with a 100% penetration rate of automated vehicles. A study that researched the effect of the penetration rate was the study of Houshmand et al. (Houshmand, Wollenstein-Betech, & Cassandras, 2019). This study shows that an increasing number of participants leads to better network performance. However, it has also shown that most of the effect will be reached in the first 50% of the penetration rate. Therefore, it might be not necessarily that every vehicle must participate for the concept to be successful. Unfortunately, this study has some limitations. It assumes that vehicles that are not connected will drive user optimum. In the real world, this is not the case and other research shows that many people are unwilling to change the route for travel time benefits below 10 minutes (Wardman, Bonsall, & Shires, 1996; Reinolsmann, et al., 2020). With the knowledge that not everyone gets the information that is needed to drive user optimum, the approach of the study of Houshmand et al. is too simplistic to represent real traffic behaviour. This means that the effect of the penetration rate of automated vehicles in real-world traffic and its impact on the success of the concept of the coordinated approach is still unknown.

1.2 Research problem

So far, the SOCRATES$^{2.0}$ project developed a cooperation framework (SOCRATES$^{2.0}$, 2020) that described the model of a coordinated approach for smart routing. This model implements an intermediary to coordinate the tasks of network management. The full potential of this type of model is studied by several researchers with studies in which cooperation between all vehicles is present (El Hamdani & Benamar, 2018; Kuru & Khan, 2020). However, there are concerns about efficiency when political/societal acceptability is not fully granted (Koller-Matschke, 2018). With the different options for a route guidance policy, for example, voluntary or mandatory for users and service providers, it is yet not known whether this concept is still effective when not everyone is participating (Bagloee, Tavana, Asadi, & Oliver, 2016). A previous case study with human drivers shows that 20.000 vehicles participating in the Amsterdam region were still not enough to reach a significant effect on the network performance (Wilmink, Jonkers, Snelder, & Klunder, 2017). However, a simulation study on the effect of the penetration rate of automated vehicles shows that most of the effect is reached in the first 50% (Houshmand, Wollenstein-Betech, & Cassandras, 2019). Unfortunately, all other drivers drove user optimum in this study which is not the case with real-world traffic. Replacing all current vehicles with automated vehicles will take decades because these vehicles first must be commonly affordable before all human drivers will be replaced (Litman, 2021). This would mean that not all vehicles will cooperate and it is questionable if the concept of a coordinated approach, with an intermediary to coordinate actions, will be effective enough for policymakers. Insights in the effect of regulations in the current traffic situations and during the transition period could help in deciding to invest in such an approach. In conclusion, it can be stated that it is yet unknown whether this concept will be effective while not every vehicle complies with route guidance.

1.2.1 Research Objective

This study aims to quantify the impact on the traffic flow performance of different regulation strategies for a centralised route guidance system where road authorities and service providers work together in a coordinated approach.

1.2.2 Research Questions

What is and what will be in the future the impact on the daily traffic flow performance of different regulation strategies for a centralised congestion avoiding route guidance system where road authorities and service providers work together in a coordinated approach?

Sub-questions:

1. How can road authorities and service providers work together in a coordinated approach to give route advice and what do they want to achieve?
2. What are possible policy regulations for a centralised route guidance policy to guide cooperative vehicles to increase the impact on the traffic flow?

1.3 Scope

As not everything can be included in this study, this study is bound to the following scope.

Traffic situation

The impact on the traffic flow is scoped to a ring structured network in daily rush hour situations. No rare events will be simulated and the ring structure will guarantee multiple detour options. To determine the impact during events or on lower-order networks, more research is needed.

Cooperation between road authorities and service providers

For this study, it is assumed that road authorities and service providers can cooperate on the level of a coordinated approach when an intermediary is implemented which coordinates actions as described in the SOCRATES$^{2.0}$ cooperation framework (SOCRATES$^{2.0}$, 2020). This research will present how these interactions conceptual work. However, it will not be explained how this should be implemented in the real world. The potential of other cooperation models as described in the SOCRATES$^{2.0}$ cooperation framework will not be a part of this research. But some of the results might apply to other cooperation models as well.

Measures

This research only considers rerouting measure. This means that the impact of the Dynamic Route Information Panels and the route navigation systems are included, but other measures like ramp metering and traffic light optimisation are out of scope. A combination with other measures would interfere with the results and are for that reason excluded of this study.

Network objectives

To obtain network-wide traffic management goals, four types of measures can be defined (AVV; Goudappel Coffeng; Adviesgroep voor Verkeer, 2002). These measures optimise the throughput, prevent spillback, reduce inflow and reallocate traffic. In this study, the network objectives will be reached with the reallocation of traffic over the network. This will also lead to a reduced inflow on specific roads and prevent congestion which lead to potential spillback. Nevertheless, this will not be the focus during this study.

Impact analysis

This research aims to research the potential of a centralised route guidance system with different policy regulation strategies. When the optimum of a strategy is reached before 100% penetration rate of automated vehicles, the most optimal composition of human drivers and automated vehicles will be approached with a precision of 10%. Determine the exact optimum is not part of this study.

Network for simulation

To limit the amount of work, a network that is available at the TU Delft that can be used in MARPLE is chosen. That the available model may not be the optimal model will be accepted for the sake of time savings.

Scenario analyses

Only scenarios based on the cooperation framework of SOCRATES$^{2.0}$ are considered. Scenarios without cooperation that might be beneficial, like a congestion avoiding algorithm provided by individual service providers, are not considered during this study.

Model

To limit the additional work a model is chosen and the functionalities are used as available. Additional changes to the model are not made during this study.

1.4 Framework of the Research Process

A framework, shown in Figure 3, is set up to provide an overview of the research structure. The whole research can be divided into four phases. The first phase defines how road authorities and service providers could cooperate and how this cooperation can be regulated. The second phase selects simulation tools and algorithms to translate the findings of phase one into scenarios. In phase three, the actual simulation work is done and in phase four these results are analysed and reported.

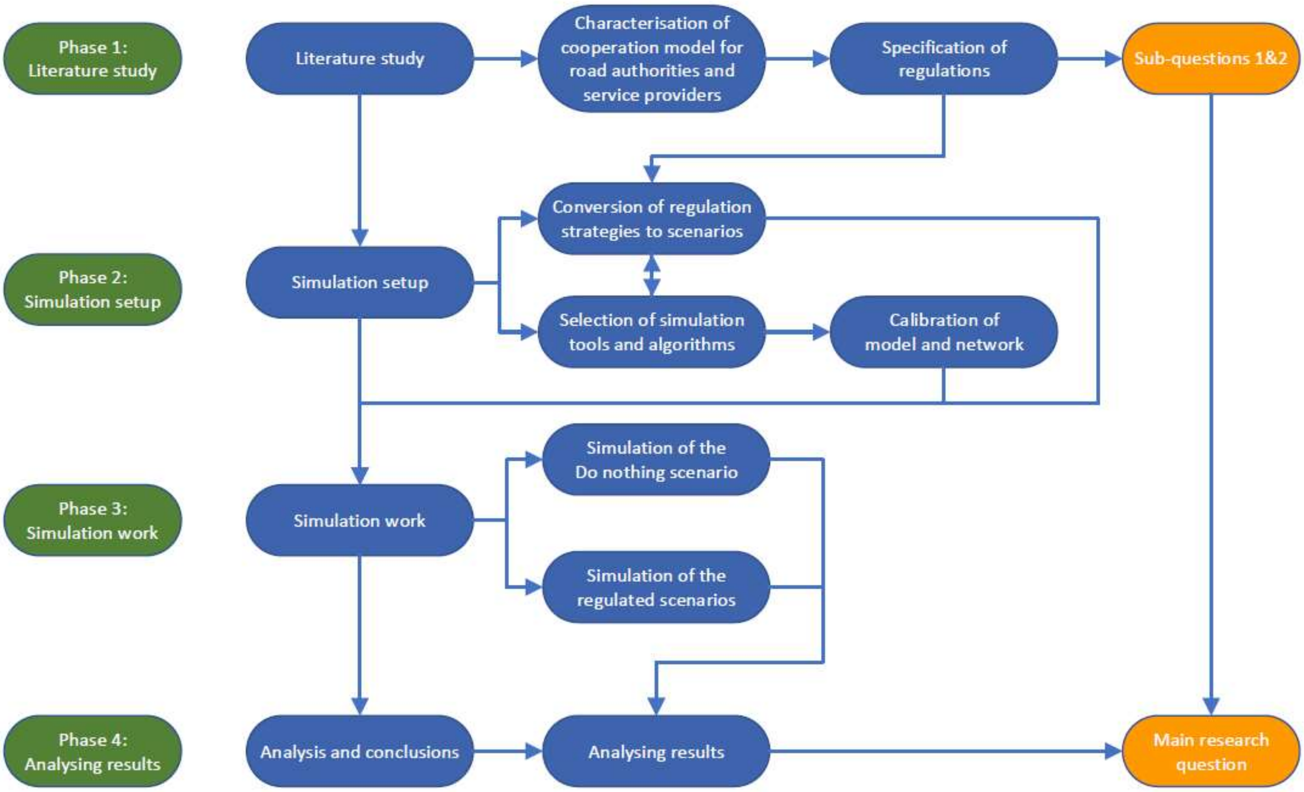


Figure 3 Schematic overview of the research structure

2 Cooperation between road authorities and service providers

This chapter characterises the cooperation between road authorities and service providers for a centralised route guidance system. Because of the scope of this project, the basis of this literature study is executed through the SOCRATES$^{2.0}$ cooperation framework on the coordinated approach level. To describe this approach, used literature mainly consists of the available literature on the website of Socrates2.org. The critical review of this coordinated approach will mainly be performed with the study of Jaag & Trinkner (Jaag & Trinkner, 2011) which provides a framework for regulation and liberalization in network industries. The literature is complemented by literature found in the databases of Google Scholar and Scopus with the combination of the following keywords: Platform market, Platform industries, Intermediary, Unbundling, Network Effects, Regulations, Network industry, Vertical segregation. In addition, the forward and backward snowballing technique is applied to the most relevant literature that was found to find more articles. At the end of the chapter, the first sub-question: *How can road authorities and service providers work together in a coordinated approach to give route advice and what do they want to achieve?* is answered. The how part of the sub-question is discussed in the first three paragraphs and the what part is answered in paragraph 2.4.

2.1 The coordinated approach of the SOCRATES$^{2.0}$ cooperation framework

As described in the introduction, this thesis studies the effect of regulation for a centralised route guidance system. To research this, first, it must be clear how a centralised route guidance system works according to the model of the coordinated approach. This is performed by the explanation of the expanded cooperation model matrix, by the explanation of the different intermediary roles and by the possible implementation strategies for these intermediary roles. When the report later refers to *''this concept''*, the coordinated approach model formulated by the SOCRATES$^{2.0}$ project is meant.

2.1.1 The expanded Cooperation model matrix

To structure the debate about how the cooperation between actors should be organised, the SOCRATES$^{2.0}$ project developed the expanded cooperation model matrix (Koller-Matschke, 2018). This matrix is three dimensional and describes the level of detail, the level of commonality and the level of commitment. The coordinated approach requires co-creation and a commonly agreed 'truth' for all participating actors. This means that the dimension of the level of commonality falls and the result is a two-dimensional matrix which is highlighted blue in Table 1. This sub-paragraph describes the meaning of the different levels of detail and commitment. Table 1 will be used in chapter 3 to explain the meaning of different policy strategies to regulate the cooperation between all actors.

Table 1 Expanded Cooperation Model matrix within blue the scope of this thesis project (Koller-Matschke, 2018)

Level of commonality	No common – Informing each other	Co-creating 1 commonly agreed 'truth'	
Level of commitment	Free – No obligation	Free – No obligation	Committed - Obligation
Situational			
Operational			
Tactical			
Strategic			

Level of commitment

The level of commitment is an important variable for this research. There are two options for the actors involved. Free/no obligation: Actors can act independently from each other and may (ab)use the data for their benefits in a way that puts others at a disadvantage. The other option is committed/obligation: The commonly agreed plan will be executed voluntarily or mandatorily by actors. Different policy strategies can be made with different levels of commitment for different levels of detail. Chapter 3 elaborates on the most promising policy strategies and translates them into scenarios for the simulation.

Level of detail

To cooperate in traffic management, traditionally three layers of traffic management from policy to operational level can be defined (Spoelstra, van Waes, Mann, Konstantinopoulou, & Tzanidaki, 2017). These layers are, Strategy, Tactical and Operational. The SOCRATES$^{2.0}$ project described the situational layer as an additional level of detail. These four layers of detail are described below with the assumptions in the coordinated approach of the SOCRATES$^{2.0}$ cooperation framework for this thesis.

Strategic layer

On a strategic layer, policies are decided. These policies result in, for example, a control vision for a network and/or an area or a tactical framework for the deployment of traffic management within circumstances to be determined beforehand. In detail, this could result in a priority of a specific traffic flow in the network and/or the priority of specific vehicles. In this thesis, no priority policies are applied because this would make the simulation less generic. The policy about the possible obligations of the coordinated approach for service providers and road users will vary in the scenarios for the simulation. Furthermore, the objective of the control is a system optimum traffic flow.

Tactical layer

On a tactical layer, the first translation of the strategic level to the implementation on the street is described. An example of tactical traffic management is a traffic management plan for a specific bottleneck or designing control scenarios for the deployment of traffic management at a specific location and/or during a specific period. Because of the scope of this thesis, only the measure of rerouting traffic over the network is considered to solve inefficiencies in the traffic flow. The strategy table describes, according to the tactical layer, when the network manager should suggest rerouting vehicles.

Operational layer

On an operational layer, the traffic management resources are deployed on the road according to the traffic management plan. With the scope of this study, this happens by sending out messages/instructions to road users with roadside equipment, in-car equipment or personal communication devices. In this thesis, it is assumed that vehicles have a continuous connection to receive instructions. The method of acquisition of this route guidance is out of scope.

Situational layer

On a situational layer, the status of the network is represented. The status of the network can be described by sensors to determine the air quality, sound levels, traffic volumes, etcetera. Furthermore, additional information about the network state can be obtained by the status of the traffic management measures that are active like active signs, warnings, etcetera. This research scopes this situational level to the data of the traffic flow like volumes, speeds and travel times. Results of air quality are assumed as not relevant because this might not be an issue by the time automated vehicles enter the network.

2.1.2 The role of intermediaries

The SOCRATES$^{2.0}$ project describes four intermediary roles which should all be fulfilled to implement the coordinated approach successfully. These roles are the network monitor, the strategy table, the network manager and the assessor. This sub-paragraph describes the function of each intermediary role. When the report later refers to the intermediary without specifying the role, the combination of all roles is considered.

Network monitor

The network monitor creates a common view based on the data of all parties. The network monitor will provide data collection, data fusion and data completion activities. This will result in the determination of the common current and predicted traffic state. This role can be implemented separately or together with the roles of the strategy table and the network manager. This research assumes that the function of the network monitor is fully implemented. However, it is not explained how this process will happen in the real world because this is out of scope.

Strategy table

Because of the joint approach to guide road users, there should be a common goal. Service providers and road authorities discuss the common goals and the priorities of measures that should be taken in different situations. The strategy table describes the agreed common goal in terms of Key Performance Indicators (KPI's) and describes when and how measures should be undertaken. The Network manager executes the strategy table to determine what measures are effective to create the desired impact. In this thesis, the measures are scoped to rerouting and the KPI's are formulated to measure the impact of rerouting traffic. Other measures like ramp metering can also be part of the strategy table but are out of scope for this study.

Network Manager

The network manager executes the strategy table based on the information given by the network monitor. This role can be combined with the roles of the network monitor and the strategy table. The network manager, in the scope of this study, gives all participating parties orders to execute. This means that the network manager decides which route the service provider presents to the users and which information the road authorities present on the DRIP. The implementation of the network manager could be as an independent organisation or it could be implemented by one of the existing traffic management centres. In this thesis, this role is executed by the simulation package and no further description toward the real world is necessary.

Assessor

The assessor monitors if the strategy table is executed correctly. This role can be performed by an independent organisation or separately by all individual actors. The assessor checks among others if the right measures are taken and if the benefits of the system optimum approach are equally divided. Because the simulation is executed in a controlled environment, there is no need to implement this role in the simulation. For this reason, it is assumed that all partners have full insights and that they are convinced that the strategy table is executed correctly.

2.1.3 Implementation options intermediary

The previous paragraph described what the role of the intermediary contains. This paragraph describes how the intermediary can be implemented and what kind of assumption will be made for this study. The SOCRATES$^{2.0}$ project examined in total five options for intermediaries. These options are:

- No intermediary;
- Multiple intermediaries for data aggregation;
- One intermediary for governments for aggregation & coordination;
- One distributed intermediary for aggregation and coordination;
- One single intermediary for aggregation & coordination.

Because the first two options do not lead to coordination, these options are out of scope. The third option is interesting because cooperation between road authorities and service providers is established without obligations. The fourth and fifth options are, besides the property rights of the intermediary, in concept the same. In both situations, the SOCRATES$^{2.0}$ project assumed that all parties give their commitment to the system and they operate as an integrated system.

One intermediary for governments for aggregation and coordination

In this option, one intermediary is established for road authorities while service providers share their data. How the process from gathering data to executing measures conceptually works for this option is presented in Figure 4. In this case, all data of participating actors is shared back and forth. However, all service providers still work independently from each other. The traffic management centres of the road authorities will adapt their measures based on what service providers do. The service providers will optimise their service based on the aggregated data of the intermediary. In Figure 4, all items that do not relate to smart route advice are omitted compared with the source of the figure.

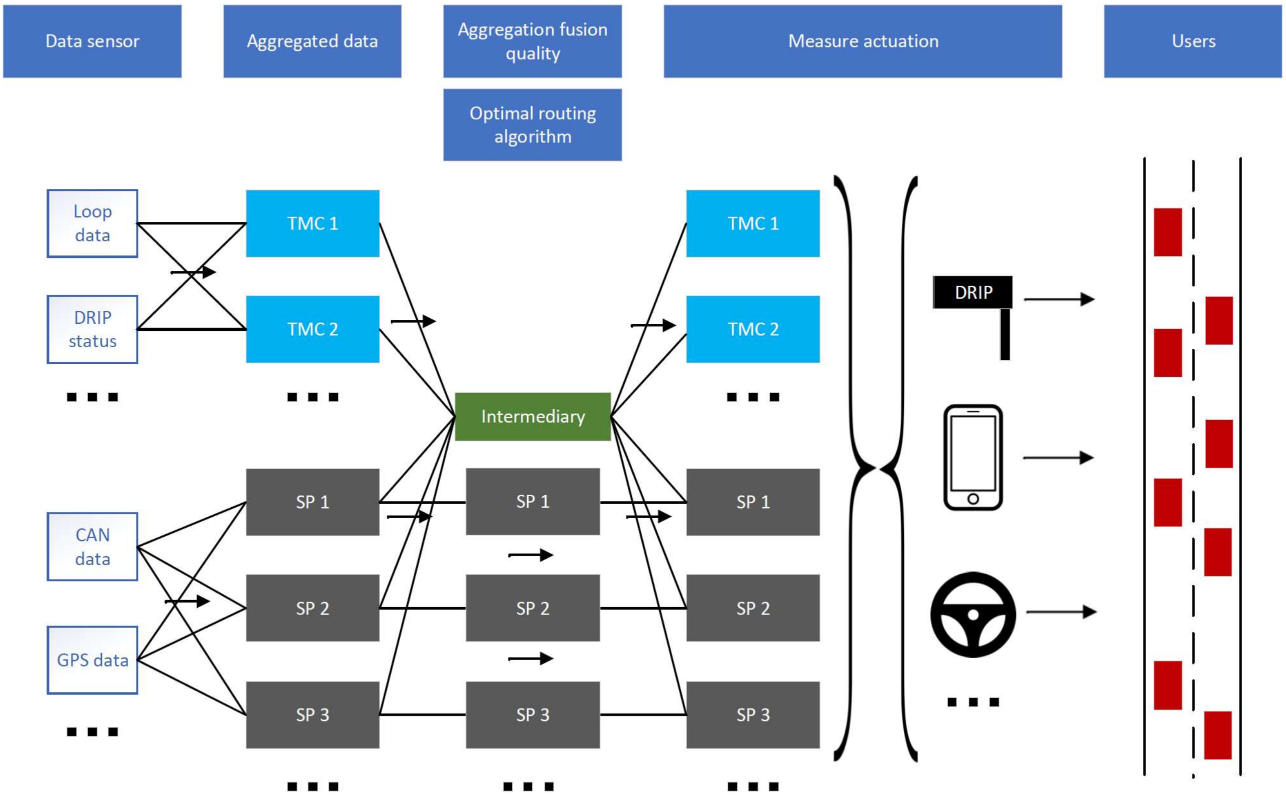


Figure 4 Interaction scheme with voluntary use of intermediary services, based on intermediary option three from proposed cooperation framework SOCRATES$^{2.0}$ (Koller-Matschke, 2018)

One single or distributed intermediary for aggregation and coordination
In this option, one centralised or distributed intermediary is established whereby the use of its services is obligatory. This means that all traffic management centres and all service providers are connected to the services of the intermediary. The task of the intermediary is to generate a common truth based on all available data of all parties and to provide instruction to all parties for their system behaviour. In this option, it is prohibited to bypass the intermediary or to deviate from the instructions of the intermediary. How the process from gathering data to execute measures conceptually works with the interaction of obligatory use of the intermediary services is presented in Figure 5. All items that do not relate to smart route advice are omitted compared with the source of the figure.

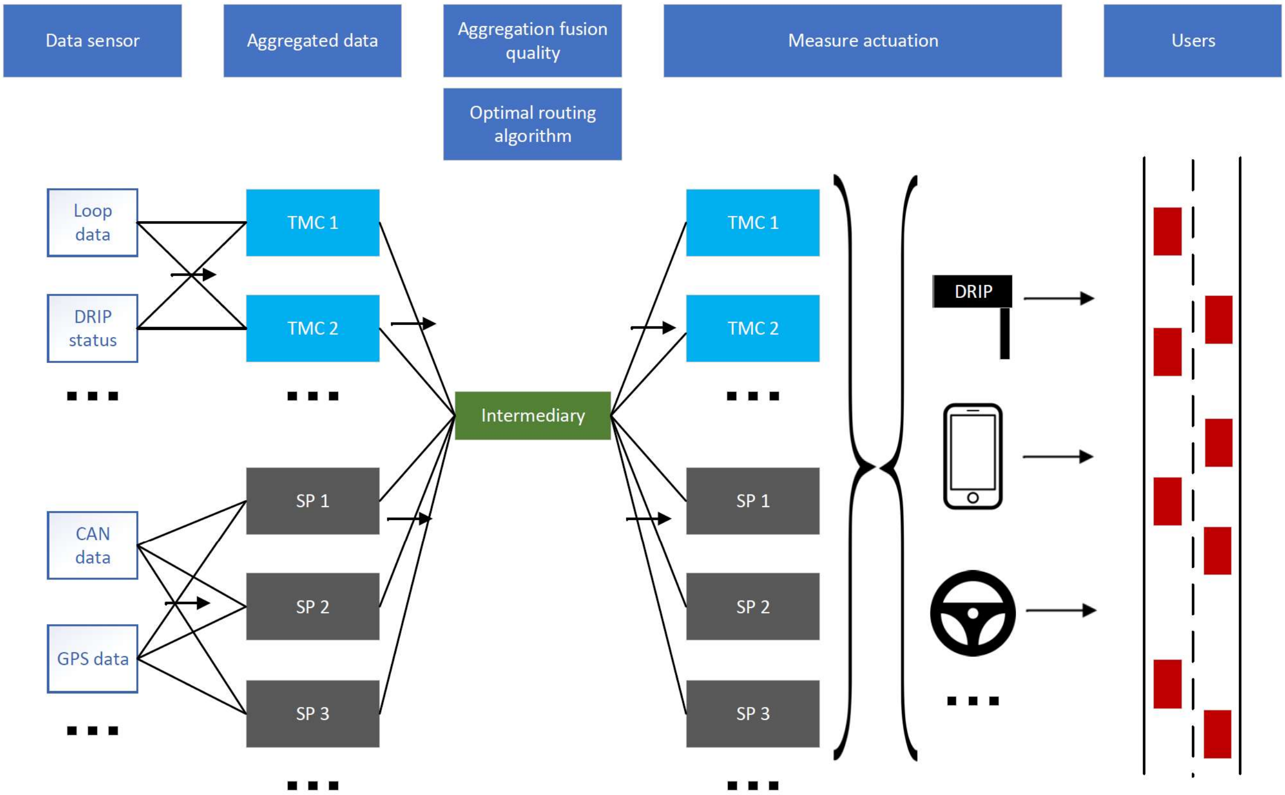


Figure 5 Interaction scheme with obligated use of intermediary services, based on intermediary options four and five from proposed cooperation framework SOCRATES$^{2.0}$ (Koller-Matschke, 2018)

2.2 Review coordinated approach SOCRATES$^{2.0}$

The road network is considered to be a network industry (Glachant, 2002). With the introduction of in-vehicle personal route information, the complexity increases because new actors, the service providers, have entered the field. These service providers pursue their own goals and with the future introduction of automated vehicles, their role will grow. Service providers use a user optimum approach which leads to network inefficiencies of up to 30% (Wilmink, Jonkers, Snelder, & Klunder, 2017). So far, the model of the coordinated approach of the SOCRATES$^{2.0}$ project is presented as the solution for future network inefficiencies. A network industry that has already unbundled the network management and designated an actor as coordinator is the Railway network industry. For this industry, this should be the solution for more competition and a more efficiency. However, the Railway network industry has concerns about defective coordination and cost-ineffectiveness that may result in incentive misalignment between entities resulting from this unbundling (van de Velde, 2015). This paragraph utilises the framework for regulation and liberalization in network industries (Jaag & Trinkner, 2011) and considers the perspective of platform markets to criticise the SOCRATES$^{2.0}$ coordinated approach model on limitations. This review gives input to formulate the final cooperation interaction scheme described in paragraph 2.3.

2.2.1 Identify market failures

In perfectly competitive markets the resulting competitive market equilibrium is Pareto optimal and there are no market failures (Jaag & Trinkner, 2011). In the case of the road network with different Service Providers and the Traffic management centre, several market failures that can be categorised. Figure 6 categorises these market failures in; A1: Natural monopoly, A2: Incomplete markets and A3: Market imperfections. Category A1: Natural monopoly can be omitted because this is not the case in the road network for traffic management issues. The Pareto optimum means that one cannot make anyone better off without making at least someone else worse off. If this Pareto equilibrium will be reached depends on which level of detail actors are defined in the network industry.

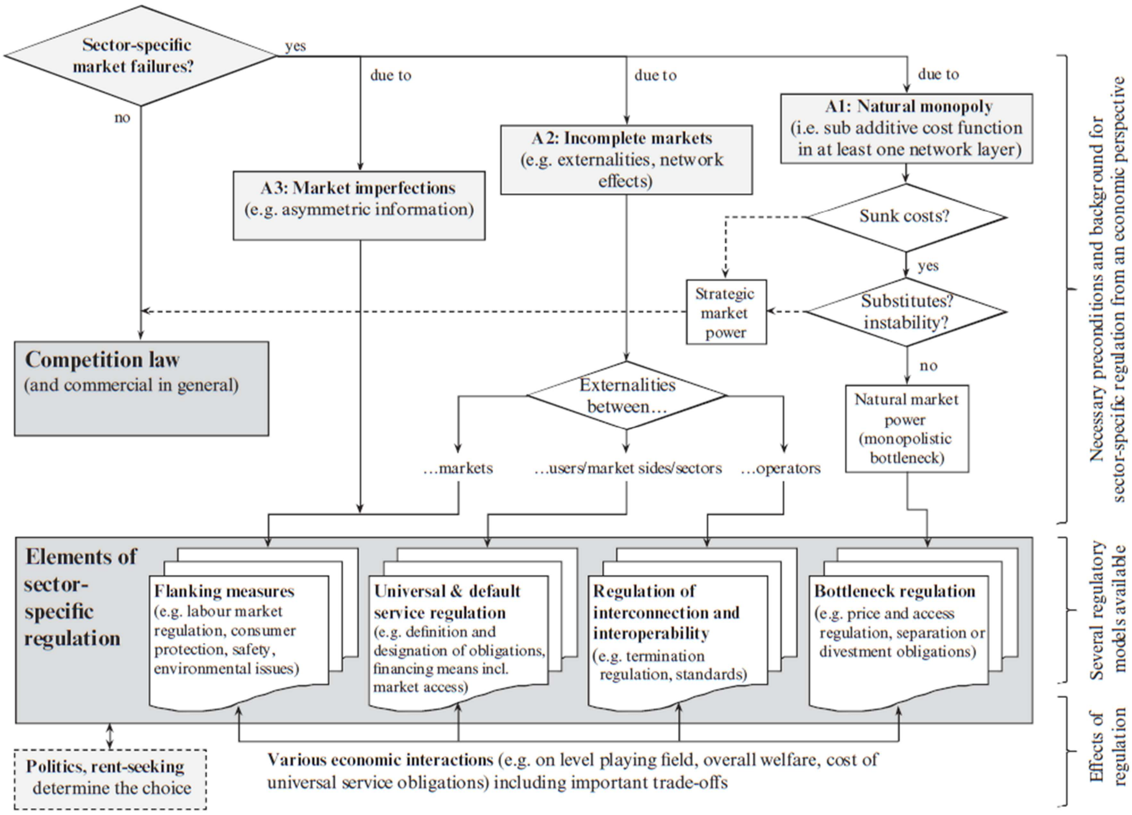


Figure 6 Analytical framework sector-specific regulations in network industries (Jaag & Trinkner, 2011)

Pareto equilibrium

It can be discussed if the Pareto equilibrium will be reached. This depends on which level of detail the actors are defined in the road network. If actors are defined on the level of individual road users, the Pareto equilibrium will be reached. In this case, it is impossible to improve the travel time of an individual without making another one travel time worse. This phenomenon is in the transportation field named by the first principle of Wardrop (Wardrop, 1952). In this situation, the Pareto equilibrium is reached. However, it is possible to improve the average travel time. To reduce the average travel time, some road users must detour for the benefit of other users. When actors are defined on the level of service providers and traffic management centres, which represents a group of road users, the Pareto equilibrium is not reached. In this case, they can reroute some of their users to reach a lower average travel time (Houshmand, Wollenstein-Betech, & Cassandras, 2019). In the situation of cooperation of all actors, the lowest average travel time for the system can be reached. In this case, an individual road user can reroute for its benefits. However, this would also lead to a longer average travel time for the community. This phenomenon leads to a system optimum and is known by the transportation field as the second principle of Wardrop (Wardrop, 1952).

A2: Incomplete markets

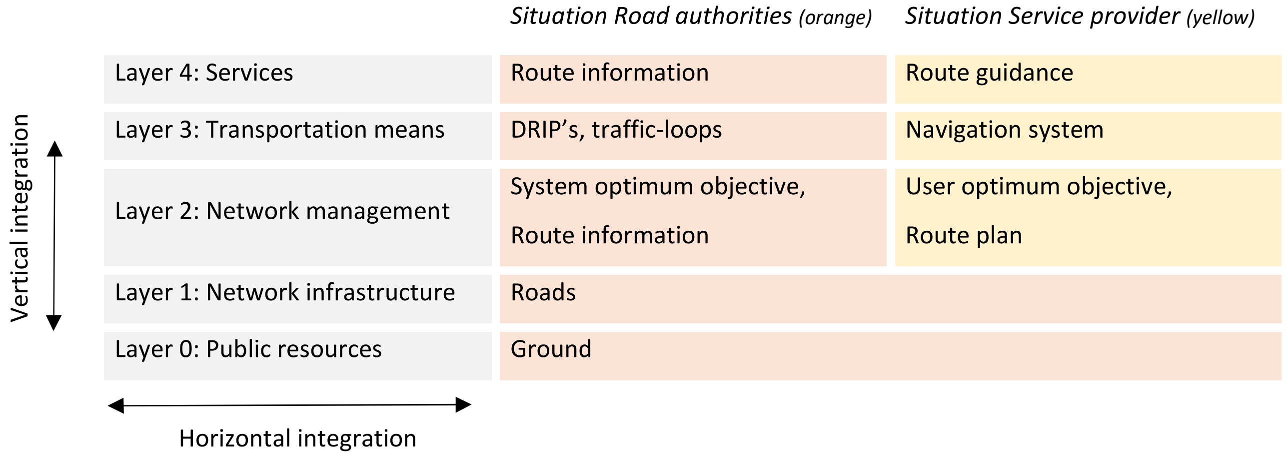
Current user optimum routing behaviour of service providers will lead to more network inefficiencies with the growing use of navigation systems. With the introduction of automated vehicles, these inefficiencies might get even worse. The market is called incomplete because network effects are not optimal in this situation (Jaag & Trinkner, 2011). Network effects are present if users care about the participation and usage decisions of other users (Belleflamme & Peitz, 2018). In the case of the traffic flow performance, this means that the routing behaviour of other users will affect the travel time of others in case of congestion. A previous study shows that the more users commit to the route guidance service the lower the total travel time will be (Houshmand, Wollenstein-Betech, & Cassandras, 2019). This means that there is a positive network effect for the route guidance service.

A3: Market imperfections

The market is imperfect because all actors do not have perfect information over the network to make their decisions. The traffic management centre knows what events happen on the network, the exact capacities of roads and knows the current traffic flows. On the other hand, the service providers know the origin and destination of their users and must predict capacities and current flows of the network. Service providers cannot determine, based on the data they have, the exact flows of the network and if an event reduces capacity, they do not obtain that information. For this reason, they base their route guidance on real-time traffic information, without considering the future evolvement of traffic in the network (Bilali, Isaax, Amini, & Motamedidehkordi, 2019). With complete information, service providers and traffic management centres can improve their services which result in more satisfied road users.

2.2.2 Vertical separation network layers

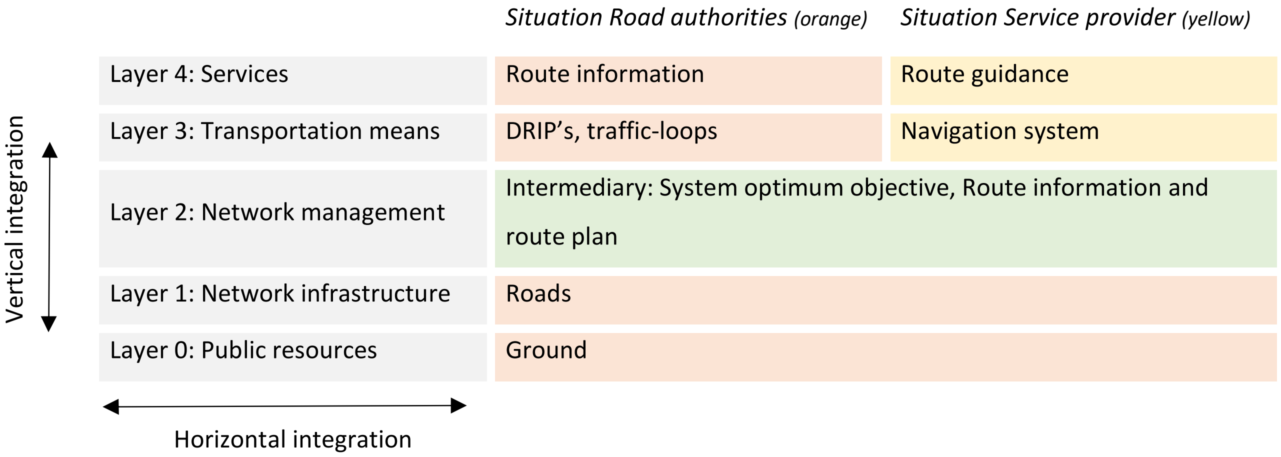
A common characteristic of all network industries is that it forms a coherent and interrelated system (Jaag & Trinkner, 2011). Figure 7 illustrates the relevant network layers according to the general framework for regulation and liberalization in network industries with the relevant elements for route guidance. The solution of the SOCRATES$^{2.0}$ project is to unbundle the network management layer by implementing an intermediary for this function. In the current situation for the road networks, the first two layers are owned by governmental parties with some toll roads excepted (De Palma & Lindsey, 2000). In the case of route information, the other layers are also traditionally owned by governmental parties. This results in the traffic management centre, which uses DRIPs to inform human drivers with route information. With the introduction of personal route guidance systems, service providers enter the field with their user optimum objectives, a navigation system and personal route guidance services. An overview of this horizontal segregation between road authorities (in orange) and service providers (in yellow) is given in Figure 7.



	Situation Road authorities (orange)	*Situation Service provider (yellow)*
Layer 4: Services	Route information	Route guidance
Layer 3: Transportation means	DRIP's, traffic-loops	Navigation system
Layer 2: Network management	System optimum objective, Route information	User optimum objective, Route plan
Layer 1: Network infrastructure	Roads	
Layer 0: Public resources	Ground	

Figure 7 Segregation of Network layers vertical integrations per actor, current situation road network, based on (Jaag & Trinkner, 2011)

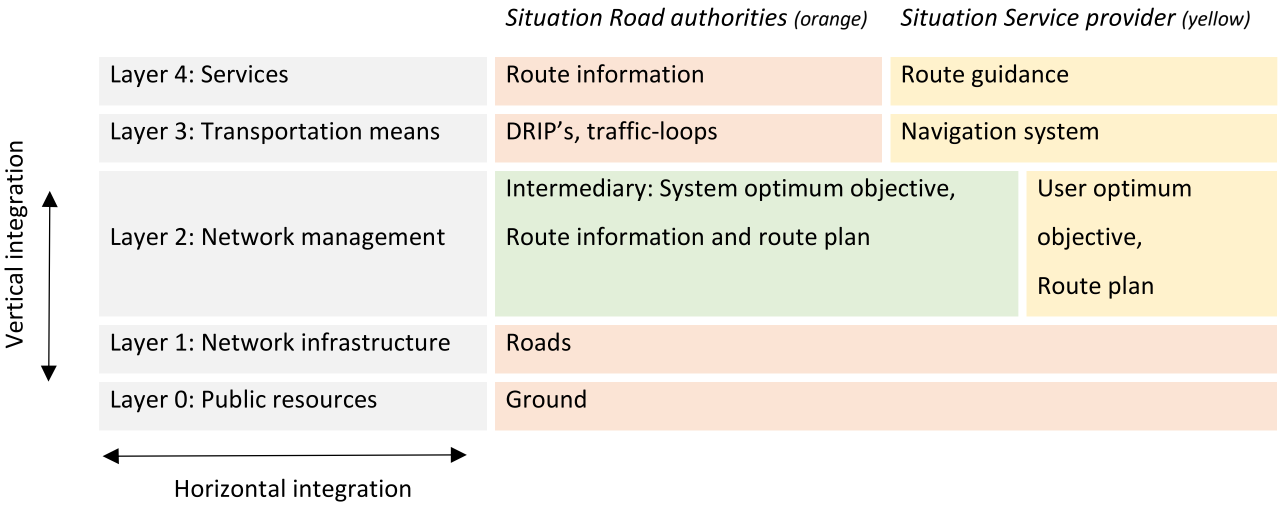
The identified regulation of the SOCRATES$^{2\cdot0}$ project is the introduction of an intermediary to the network. This intermediary operates the network management layer. The intermediary combines the collected information of road authorities and service providers, execute the commonly formed strategy table and provides information about the permitted actions to all involved actors. This results in new segregation of network layers as presented in Figure 8, within green the intermediary.



	Situation Road authorities (orange)	*Situation Service provider (yellow)*
Layer 4: Services	Route information	Route guidance
Layer 3: Transportation means	DRIP's, traffic-loops	Navigation system
Layer 2: Network management	Intermediary: System optimum objective, Route information and route plan	
Layer 1: Network infrastructure	Roads	
Layer 0: Public resources	Ground	

Figure 8 Segregation of Network layers vertical integrations per actor, suggested situation road network with in green the new intermediary, based on (Jaag & Trinkner, 2011)

There are concerns about the acceptability of the concept which makes it unsure if this solution will have a monopoly on the network management layer naturally. If this monopoly situation will not occur naturally and no policies are formed to obligate parties to use this intermediary, there is still no full alignment on the network management layer. This leads to the situation presented in Figure 9. In this figure, it is assumed that all road authorities and only a part of the service providers commit to the intermediary. It remains to be seen whether the intermediary without a monopoly on the network management has an added value. Another point to consider is if this will not lead to an incentive misalignment between entities like this sometimes happens in the railway sector (van de Velde, 2015). If the use of the intermediary is not obligated, it could be abused to use the information of other service providers and network management centres to improve their user optimum route guidance which might not lead to a better performance of the traffic flow.



	Situation Road authorities (orange)	*Situation Service provider (yellow)*
Layer 4: Services	Route information	Route guidance
Layer 3: Transportation means	DRIP's, traffic-loops	Navigation system
Layer 2: Network management	Intermediary: System optimum objective, Route information and route plan	User optimum objective, Route plan
Layer 1: Network infrastructure	Roads	
Layer 0: Public resources	Ground	

Figure 9 Segregation of Network layers vertical integrations per actor, suggested situation road network without obligations with in green the new intermediary, based on (Jaag & Trinkner, 2011)

2.2.3 Regulation of the intermediary role

Figure 10 presents seven regulatory models for bottleneck regulation. These models are not fully compliable for the network management layer because the bottleneck is not naturally formed. However, these models give some interesting insights. The more regulations are applied, the more this will influence the innovation and investment incentives. At this moment, service providers can distinguish themselves by providing the best route guidance to limit the travel time for their users and by presenting route information in the most pleasant way possible. If the intermediary takes away the freedom for service providers to determine the route of their users, this limits the competition in the market for route guidance. This leads to a negative effect on long-term investments to improve their services because the benefits of investments might not come to the investor alone. For example, this could mean that service providers would not invest in improving data collection.

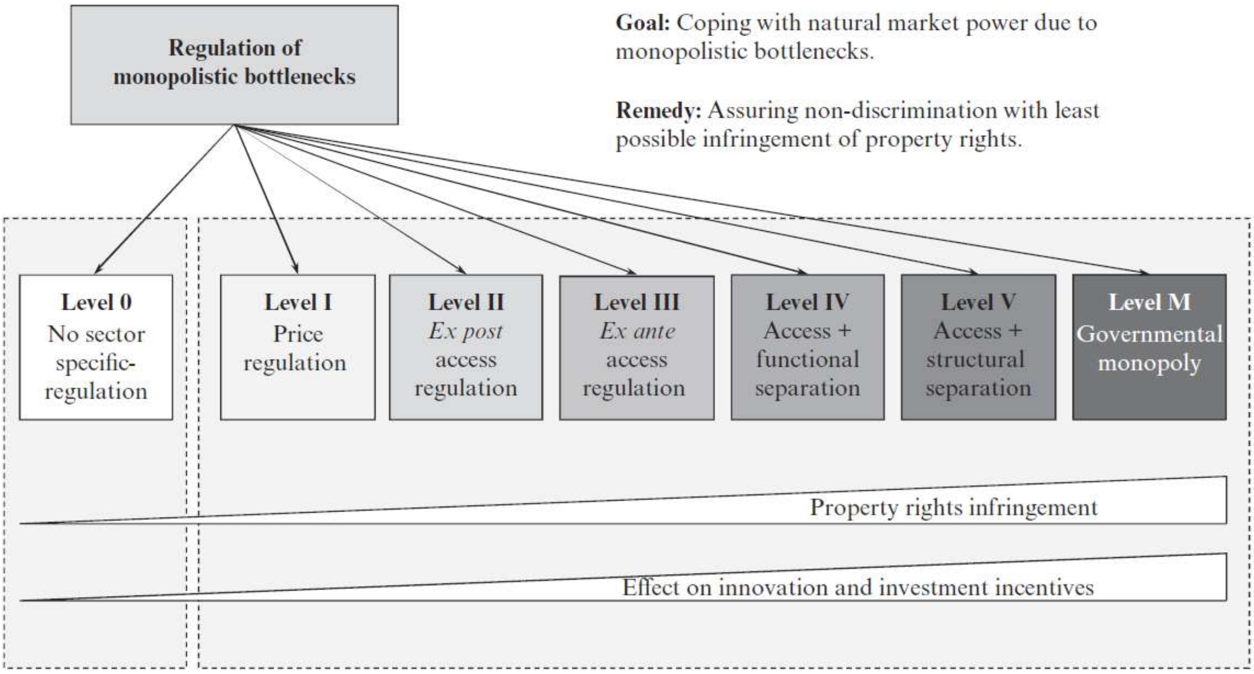


Figure 10 Regulatory models for bottleneck regulation (Jaag & Trinkner, 2011)

For the intermediary in the coordinated approach, two regulation solutions are possible. The first one is a monopoly (Figure 10, level M) where the use of the services of the intermediary is compulsory. The second one is a structural separation, (Figure 10, level V) where an independent intermediary is introduced without compulsory use. In the case of the structural separation, it is important to note that bypassing the intermediary by service providers is not forbidden and the use of services of the intermediary is voluntary. Because the compulsory solution leads to a higher penetration rate of system optimum drivers, which has shown to be more effective (Houshmand, Wollenstein-Betech, & Cassandras, 2019), it is expected to be the most effective to improve the traffic flow. However, the vision of the Netherlands is that route information is left to the market (H. Taale, personal communication, March 17, 2021). Liberalisation is a sensitive issue and with the liberalisation of the network management layer, the role of service providers could be limited to just be a gateway? This makes it important to research both regulation strategies for the cooperation between road authorities and service providers.

2.2.4 The intermediary as a platform market

Markets with platforms can be broadly defined as ‘‘markets where the interaction between at least some participants is facilitated and managed by an intermediary’’ (Belleflamme & Peitz, 2018). This would mean that the intermediary, as described in the SOCRATES$^{2.0}$ coordinated approach model, creates a platform market for route guidance. However, when going into more depth this definition does not hold. Service providers and road authorities do not interact at this moment, so they do not need an interaction to deliver their services. Another characteristic of a platform market is that positive network effects prevent participants from leaving the platform (Eisenmann, Parker, & van Alstyne, 2011). In the case of an intermediary for route guidance, the most benefits of the platform would go to non-participating users which follow a user optimum approach (Houshmand, Wollenstein-Betech, & Cassandras, 2019). This is because participating users will divide the detours to limit congestion and the non-participating users do not detour but only take advantage of the reduced congestion. Because the traditional issues in platform markets do not hold for the concept of the coordinated approach, further investigation of the Socrates project as a platform market has not led to any additional insights.

2.2.5 Lessons learned by the review of the coordinated approach of SOCRATES$^{2.0}$

The coordinated approach of the SOCRATES$^{2.0}$ project has potential. However, several lessons can be learned based on the critical review that is performed with the framework for regulation and liberalization in network industries. This subparagraph gives an overview of these lessons and indicates how to deal with them during this study.

Flawed coordination

One of the main issues found by unbundling is flawed coordination (Brunekreeft, 2015). Especially this problem occurs while multiple coordination centres emerge. Because of the size of the entire network, it can be expected that the network will be divided into several regions. For example in the Netherlands, five regional traffic centres control a part of the highway network (Rijkswaterstaat, Verkeerscentrum Nederland, 2021). To simulate the entire network there is one National model (LMS). However, there are also four Region models to increase the level of detail (Rijkswaterstaat, NRM/LMS-data, 2021). This issue of coordinating the regional intermediaries is not addressed in the SOCRATES$^{2.0}$ cooperation framework. For this study, this issue is not a problem because the scope of the simulation is a single ring network. For that reason, there is one single coordinating intermediary and this problem is not relevant during this study.

Lack of competitive incentives

Another problem that was addressed is the potential lack of competitive incentives (Jaag & Trinkner, 2011; Armstrong & Sappington, 2006). Unbundling the network management layer reduces the possibilities for service providers to distinguishes themselves. Especially for network industries, this leads to a reduction of investments, because network industries are coherent and interrelated. An investment in the system will not lead to the exclusive rights to harvest the benefits of the investment. Because this study focuses on the performance of the traffic flow, the pros and cons of the lack of competitive incentives are left out of the scope.

Bypassing the intermediary

A limitation that can lead to a serious impact on the performance of the traffic flow for the coordinated approach is the option of bypassing the intermediary. Without strict regulations, there are possibilities to bypass the prescribed regulation (Jaag & Trinkner, 2011). Without strict regulations, the assumption that all service providers will participate and share their data would be a utopia. This is underpinned by the notion that non-participating parties obtain more benefits from the system in comparison to the participating parties (Houshmand, Wollenstein-Betech, & Cassandras, 2019). The possibility of a bypass can lead to undesired behaviour which is described in paragraph 2.3.

Conclusion

In conclusion, it can be said that bypassing behaviour can lead to a less successful implementation of the intermediary and unfair distribution of system benefits. The next paragraph zooms in to this bypass behaviour. Chapter 3 will formulate regulations to prevent the bypass behaviour.

2.3 Final cooperation interaction scheme

The review of paragraph 2.2 shows that the interaction scheme of the SOCRATES$^{2.0}$ project, presented in Figure 4, is not complete. Without strict regulations, multiple other behavioural options for service providers arise. This results in the new interaction scheme of Figure 11, which shows how all actors work together in a coordinated approach. In this scheme, every actor collects data and merges it. The intermediary combines all the datasets that are shared and determines the optimal routing for all vehicles. Some of the service providers do not participate and may share their data, but they still calculate their optimal routing for their users. Based on the calculated optimal routing, the measures will be put in place to instruct the road users.

Figure 11 presents three types of service providers which may exist in several individual service providers. These types are:

- Participating service providers (SP1)
  In this case, the service provider behaves in an exemplary manner and fully commits to the intermediary.
- Data sharing service providers (SP2)
  In this case, the service provider shares its data with the intermediary. However, it still determines an optimal routing for its users with its own user optimal algorithm.
- Non-participating service providers (SP3)
  In this case, the service provider behaves independently without any cooperation.

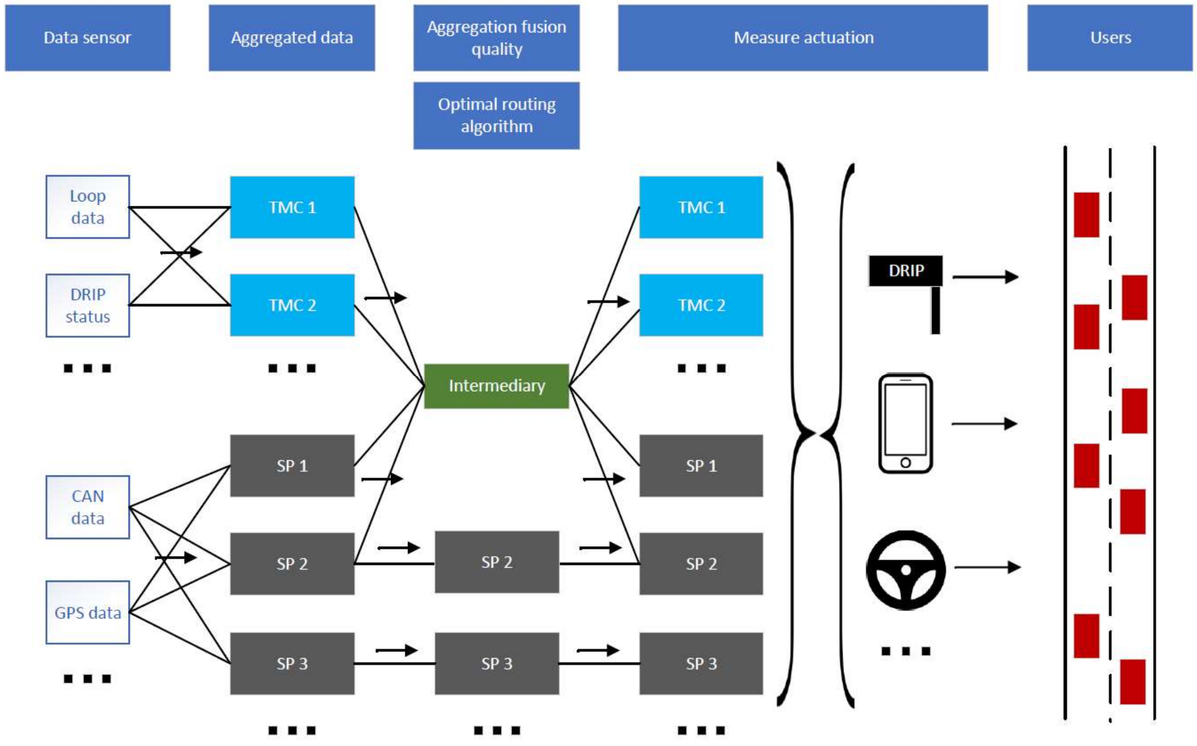


Figure 11 Interaction scheme with voluntary use of an intermediary with bypass behaviour, based on intermediary option three from proposed cooperation framework SOCRATES$^{2.0}$ (Koller-Matschke, 2018)

2.4 Cooperation objectives

The previous paragraphs describe how service providers and road authorities interact during cooperation. This paragraph presents what they want to achieve during this cooperation. Firstly, an overview of the objectives of the SOCRATES$^{2.0}$ project and how these can be implemented for this research is given. Secondly, these objectives are translated into measurable indicators for the simulation.

2.4.1 Objectives of the coordinated approach of SOCRATES$^{2.0}$

The SOCRATES$^{2.0}$ project formulated four objectives for the entire project (Koller-Matschke, 2018). These objectives are formulated by road authorities, service providers and car manufacturers for all use cases that SOCRATES$^{2.0}$ has formulated. This means that not every objective is completely relevant for this study. This subparagraph discusses all objectives and scopes them to the relevance for this research. The objectives are:

- A safer, cleaner and more efficient traffic flow and optimum use of the road capacity;
- Better services to the road users and better quality of life for citizens;
- More cost-effective traffic management by optimising the use of existing road capacity;
- Economic growth and the creation of more jobs by reducing traffic problems and by creating new business opportunities.

A safer, cleaner and more efficient traffic flow and optimum use of the road capacity

For this objective, the focus lies on the efficiency of the traffic flow. This will interest both service providers and road authorities. Service providers strive for the fastest route for their users and road authorities strive for the most optimal traffic flow. While the traffic flow improves, the travel times for most individual road users will decrease and the average travel time will be lower. Safety is hard to measure in a simulation and not the main objective of the service providers. However, traffic in congested conditions has more risk for accidents than traffic in free-flow conditions. This means that a more optimal traffic flow will improve traffic safety, however, it will not be quantified. To make statements about the pollution of the traffic there are too many uncertainties. With the rise of clean vehicles, the pollution of traffic might not be an issue in the future. However, current regular vehicles show, in comparison to free-flow conditions with a speed of 120 km/h, that traffic in congestion leads to 18% more NOx and 44% more CO2 emissions (Ligterink & Smokers, 2016). This means that this objective will also be met with the measurement of the traffic flow efficiency. However, like traffic safety, it will not be quantified.

Better services to the road users and better quality of life for citizens

Service providers strive for satisfied users and always search for options to improve their service level. The service level during this research is determined by the operating conditions that exist within a traffic stream, such as the average travel speed and the perceptions of motorists regarding manoeuvrability and comfort (Laetz, 1990; Choocharukul, Sinha, & Mannering, 2004; Washburn & Kirschner, 2006). The quality of the service is also determined by how route guidance messages are presented. Because no distinction is made in presenting messages, this is out of scope. Because a higher level of service leads to more satisfied road users, this could also be an important indicator to convince service providers to participate in the cooperation. Preference indicators for a route, like a beautiful view during the trip, are left out of scope because this would make the simulation more complex and situation specific. The average travel speed of a single vehicle is a microscopic indicator that is often obtained from simulations. Because people do not like congestion and roads with lower speed limits, this indicator indicates the satisfaction of the route choice. Although this indicator should be as high as possible, it is not the objective to get this indicator as high as possible. Otherwise, a detour in free-flow condition with a higher speed limit would get the preference above a shorter travel time. Next to the travel speed and route preference, the perception regarding to manoeuvrability is an indicator of the service level. This indicator can be measured by density, percentage of trucks or vehicle headways. This study does not include variations in vehicle type. This makes this indicator unmeasurable. Because this study will report results on the macroscopic level, the headway could be replaced with the density that includes the average headway for all vehicles. Because density will differ on links but stay constant for all links, measuring the total network delay would be more suitable to indicate the service quality. While roads become busy, there is already some delay because the speed limit is not reached which indicates that vehicles have less manoeuvrability.

More cost-effective traffic management by optimising the use of existing road capacity
Currently, the traffic management centre is limited with its information provision by the DRIPs on the side of the roads. These systems are expensive and they are in many situations only relevant for 30% to 40% of the road users (KiM, 2017). Service providers have a continuous connection with their users and can provide information that is relevant for a specific driver. With the existing hardware and the future predictions for automated vehicles, a centralised system that only covers the management task could be more cost-effective than the current measures of all individual traffic management centres. The costs for implementation are out of scope for this research. However, the benefits are considered with the previous two objectives.

Economic growth and the creation of more jobs by reducing traffic problems and by creating new business opportunities.
A reduction of travel time leads to higher accessibility of an area which makes it more interesting to invest in. This is the well-known principle of the transport-land use feedback circle (Wegener, 1996). The SOCRATES$^{2.0}$ project strives for this goal, however, this is not within the scope of this research. This is also the case for the potential business opportunities which can be implemented by the service providers. They could for example let users pay an additional fee to always get the fasted route and give the detour to users that pay less. The full potential for the business of service providers is just like the economic growth out of scope.

2.4.2 Key performance indicators for traffic flow

The performance of the traffic flow can be expressed in three levels of detail. These levels are the network as a whole, the performance on a specific road or route and the handling results for individual vehicles. The more detail, the more distinctions can be made to different sub-groups. However, more detail means more data and more calculation time. In the ideal situation, a distinction between participating and non-participating service providers is made. With this distinction, the benefits per behaviour of service providers can be presented to convince them to participate. However, this is not possible in the macro simulation model that is chosen in chapter 4. Because the traffic flow indicators of the whole network can make it seem as if the differences are very small, some important roads or origin-destination indicators must be included as well. To indicate the performance of the traffic flow, several options are available. These are the travel time, delay, speed and outflow. In this study, the travel time and delay are chosen to be the parameters to determine the performance of the traffic flow. The travel time will include the additional time of a detour where the total delay tells something about the amount of congestion. Because the average speed of the network increases with a congestion free detour, this will not always lead to a better performance of the network and can overestimate the benefits. Because the capacity drop is not simulated, the outflow per link is less interesting. Because the model will be empty at the start and the end of the simulation, the resulting outflow will be equal and that makes it more difficult to draw conclusions based on this information.

2.4.3 Key performance indicators for service quality

As described in paragraph 2.4.1, several indicators can be measured to determine service quality. Within the scope of this project, this indicator should indicate the travel experience of the driver without any environmental or information transfer elements. The quality of the trip is determined by the level of manoeuvrability and traffic speed. People like to drive in free-flow conditions and prefer routes with a higher speed limit. The most obvious indicator is the average traffic speed of the vehicle. A lower speed results in less satisfaction about the trip because of lower speed limits or congestion. For this reason, the speed for the vehicles should be measured as the aggregated network speed to take the detour speeds into account. In the case of manoeuvrability, the level of detail should be more general and determined per route. All routes would get a score based on how dense the road relatively is. Since in most situations this is expressed by the intensity/capacity (i/c) ratio, this will also be applied for this study. According to the Dutch manual capacity values infrastructure, every i/c ratio below 0,8 is ranked as good, between 0,8 and 0,9 as moderate, between 0,9 and 1,0 as bad and above 1,0 as very bad (Goemans, Daamen, & Heikoop, 2011). Due to a problem with the loading of the results into OmniTRANS, this measurement was not possible. As an alternative, the total network delay can indicate how dense the roads are. Because highly dense routes slow down traffic and already lead to a measured vehicle delay, this can also be used to indicate the quality of the trip. Additionally, because the general indicator of delay does not discriminate within locations in the network, all links with congestion will be measured and presented on a map.

2.4.4 Formulation objective

This research focuses on the improvement of the traffic flow. As a result, the average travel time of all road users should be minimal to strive for better traffic flow performance. The mathematical objective of the coordinated approach is to minimise the total travel time of all vehicles together. This objective is described below.

$$Minimise \sum_{v=1}^{n} t_v$$

$t_v = travel\ time\ of\ vehicle\ v$
$v = index\ of\ vehicle$
$n = total\ number\ of\ vehicles\ in\ the\ network$

Other considered objectives for a system optimum approach are the minimisation of the energy consumption, the environmental pollution or the total network delay in the system. Because not every user care about the financial benefits of reduced energy consumption, this is not a commonly agreed objective. In the future, the sale of fossil fuel vehicles is banned in many western countries (Coltura, 2021) and only clean energy sources will be available. This makes an objective to minimise environmental pollution in the future no longer relevant. Minimising congestion might be a good objective. However, this would not result in the lowest average travel time for all users by definition (Summerflied, Deokar, Xu, & Zhu, 2020). In an extreme situation, this could result in extreme detours, which could result in a longer average travel time. From the perspective of the user, this does not lead to a more ideal situation. This makes the minimisation of the travel time the most suitable objective.

2.4.5 Summary of objectives and indicators

The discussion above has resulted in a set of KPIs and an objective that is suitable for all actors. A summary of all KPIs can be found in Table 2 Key Performance Indicators and the objective can be found in Table 3 Objective for the coordinated approach.

Table 2 Key Performance Indicators

Indicator	**For what**	**Unit**
Travel time	All vehicles	Veh.hrs / Min/veh
	Some interesting routes	
	Some interesting OD pairs	
Average aggregated speed	All vehicles	Km/h
Delay	Total network	Veh.hrs
Congestion	Links	m
	Total network	

Table 3 Objective for the coordinated approach

Indicator	**Goal**	**Unit**
Total travel time	Minimise	Veh.hrs

2.5 Conclusions

With the critical review of the SOCRATES$^{2.0}$ project and the formulation of the common goals of both service providers and road authorities, the first sub-question: *How can road authorities and service providers work together in a coordinated approach to give route advice and what do they want to achieve?* is answered. The review of the SOCRATES$^{2.0}$ project shows that the vertical segregation of the network management layer by the implementation of intermediaries can set up cooperation between road authorities and service providers. Every actor collects its data and the intermediary combines this information to advise on the measures to be taken out by all actors based on a commonly agreed strategy table. However, as shown in Figure 11, this approach can lead to several options for bypassing behaviour. The service providers can be categorised into three categories based on their behaviour; service providers that participate, service providers that only share data, service providers that do not participate. If this bypassing behaviour will form a problem is the main question for this research. Based on the objectives of the SOCRATES$^{2.0}$ project the main common goal is to minimise the travel time is formulated. While the travel time is minimised, almost all other objectives will likely be improved as well. Next to the travel time, it is also important to indicate the performances of other objectives that are relevant to this study. This means that the quality of the service is indicated, next to the travel time, by the average travel speed of vehicles and the total delay in the network. With this set of key performance indicators, it is possible to evaluate the performance of the intermediary as an assessor.

3 Policy regulations for route guidance

The previous chapter describes how road authorities and service providers could interact during a cooperative approach and what they want to achieve. To prevent the described bypass behaviour of service providers and stimulate the desired behaviour, several policy strategies with different regulations can be distinguished. This chapter elaborates on these policy regulations and explains possible outcomes in terms of routing behaviour. This will answer the question: *What are possible policy regulations for a centralised route guidance policy to guide cooperative vehicles to increase the impact on the traffic flow?*

3.1 Regulations

In this paragraph, different individual regulation measures are described. To describe the effect on the behaviour of road users of these measures, Figure 12 Scheme for route behaviour with possible regulations, is developed to visualise the options to regulate the use of the services of the intermediary.

3.1.1 Scheme for routing behaviour

The interaction scheme of Figure 11 shows how all actors can cooperate. However, in terms of regulations, it is the intention to change the routing behaviour of vehicles in the network. This can be accomplished with regulations for service providers and individual vehicles. For this reason, the scheme of Figure 11 will be translated into a scheme that leads to vehicle behaviour where regulations can be placed to get more drivers in the network with the preferred routing behaviour.

At the top of the scheme of Figure 12 the composition of the vehicle fleet is distributed in human drivers and automated vehicles. This is done because automated vehicles will be routed by the system of a service provider and human drivers can be stubborn and ignore every route advice they get. This leads to three categories of influence; Vehicles that cannot be influenced, vehicles that are influenced by the traffic management centre and vehicles that are influenced by the service providers. The first category cannot be reached with regulations. For the second category, it is assumed that the traffic management centre strives to guide vehicles in a congestion avoiding approach. The third category, that is influenced by the service providers, drive without regulations according to the user optimum algorithm. However, with regulations, this group can be switched to a congestion avoiding approach. Because people must comply with the route guidance, not all people with a congestion avoiding route advice will accept it. This leads to three groups of vehicles behaviour. Vehicles with a fixed route choice, vehicles who drive congestion avoiding user optimum and drivers who drive user optimum. The Ω signs in Figure 12 are positions of regulatory measures and are explained in the next subparagraph 3.1.2.

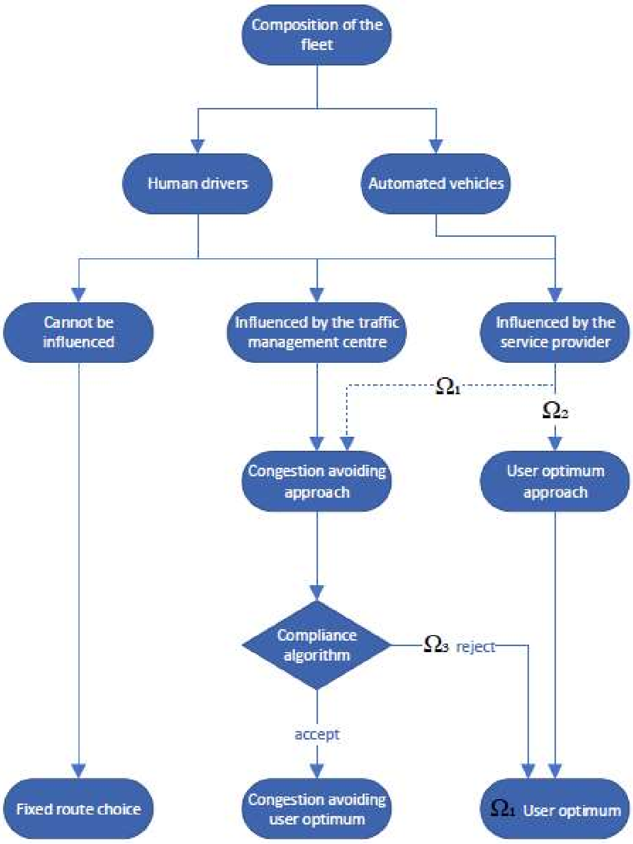


Figure 12 Scheme for route behaviour with possible regulations

3.1.2 Measures for regulation

In total, there are three measures formulated to force influenceable vehicles to drive according to the congestion avoiding user optimum. This subparagraph explains the individual measures. The subsequent paragraph combines these measures to create different policy strategies.

Ω_1: Implementation of the intermediary
The first regulation, named Omega 1, is the implementation of the intermediary. In Figure 11 this means that the intermediary becomes available and next to the behavioural groups SP3, the behaviour of groups SP1 and SP2 become available. The intermediary makes the path to congestion avoiding user optimum routing for service providers possible. This is presented with the dashed line, with the Omega 1 sign, in Figure 12. Next, this regulation also makes it possible for service providers possible to exchange data to improve their user optimum algorithm. For this reason, the Omega 1 sign is added to the user optimum algorithm. The distinction between different user optimum algorithms will be made later.

Ω_2: Regulation that forces service providers participate with the services of the intermediary
The second regulation, named Omega 2, forces service providers to use the services of the intermediary. This means that in Figure 11 it is not possible to behave like behavioural groups SP2 and SP3. When this regulation is active, service providers cannot directly offer user optimum route suggestions to their users. Service providers are obligated to execute the instructions of the intermediary and offer the congestion avoiding user optimum routing to their users.

Ω_3: Regulation that forces road users to accept the route guidance
With the third regulation, named Omega 3, the option to reject the congestion avoiding algorithm is blocked. Road users will be forced to comply with the congestion avoiding user optimum routing. In this case, all guided vehicles will avoid congestion to improve traffic performance.

3.2 Policy strategies for route guidance policies

Based on the measures described in paragraph 3.1, several policy strategies can be formed. These strategies are described with possible scenarios on the impact of actors' behaviour in the next subparagraphs. The formed policy strategies are:

- Do nothing;
- A regulated intermediary, free of obligations;
- Obligated use of intermediary services, but voluntary use for road users;
- Obligated use of intermediary services and mandatory use for road users.

To describe these strategies, Table 1 Expanded cooperation model matrix, shall be completed for every strategy. This table describes the regulation per level of detail. These levels are:

- Situational: Agreement on the status of the network.
- Operational: Agreement on the measures to be taken.
- Tactical: Agreement on target service level.
- Strategic: Agreement on goals/objectives to be pursued.

3.2.1 Do nothing

The first strategy is to do nothing. In this case, cooperation between actors will not be established. All service providers act independently, strive for a user optimum approach and they do not share any data. The behaviour of service providers and road authorities are presented in Table 4 Cooperation model matrix, scenario: Do nothing. Compared to the current situation with the introduction of automated vehicles, all vehicles will eventually route user optimum without having perfect information of the network.

Table 4 Cooperation model matrix, scenario: Do nothing

Level of commonality	No common
Level of commitment	Free – No obligation
Situational	Only separated observations
Operational	No alignment, users can reject measures
Tactical	User optimum for service providers, system optimum for road authorities
Strategic	No strategic common goals formulated

3.2.2 A regulated intermediary, free of obligations

The second strategy is to establish an intermediary without any obligations. In this situation, the behaviour of service providers can be grouped into three different subgroups as described in Figure 11. These groups consist out of service providers who participate, who only share data and who act independently. In this strategy, there are no strict regulations and road users can choose to comply with the route guidance or reject it for a user optimum routing. Therefore, the service providers who participate will not suffer competitive disadvantages from longer travel time for their users who comply. Because of the absence of a regulator that forces service providers to participate, three scenarios must be researched. The first is a situation where service providers only use the shared data and ignore the instructions of the intermediary. The second is that just a part of the service providers will participate. And for the third scenario, all service providers will participate. In the last case, this will lead to the same result as the obligation for service providers to participate. How large the share of participators would be by nature is unknown and no research has been found to underpin a distribution. In the second scenario, it is assumed that half of the service providers will participate. This will give the most insights because no participation and full participation is both researched. This means that the second scenario lies between the two.

Table 5 Cooperation model matrix, scenario: Regulated intermediary, free of obligations

Level of commonality	Co-creating one commonly agreed ‘truth’	
Level of commitment	Free – No obligation	Committed - Obligation
Situational	Part of the service providers have an independent view based on shared data	Part of the service providers have a common view of the network status
Operational	Users can reject measures, Part of the service providers act independently	Part of the service providers have system alignment
Tactical	User optimum approach for a part of the service providers	System optimum approach for road authorities and part of the service providers
Strategic	Part of the service providers have no common goals	Part of the service providers strive together with road authorities for a system optimum performance

3.2.3 Obligated use of intermediary services, but voluntary use for road users

The third strategy is to regulate the use of the intermediary. In this case, users can still reject route guidance. However, service providers are obligated to execute the measures of the intermediary. During the period where human drivers are still on the road, the service providers will not suffer from disadvantages from longer travel time for the users of the system who are not willing to accept these. This prevents users from disconnecting the system.

Table 6 Cooperation model matrix, scenario: Complete regulations or full commitment, voluntary use for road users

Level of commonality	Co-creating one commonly agreed 'truth'	
Level of commitment	Free – No obligation	Committed - Obligation
Situational	-	Common view of network status
Operational	Users can reject measures	Full system alignment
Tactical	-	System optimum approach for all actors
Strategic	-	Common goal is a system optimum performance

3.2.4 Obligated use of intermediary services and mandatory use for road users

The last strategy is a complete regulation of the services. In this case service providers are forced to use the services of the intermediary and road users are obligated to comply with the route guidance. This could reduce the willingness of human drivers to use the route guidance system. Human drivers could still reject the routing and drive according to their knowledge of the network. However, automated vehicles need the services of the service provider. A strong regulation might result in a longer transition period. However, eventually, all vehicles will be automated and this strategy will lead to a situation where all vehicles route according to the congestion avoiding user optimum.

Table 7 Cooperation model matrix, scenario: Complete regulations, mandatory use for road users

Level of commonality	Co-creating one commonly agreed 'truth'
Level of commitment	Committed - Obligation
Situational	Common view of network status
Operational	Full system alignment without exceptions
Tactical	System optimum approach for all actors
Strategic	Common goal is a system optimum performance

3.2.5 Other strategies, not used for this research

Next to the four described strategies, another strategy could be formed. This subparagraph describes the choice for the discarded strategy.

A regulated intermediary, no obligations for service providers and obligations for road users

In this strategy, omegas 1 and 3 are active and 2 is inactive. This strategy is quite complicated to achieve. As mentioned before, the obligation for road users brings disadvantages in competitiveness for participating service providers and may let users disconnect from the route guidance system in favour of a faster routing service. This makes this strategy less likely to be implemented successfully because service providers have the incentive to disconnect from the service. Therefore, it will not be included in this research.

3.3 Conclusion

Based on the knowledge of how road authorities and service providers will cooperate, the scheme of route behaviour was formed. Based on this scheme, several regulations were formulated which are combined to different policy strategies. The set of policy strategies answers the sub-question: *What are possible policy regulations for a centralised route guidance policy to guide cooperative vehicles to increase the impact on the traffic flow?* This has resulted in three policy measures, four regulation strategies and five behavioural scenarios for the impact on the traffic flow. The policy measures are; the implementation of an intermediary, the obligation of service providers to participate and the obligation of road users to comply with the system. This leads to the following scenarios with the four policy strategies.

- **Do nothing;**
  In this strategy, no regulations are implemented and eventually, all vehicles will route user optimum without perfect knowledge of the network.
- **A regulated intermediary, free of obligations, only used for data sharing;**
  In this strategy, an independent intermediary is established which makes cooperation possible. The intermediary will aggregate the data of all participating actors and determines the optimal set of measures based on a commonly agreed strategy table. However, the suggested measures of the intermediary are ignored by the service providers. In this case, eventually, all vehicles route user optimum with a good knowledge of the network state.
- **A regulated intermediary, free of obligations, partial commitment;**
  In this strategy, an independent intermediary is established which makes cooperation possible. The intermediary will aggregate the data of all participating actors and determines the optimal set of measures based on a commonly agreed strategy table and only part of the service providers execute the suggested measures. In this case, eventually, part of the vehicles get congestion avoiding routing.
- **Obligated use of intermediary services, but voluntary use for road users;**
  In this strategy, in addition to the previous strategy, all actors are forced to use the services of the intermediary. In this case, all vehicles eventually get congestion avoiding routing. This would give the same result as in the situation that all service providers will participate voluntarily in the project.
- **Obligated use of intermediary services and mandatory use for road users.**
  In this strategy, in addition to the previous strategy, also the road users are forced to comply with the system. In this case, eventually, all vehicles will comply with the congestion avoiding routing of the intermediary.

4 Simulation methodology

The previous chapter describes the different policy strategies that can be used to increase the effectiveness of a centralised route guidance system by regulation. This chapter describes the methodology to simulate the effect of the centralised route guidance system with different scenarios of regulations on the traffic flow. It starts with the selection of simulation tools, continuing with the selection of algorithms and ending with the conversion of the regulation strategies towards the simulation components.

4.1 Selection of simulation tools

This paragraph describes the choice of simulation tools. For a more detailed version of the choice made for the software, please refer to Annex D.

4.1.1 Choice of software package

Three main types of models can be used for traffic simulations. These types are micro-, meso- and macroscopic-models (van Wageningen-Kessels, van Lint, Vuik, & Hoogendoorn, 2015). All three types of models are suitable for this study. However, the calculation time of the macroscopic model is much faster compared with the micro and meso models. With a ring structured network, the network has multiple route options and is substantial in size. This makes the macro model more suitable to do the simulations. In addition, a more detailed model could lead to more uncertainty in results because more parameters must be calibrated with the risk of measuring other phenomena. In total, 25 software packages were considered with DynusT, MARPLE and OmniTRANS StreamLine as the most promising packages. In consultation with Simeon Calvert, co-director of the DiTTlab, the availability of the packages was discussed which led to MARPLE as the only available package (S. Calvert, personal communication, May 7, 2021).

MARPLE stands for Model for Assignment and Regional Policy Evaluation and is a Macroscopic dynamic traffic assignment (DTA) model. MARPLE operates with user classes that can be used to simulate the difference in route choice behaviour and the difference in knowledge about the traffic state in the network. This makes it possible to simulate the behaviour of the different groups shown in Figure 12 and even to distinguish between the level of knowledge of different user optimum drivers.

4.1.2 Choice of network

In consultation with Simeon Calvert of the DiTTlab, three available networks that are described in his paper of 2014 (Calvert, Taale, Snelder, & Hoogendoorn, 2014) were offered. The assumed most suitable network is the Network of the Rotterdam Ring because multiple origin-destination pairs have an alternative route that requires only a small additional detour. Unfortunately, it failed to let this model communicate with MARPLE. For this reason, in consultation with Henk Taale, an alternative network with a ring property is founded in the Milan ring network of 2002 which is presented in Figure 13. Compared to the Rotterdam ring network, the Milan ring network has multiple rings that allow more route alternatives for more OD pairs. Because of this variation, this network is an even better choice to perform the simulation than the networks offered by the DiTTlab. The Milan ring network consists of 841 links and 25 zones for origin and destination.

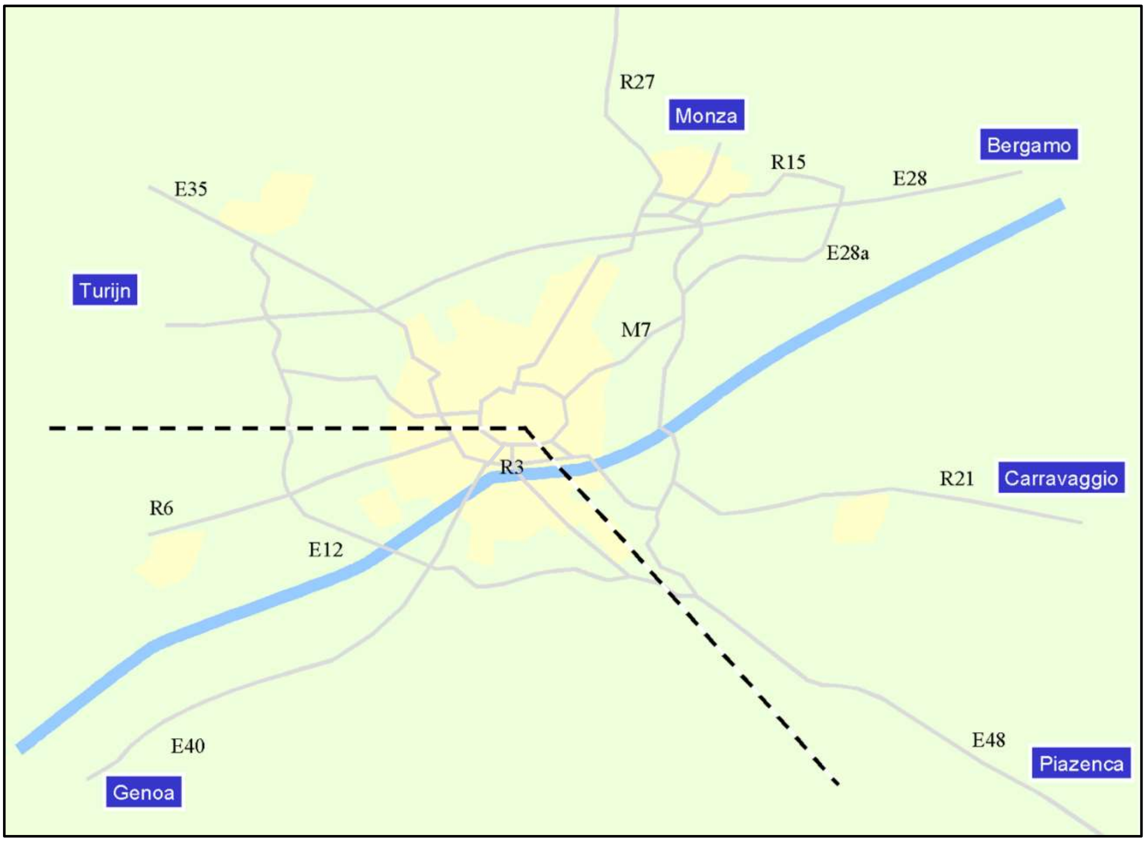


Figure 13 Milan ring network

4.2 Selection of algorithms for route guidance

There are five well-known algorithms for the assignment of traffic available in the transportation research field. These are: All or Nothing Assignment, Capacity Restrained Assignment, Incremental Assignment, User Equilibrium Assignment and System Optimum Assignment (Saw, Katti, & Joshi, 2015). However, MARPLE does not provide all algorithms. MARPLE has two user optimum optimisation algorithms available that can be performed to reallocate traffic. The next subparagraphs describe which algorithms are provided in MARPLE and which algorithms are used during the simulation study.

4.2.1 Initial allocation

MARPLE uses an initial allocation based on the C-logit model and the free flow travel times or the shortest path (Taale, 2020). After this process, the simulation starts and travel times are calculated. The initial allocation can be used for traffic that cannot be influenced by traffic information. Habitual routing behaviour consists mostly of previous experiences of the driver (Bogers, Bierlaire, & Hoogendoorn, 2014). Because traffic is not always congested, it is assumed that habitual drivers, that cannot be influenced by traffic information, will route to their perceived fastest route according to the uncongested traffic condition. Another option for the initial allocation of traffic in MARPLE is the method of the shortest path. Because this might lead to excessive use of the underlying road network, the method of the shortest path is not a useful principle and therefore the fastest route method is chosen.

4.2.2 User optimum algorithm

MARPLE has two User Equilibrium Assignment algorithms, namely, Stochastic User Equilibrium (SUE) and Deterministic User Equilibrium (DUE) (Taale, 2020). For the DUE it is assumed that drivers have perfect information over the network and choose the actual fastest route. The SUE is used while the information over the network is not perfect or incomplete and drivers choose their perceived fastest route. How good or complete the knowledge of the traffic state is, can be varied with the parameter teta. Teta changes the size of the stochastic uncertainty for the SUE assignment. A larger teta means a smaller uncertainty and represents a more complete knowledge of the traffic state. In this case, it is more likely that drivers choose the actual fastest route. The SUE algorithm uses the C-Logit route choice algorithm to consider the overlap of routes. To flatten route intensity to ensure that the simulation converts, the Multiple Successive Average method (MSA) is used. For this study, only the SUE algorithm is used where the teta describes how ‘’good’’ the quality of information for the specific group is. In the situation that all service providers work together, the teta is assumed to be large enough to indicate almost perfect information. Because in almost every situation there are still human drivers involved, the information will never be perfect like in the DUE and the SUE algorithm, with a large teta, is more suitable.

4.2.3 Congestion avoiding user optimum algorithm

Cooperative vehicles will route with a congestion avoiding user optimum algorithm. This is because MARPLE cannot combine system optimum and user optimum algorithms for different user groups in the same simulation (H. Taale, personal communication, May 12, 2021). The system optimum algorithm in MARPLE is not available by default. If the system optimum algorithm would be implemented in MARPLE for this research, it would, because of the limitation to combine it with other algorithms, only be useful for the fully regulated scenario with 100% automated vehicles. For this reason, there is searched for an alternative by means of a perceived time penalty for links above a certain intensity/capacity threshold. Because of this time penalty, participating road users will avoid routes with a (nearly) congested link. This will reduce the congestion and for that reason the travel time for other road users. In the best-case scenario, it also prevents congestion with the associated capacity drop. Unfortunately, MARPLE does not simulate the capacity drop which could lead to an underestimation of the results. Previous studies show promising results to the traffic flow performance by vehicles that avoids congestion. However, while avoiding congestion is the objective, there could be a point that the detour will be larger than the travel time benefits (Summerflied, Deokar, Xu, & Zhu, 2020). Because the time penalty on the congested route is limited during this research, vehicles will still drive the congested route while the detour becomes too large. With this concept, congestions will be avoided and therefore shrink or even be solved which leads to a better traffic flow performance.

The principle to use congestion avoidance to achieve a better traffic performance will work as follow. In case of congestion on a single lane link, all routes containing that link will have an additional travel time in terms of a percentage of the total travel time. This could result in a perceived longer travel time than the detour option. The congestion avoiding vehicles would prefer the detour and that will reduce the inflow on the congested link which will reduce the congestion. With a capacity of 1800 vehicles per hour, this would mean that every vehicle that takes a detour of x seconds will reduce the queue by 2 seconds. This means that the travel time of all passing vehicles will be reduced by 2 seconds by the offer of x seconds of the vehicle that makes the detour until the moment the congestion would be solved without the detour. Additionally, the capacity of a real-world road in free-flow conditions is 5% to 30% larger than the traffic handling of the same road in congested conditions (Yuan, Laval, Knoop, Jiang, & Hoogendoorn, 2018). That means that the handling of the traffic flow of the maximum capacity free-flow will cost 5% to 30% more time in case of a congested road. In conclusion, if the detour of some vehicles can prevent congestion, this will also lead to significant travel time benefits for all vehicles on that specific route. However, because of the limitations of the chosen software, only the first principle of reducing travel time is considered.

During the simulation, the route choice depends on the expected travel time. All vehicles will drive with a user optimum algorithm and will optimise their travel time. However, the vehicles that avoid congestion will perceive a time penalty for congested routes. In this situation, vehicles will choose the alternative route which is not congested. Table 8 shows an example of a congested route that is still faster than the free flow alternative. While the time penalty is adjusted, the perceived travel time of the (nearly) congested route is expected to be larger and the free-flow alternative is chosen.

Table 8 Example for time penalty perceived travel times, with in green the chosen route

Example for congestion avoiders		
	(nearly) Congested route	Free-flow alternative
Free flow travel time	500s	575s
Congested travel time	550s	575s
Fictional nearly congested travel time with 20% time penalty	500 + 20% = 600s	575s
Fictional congested travel time with 20% time penalty	550 + 20% = 660s	575s

4.3 Mathematical description of the model

The previous paragraph described which components of MARPLE are used for this study. This paragraph describes the chosen components of MARPLE mathematical. The mathematical description of the MARPLE model is taken from the study of Taale (2008) and adapted, if necessary, to the situation of this study. MARPLE is a dynamic deterministic traffic assignment model. For this study, the stochastic dynamic user optimal assignment (SDUE), that is implemented in MARPLE, is used to perform the simulation. The model uses the Dijkstra algorithm to generate routes. To assign traffic to these routes, a stochastic user equilibrium where the random error with parameter θ can be adjusted to represent the information knowledge of the network is used. With the C-logit model overlap in routes are considered by assigning traffic. To load this traffic, MARPLE uses a dynamic network loading model which includes congestion spillback. To smooth route flows the method of successive averages (MSA) is included and the model stops the simulation when the convergence criterion is reached.

4.3.1 Stochastic dynamic user optimal assignment (SDUE)

The definition of SDUE is: For each origin-destination (OD) pair, any road user travelling between a specific OD pair and departing during a specific time interval, cannot improve his perceived route travel costs by unilaterally changing routes during that time interval (Taale, 2008). The algorithm consists of six steps and an overview of all notations can be found in Appendix F.

Algorithm Stochastic dynamic user optimal assignment (Taale, 2008)

```
Step 1: Construct a set of routes between every OD pair with Dijkstra algorithm, see paragraph 4.3.2.
Step 2: For each time period $k$ determine an initial route flow solution $f_k^{(0)} \in \Omega$.
        Set $j:=1$.
Step 3: Calculate route cost $c_k^{(j)}(f^{(j-1)})$ using the dynamic network loading model of paragraph 4.3.2.
Step 4: Calculate new route flows $f_k^{(j)} \in \Omega$ with the C-logit model of paragraph 4.3.4.
Step 5: Smooth route flows with $f_k^{(j)} = f_k^{(j-1)} + \zeta^{(j)}(f_k^{(j)} - f_k^{(j-1)})$ see explanation of the method of
        successive averages (MSA) in paragraph 4.3.5.
Step 6: If convergence criterion is met, then stop. See for convergence criteria paragraph 4.3.6
        Otherwise, set $j:=j+1$ and return to step 3.
```

The perceived route costs $\hat{c}_k^{rod}$ for OD pair od, route r and time period k is presented by Equation 1

$$\hat{c}_k^{rod} = c_k^{rod} + tpb_k^{rod} * tpp * c_k^{rod} + \varepsilon_k^{rod}$$

Equation 1 Calculation of the perceived route costs

In this equation, tpb_k stands for the binary value which is 1 if a link on the route exceeds the I/C-Threshold value (see paragraph 5.1.1 for further explanation) and 0 if not for time period k, tpp stands for the percentage of the time penalty and ε_k^{rod} is the random component for route r for origin o and destination d. The calculation of c_k^{rod} is further described in paragraph 4.3.7.

4.3.2 Route generation

To generate routes for every OD pair, MARPLE uses the Dijkstra algorithm to generate routes in an acceptable amount of time (Taale, 2008). For this study, the shortest route is based on the free flow travel time because this gives advantages to roads with higher speeds and reduces the advantage of cut-through routes. The applied algorithm consists of four steps and is presented below.

Algorithm Enumerate routes (Taale, 2008)

```
Step 1: Generate 8 routes from a set of 50 random drawings
Step 2: For every OD pair, find the shortest route in free flow travel time for the original cost matrix
        $\boldsymbol{C}$ and add this route to the set of routes $\mathfrak{R}^{od}$.
Step 3: For $m = 1{:}50$
        Draw the error matrix $\Lambda^{(m)}$.
        Calculate the adjusted link costs with $\boldsymbol{C}^m = \boldsymbol{C}(1 + \omega|\Lambda^{(m)}|)$.
        For every OD pair and the cost matrix $\boldsymbol{C}^m$, find the shortest route $r^{odm}$.
Step 4: For every OD pair and route $r^{odm}$:
        Check if $r^{odm}$ is shorter than the k-th longest route in the set $\mathfrak{R}^{od}$.
        Check if there is not too much overlap with the other routes in the set.
        If these conditions are fulfilled, add route $r^{odm}$ to route set $\mathfrak{R}^{od}$.
```

4.3.3 Dynamic network loading model

To obtain information about the resulting link indicators, congestion in the network and travel times, the route flows are loaded onto the network with a deterministic dynamic network loading (DNL) model (Taale, 2008). The model is deterministic and dynamic because there are no random components and the loading of the network evolves over time. The model can be described in general according to the following steps. Traffic is loaded according to the demand profile. The traffic propagates link by link from origin to destination. The travel time on the link is based on the travel time function, described in paragraph 4.3.7. At decision nodes, nodes with multiple directions, flows are distributed according to the proportion of the route flows. The model checks if there is enough space available on the next link. If there is not enough space, the traffic that wants to enter is stored in the queue on the upstream link. This means that the model blocks back traffic and this principle is described in paragraph 4.3.8. The algorithm of the dynamic network loading model is described below.

Algorithm Dynamic network loading model (Taale, 2008)

```
Step 1: Initialise all variables needed.
Step 2: Calculate splitting rates for every node and time period.
Step 3: Propagate traffic through the network using the following steps:
        Determine the initial flows per link.
        Determine free flow travel time and capacity per link and time period.
        Divide each time period in a number of time steps.
```

For every time step t:

- *Determine delay and travel time per link.*
- *Calculate the outflow per link.*
- *For every node determine the inflow.*
- *Calculate the available space for every link.*
- *For every node determine the outflow with the splitting rates.*
- *Determine the inflow for every link.*
- *Determine links with blocking back and adjust the outflow for those links.*
- *Calculate link indicators.*

Step 4: Calculate delay and travel costs c_k^{rod} for every r, d, o and k. See paragraph 4.3.7.

4.3.4 C-logit model

MARPLE uses a C-logit model. This model takes overlap in routes into account in the so-called commonality factor CF (Taale, 2008). The commonality factor CF_k^{rod} is calculated by Equation 2.

$$CF_k^{rod} = \beta ln \sum_{s \in \Re^{od}} \left[\frac{L_{rs}}{\sqrt{L_r L_s}} \right]^{\gamma}, \forall o, d, r \in \Re^{od}, k,$$

Equation 2 Calculation of commonality factor (Taale, 2008)

In this equation are β and γ positive parameters, L_r and L_s the lengths of routes r and s and L_{rs} the length of the common links shared by both routes. The commonality factor is included in the C-logit model as presented in Equation 3 and calculates the probability, p_k^{rod}, that a certain route is chosen. With this probability, the resulting flow, f_k^{rod}, is calculated with Equation 4. Here is q_k^{od} the demand for origin o and destination d at time period k.

$$p_k^{rod} = \frac{e^{-\theta c_k^{rod}} - CF_k^{rod}}{\sum_{s \in \Re^{od}} e^{-\theta c_k^{sod}} - CF_k^{sod}}, \forall o, d, r \in \Re^{od}, k,$$

Equation 3 Probability to choose a certain route (Taale, 2008)

$$f_k^{rod} = p_k^{rod} * q_k^{od}$$

Equation 4 Calculation of the route flows (Taale, 2008)

4.3.5 Method of successive averages

The route flows are smooth by the method of successive averages (MSA). Equation 5 shows how new flows are calculated. Here is j an index for an iteration in the assignment and $\zeta^{(j)}$ the parameter to smooth the flows for iteration j. This parameter is calculated by Equation 6 with arbitrary choices of $a_1 = 0{,}95$, $a_2 = 0{,}25$ and $a_3 = 0{,}05$ made by the developer of MARPLE (Taale, 2008).

$$f_k^{(j)} = f_k^{(j-1)} + \zeta^{(j)} (f_k^{(j)} - f_k^{(j-1)})$$

Equation 5 Method to smooth flows

$$\zeta^{(j)} = a_1 e^{-a_2 j} + \frac{a_3}{j}$$

Equation 6 Calculation of the parameter to smooth the flows for iteration j (Taale, 2008)

4.3.6 Convergence criteria

To convergence the simulation, Equation 7 is used with a threshold value for the convergence error, ε^*, of 1%. Usually, the convergence error is set somewhere between 0,1% and 5% (Taale, 2008). For this study, the percentage of 1% is chosen because a lower convergence criterion led to a calculation error. MARPLE presents with a lower convergence criterion for the Milan ring network a NaN value for the flow of some routes because these flows become too small to be calculated and every route should have some flow. The number of vehicles that can be influenced grows with more automated vehicles. This leads to differences in the number of iterations. For this reason, the convergence criteria should be as low as possible and have been set to 1%.

$$\max_{k} \max_{od} \max_{r \in \Re^{od}} \frac{\left| f_k^{rod(j)} - f_k^{rod(j-1)} \right|}{q_k^{od}} < \varepsilon^*$$

Equation 7 Convergence criteria (Taale, 2008)

4.3.7 Travel time calculations

The travel time of a link at a certain time step is calculated with Equation 8. In this calculation the travel time τ_{at} increases when the degree of saturation φ_{at} becomes close to 100%. This means that there is already a delay recorded before there is a queue. This is reasonable because on busy roads, it is not for everyone possible to drive their desired speed and they must slow down a bit. The equation includes the queue length κ_{at} to include the waiting time in the congestion in the calculation of the travel time.

$$\tau_{at} = \tilde{\tau}_{at} + 0{,}9 l_a \Delta_h \left(z_{at} + \sqrt{z_{at}^2 + \frac{8 k_a \varphi_{at}}{Q_a'' \Delta_h} + \frac{16 k_a \kappa_{at}}{(Q_a'' \Delta_h)^2}} \right), \forall a \in A, t$$

Equation 8 Travel time calculation (Taale, 2008)

Where Δ_h is the length of the analysis for time period h, Q_a'' the capacity at the end of the link and $\tilde{\tau}_{at}$ the free flow travel time. The z_{at} is a parameter related to the initial queue for link a at time step t presented in Equation 9. k_{at} is a link dependent parameter and is determined with Equation 10. In this equation v_a^f is the free flow speed (km/h) and v_a^c the speed at which free flow turns into congestion.

$$z_{at} = \varphi_{at} - 1 + \frac{2\kappa_{at}}{Q_a'' \Delta_h}, \forall a \in A, t$$

Equation 9 Calculation of parameter related to the initial queue (Taale, 2008)

$$k_a = \frac{2 Q_a'' \left(\frac{v_a^f}{v_a^c} - 1 \right)^2}{\Delta_h \left(v_a^f \right)^2}, \forall a \in A$$

Equation 10 Calculation of link dependent parameter (Taale, 2008)

4.3.8 Blocking back traffic

Before traffic propagates through the network, the model checks if there is enough space available on the next link. If not, the inflow of the link will be reduced to the space available and the vehicles will be stored in the queue upstream. The available space Ψ_{at} is calculated based on the length of the link l_a times the number of lanes p_a divided by the length that a vehicle occupies including the space headway l^{-veh} minus the number of vehicles that are already on the link χ_{at}. The equation is given in Equation 11.

$$\Psi_{at} = \frac{l_a p_a}{l^{-veh}} - \chi_{at}, \forall a \in A, t$$

Equation 11 Calculation of length of the queue

When the inflow u_{at} is larger than the available space Ψ_{at} or the capacity of the beginning of the link Q'_a, the inflow must be reduced to meet the constraints of Equation 12.

$$u_{at} \leq \Psi_{at}$$
$$u_{at} \leq Q'_a$$

Equation 12 Constraints for the inflow of a link

The difference between the calculated inflow u_{at} and the new reduced inflow u'_{at} will result in a queue stored upstream. The queue length κ_{at} is formulated by Equation 13 and contains the difference between the unconstrained outflow and the corrected outflow for a link at a certain time step.

$$\kappa_{at} = \tilde{v}_{at} - v'_{at}, \forall a \in A, t$$

Equation 13 Calculation of the queue length

4.4 Algorithm for the compliance of route guidance

Congestion avoiding user optimum routing is not always the optimal situation for every single user. For that reason, not everyone is willing to accept it. Multiple studies show among others that the more additional travel time, the fewer people will accept the social route guidance (Mariotte, Leclercq, Ramirez, Krug, & Becarie, 2021; Bonsall & Joint, 1991; van Essen, Thomas, van Berkum, & Chorus, 2020). This means that not all road users that use congestion avoiding routing will pursue it. In this paragraph, the components that influence compliance are given and an algorithm to determine the compliance during this research is formulated. This is all based on literature from the databases of Google Scholar and Scopus with the combination of the following keywords: Social, Compliance, Acceptance, Effect, Route Guidance, Routing, Route Information. In addition, the forward and backward snowballing technique is applied to the most relevant literature that was found to find more articles. Furthermore, Casper Chorus is consulted as a choice behaviour specialist to obtain some key literature for this topic.

4.4.1 Influences on compliance

Multiple studies show that many variables have an impact on the compliance of social routing like congestion avoiding routing. The most obvious variable is the additional travel time by the detour. Initially, about 80% of the people are willing to accept the social routing and this decreases to under 40% while the additional travel time increases (Mariotte, Leclercq, Ramirez, Krug, & Becarie, 2021; Bonsall & Joint, 1991). For this reason, this is a major variable that must be included in the mathematical formulation. Next to the travel time, there are multiple social demographic attributes of drivers that have proved to play a role in compliance (Mariotte, Leclercq, Ramirez, Krug, & Becarie, 2021; van Essen, Thomas, van Berkum, & Chorus, 2020). For example, older people are more likely to comply with social route guidance than younger people. However, social demographic attributes of drivers are mixed in a traffic stream which means that these only play a minor role in the macro analysis. What also plays a role in compliance is the information that is given to the human driver. When people are given the information to draw their conclusions, compliance will be higher (van Essen, Thomas, van Berkum, & Chorus, 2020). In this study, it will be assumed that this information is available for all drivers to simulate with a higher level of compliance. An interesting variable to influence compliance is the amount of CO2 emission. Multiple studies show that people are more sensitive to comply the social routing when they also reduce their CO2 emission (Mariotte, Leclercq, Ramirez, Krug, & Becarie, 2021; van Essen, Thomas, van Berkum, & Chorus, 2020). This means that small detours to avoid congestion are likely to be accepted. Another variable is the time of the day. It seems to be that people are less likely to accept social advice during rush hour (Mariotte, Leclercq, Ramirez, Krug, & Becarie, 2021). This could be related to the different compositions of travel motives during rush hour. For example, people who are familiar with their route, like commuters, are less likely to change their route. Last, some older studies show that people are not willing to continuously take the social detour routing. To increase compliance, social routers must get the feeling that others make the social choice too (Pruitt & Kimmel, 1977). While they got previously the best route and others took the detour, this would lead to an additional 20% of the people that will accept a detour of 25% travel time (Bonsall & Joint, 1991). This would mean that overcharging people with the social detour harms overall compliance.

Currently (June 2021), there is a new study going on at TU Delft, in the research group of Casper Chorus, about the compliance of social routes. The parameters that influence the compliance of social routing based on a logit choice model or a random regret model need more research. In a meeting with postdoc researcher Aemiro Melkamu Daniel of the research group of Casper Chorus on the second of June, the variables they research are discussed. They conduct a choice experiment to investigate the betas for the additional travel time, the travel time benefits for the collective, the number of days per week users should take a detour and the proportion of participating vehicles. Because the research is not published yet, the data is not available for this study and older studies are used to determine the compliance of the congestion avoiding routing.

4.4.2 Mathematical formulation for compliance for route guidance

To use an algorithm for compliance before the simulations runes, it should include parameters for participation rate and the additional travel time. During the literature research, no algorithm was found that is useful directly. However, there are several variables found that influence the compliance of the social route choice with the expected compliance rates for the routing advice. Some of the studies present the compliance rate concerning the relative additional travel time (Bonsall & Joint, 1991; Mariotte, Leclercq, Ramirez, Krug, & Becarie, 2021) and others as a logit choice model that describes the compliance with multiple parameters (van Essen, Thomas, van Berkum, & Chorus, 2020). All those studies start with an initial compliance rate between 80 and 88% which drops while the additional travel time increases. The limitation of the founded logit choice models is that the domain with a maximum detour of 7 minutes on a journey of 28 minutes is limited and the study results were very specific. Other studies show a more general domain relative to the travel time. The data points found in the study of Mariotte et al. in 2021 with a maximum of 50% additional travel time show comparable results with the older research of Bonsall & Joint in 1991. This makes the function of Bonsall & Joint that presents the relation between the quality of the advice still relevant. Based on the additional relative travel time, the quality of the advice is described. A quality of 150 stands in this case for an additional 50% in travel time. Both functions are combined in Figure 14 and show the relationship between travel time and compliance. The stated choice model is rewritten from travel time to relative travel time. The functions of the previous advice are as precise as possible taken from the figure of the Bonsall & Joint paper because the exact functions were missing.

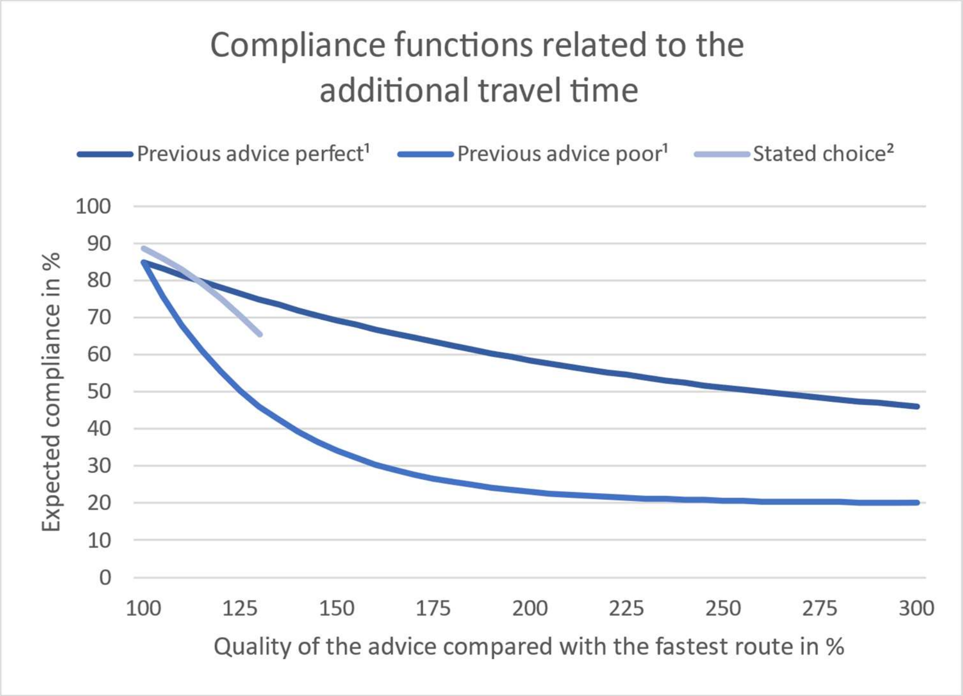


Figure 14 Compliance functions related to the additional travel time
(Bonsall & Joint, 1991)¹ (van Essen, Thomas, van Berkum, & Chorus, 2020)²

Next, it seems to be important to include a variable about the participating rate of the social routing to determine how often a participant should take a detour. This is currently studied at the TU Delft (A.M. Daniel, personal communication, June 2, 2021). This relation was also addressed in much older studies because there is a significant difference in compliance if the previous routing was the fastest (Bonsall & Joint, 1991). However, in the macro simulation package MARPLE, there is no option to include an algorithm for compliance that knows if a particular vehicle made a detour before. This means that the compliance must be determined in advance of the simulation. Only attributes that are known before the simulation starts can be used to process the compliance in the simulation. This is to avoid recalculations based on the simulation results that may lead to multiple repetitions of the simulations. A function that transforms the functions of Figure 14 from the line Previous advice poor to Previous advice perfect concerning the participation rate would be the workable solution to determine compliance for every simulation.

Additional travel time

The additional travel time can be described per individual vehicle or per group of vehicles. Because MARPLE cannot implement this parameter of additional travel time it must be determined in advance. This means that the additional travel time cannot be measured for individual vehicles. To overcome this issue, the additional travel time is based on the applied time penalty which indicates the maximum additional travel time that can be assigned. Because the maximum time penalty, that represents the detour time, is an input variable for MARPLE, this variable is clear at the start of every simulation. This means that differences between time penalties for different routes cannot be described in the simulation. This could result in the situation that for a specific route, vehicles should take a detour with 5% additional travel time still reject because the parameter is set at 15%. This because the compliance rate is higher with lower time penalties compared with larger. This would lead to a slight underestimation of the results.

Participation rate

The frequency that people must make a detour influences the willingness to participate. Because a macroscopic model is chosen, it is not possible to register this per vehicle in the simulation. However, it can be assumed that if more vehicles participate it is likely that individual vehicles receive less frequently the request to make a detour. The more vehicles that participate in the congestion avoiding routing, the higher the percentage of participating vehicles that complies with this routing. The participation rate is determined on all vehicles with the congestion avoiding routing including those vehicles that reject the routing. This is done because otherwise, the parameter of the participation rate would be dependent on the time penalty which leads to more calculations and vehicles who reject with a time penalty of 30% may accept 20%. Traffic situations are not always the same and the time penalty might be lower at the next route request. This means that those vehicles still contribute to the participating rate and increase the chance that the previous routing of the detour vehicles was the fastest route. The research of Houshmand et al. (2019) shows that the more people participate, the smaller the additional average travel time benefits would be. This indicates that with a low participation rate, all vehicles make a detour and with a high participating rate, a lot of the vehicles can still drive the fastest route. For this reason, it is assumed that till a participation rate of 10%, all vehicles received a detour before and this will decline linearly to zero if all vehicles participate.

Functions for compliance

For the function of compliance, the interpretation of the functions of Bonsall & Joint (1991), that are presented in Figure 14, is used as the basis. Depending on the compliance rate, the function transforms from the previous poor advice function to the previous perfect advice function.

Parameters:
C = Compliance in percentage
t = Value of time penalty in percentage
p = Participation rate in percentage

$$C = 20 + 65 * 0{,}97^{t}$$
$$Domain\colon \{p \geq 0 | p < 10\}$$

Equation 14 Compliance function for participation rates till 10%

$$C = 20 + 15\frac{p-10}{90} + \left(65 - 15\frac{p-10}{90}\right) * (0{,}97 + 0{,}0225 * \frac{p-10}{90})^{t}$$
$$Domain\colon \{p \geq 10 | p \leq 100\}$$

Equation 15 Compliance function for participation rates between 10% and 100%

$$C = 35 + 50 * 0{,}9925^{t}$$
$$Domain\colon \{p = 100\}$$

Equation 16 Simplified compliance function for participation of 100%

4.5 Conversion of regulation strategies to simulation

Based on the tools and algorithms that are selected, a simulation scheme is created to converse the regulation strategies to input for the simulation. This simulation scheme is an extension of Figure 12 Scheme for route behaviour with possible regulations and is presented in Figure 15. The simulation scheme distributes all traffic over four groups of routing behaviour. This scheme considers the regulations, the compliance algorithm and the assumptions that are made for the simulation. The outline of the different components of the simulation scheme is given in the following sub-paragraphs.

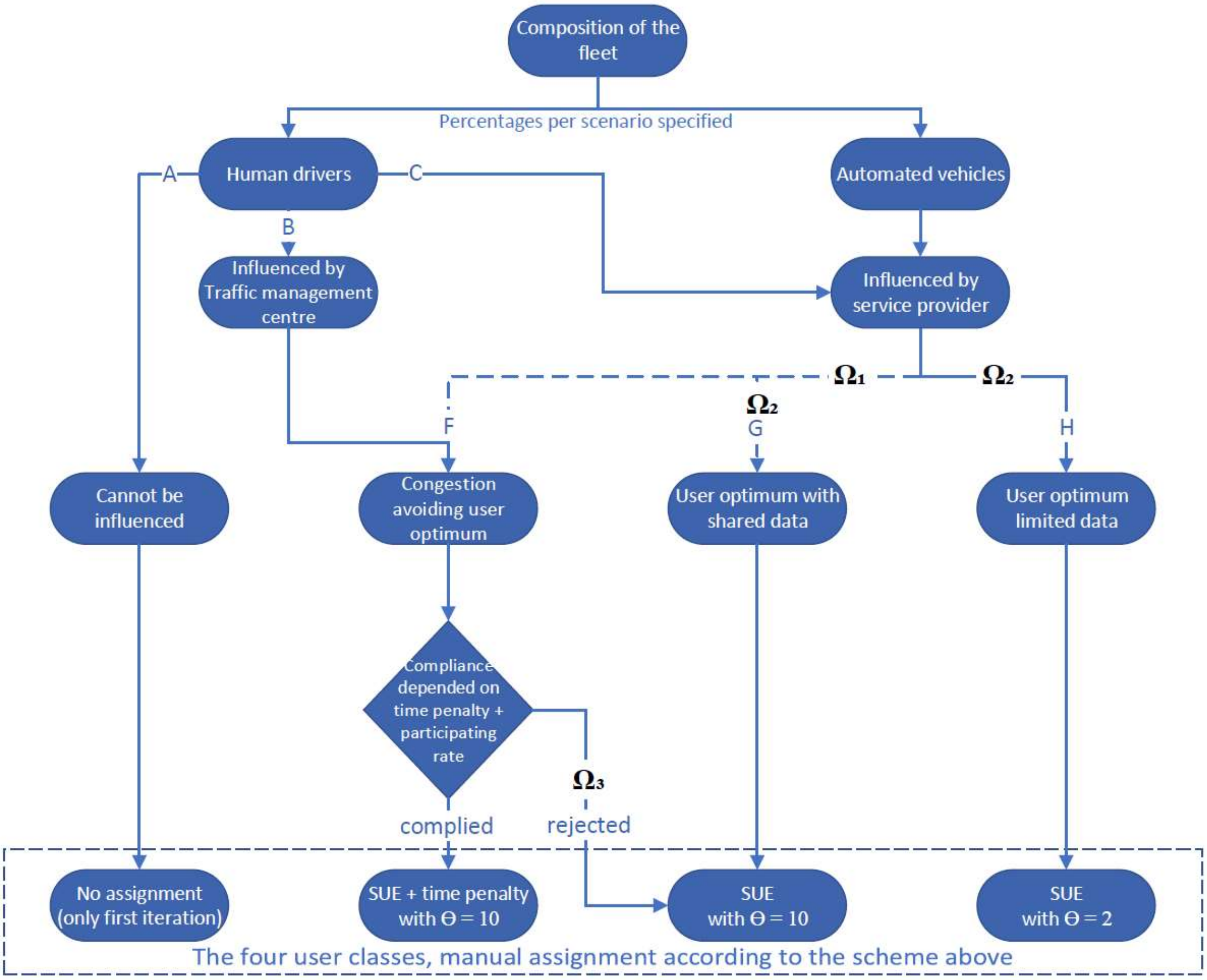


Figure 15 Simulation scheme for assignment of routing behaviour

4.5.1 Human drivers

The composition of the fleet is divided by human and automated drivers. The routing behaviour of human drivers will be categorised into three categories. Vehicles that drive habitual which cannot be influenced, drivers who get traffic information on the road which are influenced by the traffic management centre and those who drive with a route guidance system which are influenced by service providers. The simulation scheme allows to vary A, B and C in percentages to distribute these road users. The assumptions for these parameters are explained in the assumptions for the simulation, subparagraph 5.2.1.

4.5.2 Regulations

The regulations were described in paragraph 3.1 and implemented in the initial behavioural scheme of Figure 12. With MARPLE as the selected simulation tool, this scheme is updated to Figure 15 and the positions of regulation are reconsidered. The regulations have influences on the distribution of F, G, H and whether the compliance algorithm is active or not. This subparagraph describes how every regulation is implemented in the simulation scheme.

Ω_1: Implementation of the intermediary
This makes the path to the routing behaviours of congestion avoiders and user optimum with shared data for drivers that are influenced by service providers possible. This means that F and G can have a percentage larger than zero.

Ω_2: Regulation that force service providers to participate with the services of the intermediary
This regulation forces service providers to offer a congestion avoiding approach to their users. This makes a direct user optimum approach impossible and let all non-complying road users route according to the user optimum with perfect data. This regulation sets G and H to zero and F to 100%.

Ω_3: Regulation that forces road users to accept the route guidance
This regulation makes it impossible for road users to reject the congestion avoiding routing. In this situation, the compliance algorithm is not active and this results in a 100% compliance rate.

4.5.3 Time penalty / compliance

Several paths in Figure 15 lead to the compliance algorithm. The compliance is determined manually before the simulation starts based on the compliance algorithm described in paragraph 4.3. The execution of the compliance algorithm leads to the distribution of the four user classes as input for MARPLE. Because it is unknown which percentage for a time penalty will lead to the optimal situation, several simulations must be performed which all leads to other compliance rates. This means that the more precise the time penalty is determined the more simulations must be made which will cost a lot of time. The total time spent without interventions is around 33.000 vehicle hours and in total there are 89.492 vehicles in the network. This means that an average trip takes +/-22 minutes. The time penalty is rounded to 5%, which means that each change in the time penalty results in an average change of one minute in the perceived travel time of those who avoid congestion. A time penalty of 1% would only lead to an average change of 13 seconds perceived travel time which is not so much. Because of rounding, this might result in the same user class distribution of the previous time penalty. With the combination of the conversion error of 1% in MARPLE, this could lead to wrong conclusions about the optimal time penalty. This could happen because the optimum may vary more randomly where a continuous displacement of the optimum is expected. When the compliance algorithm is active, it distributes traffic, based on the percentages of participating vehicles and the time penalty, over the user classes SUE + time penalty with $\Theta=10$ and SUE with $\Theta=10$.

4.5.4 User classes

The Simulation scheme for assignment of routing behaviour ends in the distribution of user classes for the simulation. This paragraph describes the parameters of MARPLE for the different user classes.

No assignment (only first iteration)
The first user class in MARPLE is not influenced by traffic information and is assigned according to an initial iteration of the simulation (Taale, 2020). This means that the route choices of this user class are not changed during the simulation. The time penalty is not included for this group and the teta value is 0.

SUE + time penalty with ϴ = 10
This group will avoid congestion. To avoid congestion a time penalty is included for routes with (nearly) congested links. The size of this time penalty depends on the simulation itself and is not determined in advance. This group is connected with the intermediary and shares data which means that the quality of traffic information is increased. In the case of perfect information, the value of teta should be infinity (Taale & van Zuylen, 2003). However, with changing traffic states, data errors and human drivers the information will never be perfect. For this reason, the teta value will be set to 10 which was also indicated as complete information in a study of the developer of MARPLE (Taale, Cooperative Route Guidance - A Simulation Study for Stockholm, 2020).

SUE with ϴ = 10
This group only considers their travel time and uses the data of the intermediary to achieve the lowest travel time. This means that there is no time penalty included and the teta is at the same level as the group that avoid congestion.

SUE with ϴ = 2
The last group is the group of service providers that act independently. Because a service provider represents a group of individual vehicles there is some information available about the current traffic state. According to the manual of MARPLE, a teta value of 0 means poor informed and 3 good informed (Taale, 2020). Because information is far from complete and some vehicles may not have an updated system, the value 2 is chosen for the teta of the independent acting service providers group.

5 Scenarios and results

In this chapter, the scenarios are defined, the assumptions to implement these scenarios into the model are described, the model is calibrated and verified and the results of the simulations are presented. The assumptions for the simulation are made based on literature and simulation tests. Paragraph 5.3 describes the scenarios that are performed. 5.4 presents the results and in the last paragraph, these results are discussed.

5.1 Calibration and verification

MARPLE is a software package that already exists since 2004 (Taale, 2020) and it is used for multiple studies (Taale & van Zuylen, 2003; Taale, 2020) it is not needed to verify the core of the software packages. However, the new additional variables of the threshold values for congestion and the implementation of the time penalty were never used before. Because these developments are new in the packages, these functions will be verified. Figure 16 presents a small model with two routes which is used to verify the adjustments to MARPLE. The demand is in total 3000veh/h and both routes have a bottleneck saturation flow of 2000veh/h. Because the top route is 1500 meters shorter than the bottom route and both routes have the same speed limit, the top route is the preferred route. During the verification, there are 50% habitual drivers and 50% are well informed (ϴ=10) drivers that will use the time penalty. The files used in MARPLE can be found in Appendix B Files for verification MARPLE update (test network).

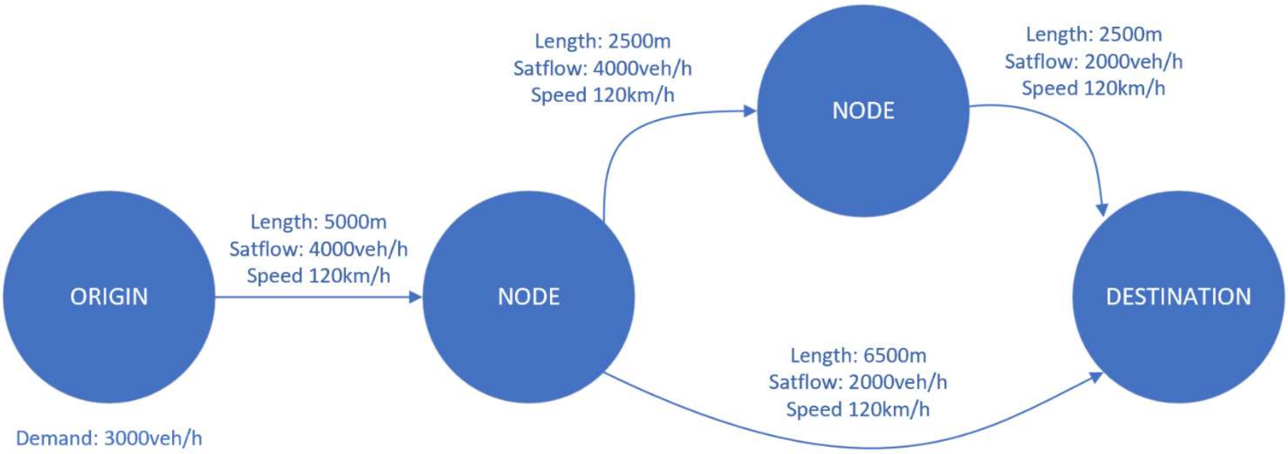


Figure 16 Network used for verification of adjustments in MARPLE

5.1.1 IC-Threshold for the use of a time penalty

The IC-Threshold for use of a time penalty will determine when the time penalty will be added to routes with a higher IC-Threshold as indicated. This means that with an IC-Threshold of 100%, the IC-Threshold is the saturation flow. This would not have an effect because the flow, except for the heterogenic properties of the calculation, cannot be larger than the capacity. To verify the newly added function, the situation without the time penalty will be compared with a situation with 200%, 100%, 95%, 75% and 0%. It is expected that with 200% the time penalty has no effect because this value cannot be reached, with 95% there will be no congestion, with the 75% the flow on the shortest route is around 1500 veh/h and with 0% all routes have an additional travel time that will result in no significant effect. The results presented in Table 9, show that the IC-Threshold works correctly. The small deviations in the results that should be the same can be explained by the additional iterations to redistribute traffic based on the time penalty. For this test, the time penalty is set to 25%.

Table 9 Verification results for IC-Threshold

IC-Threshold	Expected result	Results Total delay	 Flow top route
Result before additional iterations	-	95,75 veh.h	1950-2050 veh/h
200%	+/- Same as not active	93,56 veh.h	1950-2050 veh/h
100%	Same as not active	95.75 veh.h	1950-2050 veh/h
95%	Lower delay, flow below sat/flow	39,98 veh.h	1900 veh/h
75%	Top route flow +/-1500 veh/h	26,62 veh.h	1500 veh/h
0%	+/- Same as not active	95,51 veh.h	1980-2050 veh/h

5.1.2 Time penalty

To verify the time penalty, the IC-Threshold has been set to 75%. If the time penalty is 0% there should be no effect and with a small time penalty of 1% the top route is still faster and no significant effect is expected. While the time penalty becomes larger like 20% or 100% it is expected that the flow on the top route will converge to 75% of the saturation flow and that the congestion is solved. The results in Table 10, show that the time penalty works correctly and all results are in line with the expectations.

Table 10 Verification results for Time penalty

Time penalty	Expected result	Results Total delay	 Flow top route
Result before additional iterations	-	95,75 veh.h	1950-2050 veh/h
0%	+/- Same as not active	93,56 veh.h	1950-2050 veh/h
1%	Lower delay, effect limited	87,16 veh.h	1960-2040 veh/h
20%	Lower delay, effect significant, flow 1500 veh/h	26,62 veh.h	1500 veh/h
100%	Flow top route converge to threshold	26,63 veh.h	1500 veh/h

5.1.3 Reduction of traffic volume

After the first simulations, the traffic volume of the calibrated network of the Milan ring has proven to be too large for the concept of a time penalty for all routes with congested links. Many route pairs, that have the same origin-destination, got the time penalty that cancels out the effect of the time penalty. The effect of the simulations was in many cases under 1%. With a confidence error of 1%, it cannot be concluded if the effect was there or if it was the error that gave the effect. This has resulted in the reduction of the flows in the Milan Ring network to 80%. After the reduction of the flows, the reduction of total delay in the scenario with full regulations is 11,4% instead of 4,6% with the 100% flow. This makes fewer effective scenarios more reliable in the results and even more stable. For example, the 5.00 scenario has, with the 80% traffic volume alternative, an effect of 4,3% on the total delay instead of only 1%. Because the 5.00 scenario is fully regulated, the number of vehicles that avoid congestion in this scenario is set maximum. Less regulated scenarios have fewer vehicles that avoid congestion which leads all to differences below 1% which make it impossible to draw conclusions.

5.2 Assumptions

The simulation relies on several key assumptions. These contain the routing behaviour of human drivers, the step size of the penetration rate of automated vehicles, the adjustment of the IC-Threshold, the ideal time penalties and the number of iterations with the applied time penalty. Literature, data or logical reasoning underpins these assumptions.

5.2.1 Routing behaviour of human drivers

The route behaviour of current traffic can be categorised into three categories. These are: cannot be influenced, influenced by traffic management centre and influenced by service provider. To underpin the distribution of route behaviour the literature databases of Google Scholar and Scopus are consulted. This is performed with the combination of the following keywords: Effect, Influence of, On-trip information, DRIP, Dynamic Route Information Panel, VMS, Variable Message signs, Navigation app, Navigation system, Traffic Information, Route advice, Route guidance.

Influenced by the service provider

Nowadays around 91% of the people have navigation equipment available and 80% of the people who travel for business (KiM, 2017), which is 4% of all trips (Ministerie van Infrastructuur en Waterstaat, 2020), or who go for a day out uses a navigation application (KiM, 2017). Of those people, 35% receive online congestion updates (KiM, 2017) and can change route based on real-time traffic information. Because the online congestion updates are relatively new, it is assumed that this percentage will increase in the future. Because of these future predictions, it is assumed for this study that all vehicles that drive with a navigation system receive online congestion updates. However, the percentage of road users that have navigation equipment available is high, it is not so often used on the road. Roughly 25% of all drivers use such a system on regular basis (KiM, 2017; Knapper, van Nes, Christoph, & Hagenzieker, 2015) and only about 10% always uses a navigation device (KiM, 2017). The exact percentage of road users that use a navigation device is hard to determine because it is also dependent on the traffic state. For this study, it is assumed that independent of the traffic state, 20% of the road users use a navigation device. This percentage is based on 10% that always uses a navigation system, 5% for the people who drive for business and a day out and an additional 5% for drivers who use a navigation system on regular basis but not always. Thus, parameter C is 20%.

Influenced by the traffic management centre

The information of the traffic management centre presented by a DRIP is relevant for 30% to 40% of the road users (KiM, 2017). However, road users seem not willing to change route based on the information on the DRIP when the difference in travel time is limited. Because small delays are mostly accepted, only 5% to 6% of the road users would change route if the travel time benefits are below 5 minutes (Wardman, Bonsall, & Shires, 1996; Rijkswaterstaat, 2015). The traffic management centre has more impact during events like road accidents. However, traffic events are not within the scope of this study. Because this study uses a compliance algorithm, the percentage of 5% to 6% influential road users by the traffic management centre is too small. The algorithm would reduce this percentage instead of giving a result of 5% to 6%. Because the DRIPs are only relevant for 30% to 40% of the road users and only 30% to 35% of them use on trip information, it is assumed that 10% of the road users are influenced by the traffic management centre. In combination with the compliance algorithm, the outcome is comparable to 5% to 6% of the vehicles that change route. Thus, parameter B is 10%.

Influenced by the radio

Traffic information by radio has, in the Netherlands, a frequency of somewhere between 30 and 60 minutes and during rush hour sometimes every 15 minutes (ANWB, sd). According to the research of the Dutch Kennisinstituut voor Mobiliteitsbeleid, around 46% of the drivers use the radio and receive route information (KiM, 2017). However, this information is generic, applicable to the whole country and during rush hours, this information is limited to the congestions with the longest travel delays. This means that in the case of a traffic accident with major consequences this information is most useful for the driver. However, in usual rush hour traffic conditions this information is not very useful. With the notion that almost half of the 46% of the drivers already listened to the radio before they start their trip (KiM, 2017) and that other researches came with an even lower effect of 14% during major disruptions (Taale, 2020), the effect of the radio for this study with usual rush hour traffic conditions is assumed to be limited and by that reason not taken into account.

Cannot be influenced

According to several studies, lots of road users are not sensitive to on trip traffic information. The range of traffic that can be influenced by on trip traffic information is somewhere between 30% and 35% of the road users (Gan & Chen, 2013; Iraganaboina, Bhowmik, Yasmin, Eluru, & Abdel-Aty, 2021; Reinolsmann, et al., 2020; Rijkswaterstaat, 2015; KiM, 2017). This percentage seems to be even smaller while roads are quiet or extremely busy. In these situations, the DRIP had no obvious effect (Westerman, 1997). However, these studies were performed 25 years ago at the start of the implementation of the DRIP and people are nowadays more familiar with the information of the DRIP which could lead to a better response. Sadly, a study in the Netherlands shows that only 5,1% of all respondents said that they changed route based on the presented route information and that they are in general willing to accept a delay of 10 to 15 minutes instead of driving a detour (Rijkswaterstaat, 2015). In conclusion, road sided traffic information is mostly ignored or irrelevant and most of the in-car navigation devices are not used. This led to the proportion of traffic that cannot be influenced somewhere between 65% and 70%. Because the more recent studies show values of 69% to 70% and the Rijkswaterstaat presented a value of 70% the parameter A for this study is set to 70%.

5.2.2 Penetration rate for automated vehicles

In the future, it is predicted that, after the introduction, the number of automated and connected vehicles increases until a 100% penetration rate is reached. The effect during this transition period is not well researched and the results of these few studies are not in line with each other. In a study in a Braess network and a subnetwork of Eastern Massachusetts, a higher penetration rate leads to increased network benefits. However, most of the network benefits were already reached at a penetration rate of 50% (Houshmand, Wollenstein-Betech, & Cassandras, 2019). Another study with a simplistic network shows that an increasing penetration rate of automated vehicles to prevent congestion not always leads to better network efficiency (Summerflied, Deokar, Xu, & Zhu, 2020). The highest efficiency score was around a penetration rate of 73%. In this study, different policy strategies lead to different numbers of vehicles routing according to the congestion avoiding user optimum algorithm. This could lead to a different optimal penetration rate of automated vehicles for every regulation strategy. Because finding out the ideal penetration rate is not part of this study, the penetration rate is analysed in steps of 10%. This gives enough information about where the optimum approximately is and when this optimum has almost been reached.

5.2.3 IC-Threshold

The IC-Threshold value is assumed to be ideal for this simulation at 95%. As seen in the verification of MARPLE, the simulation will converge flows to this threshold value. For this reason, it would be logical to choose an as high as possible threshold value. However, because of the stochastic properties of the simulation, the flow on the link will vary every timestep and an IC-threshold of 99,9% would not solve all congestions until all flows would converge to the threshold. Because the ConvErr is set to 1%, which means that the iterations will stop if less than 1% of the flows change route, and flows are partly stochastic this will never be reached. Next, according to the Dutch ministry Rijkswaterstaat, an I/C ratio of 100% would lead to congestion within 30 minutes for sure (Rijkswaterstaat & Wittenveen+Bos, 2019), which is not the preferred situation. According to Rijkswaterstaat, it is preferred to get an I/C ratio of below 90% to minimise the chance of congestions. Because this probability of congestion with the capacity drop is not simulated in MARPLE this effect could not be calculated. To determine what the best IC-Threshold is, a small experiment with the test network and the Milan ring network is conducted with penalty steps of 5%. Three different IC-threshold values were used during the simulation. These three are the preferred 90% of Rijkswaterstaat, the 95% which is in between and the maximum use of the capacity of 99%. The results are presented in Figure 17 and Figure 18. The results of the example network would indicate that the IC-Threshold of 90% performs best. However, the performance of 90% and 95% are quite similar in comparison with the 99% IC-Threshold. The difference can be explained by the still existing queues for the 99% where they are solved for the 90% and 95%. In the Milan ring network, the IC-Threshold of 99% gave a calculation error and the 95% IC-Threshold resulted in the best performance. The explanation why the 95% performs better than the 90% IC-Threshold value can be found in the number of time penalties that were given and the use of capacity in the network. A low IC-Threshold results in less optimal use of capacity by requesting more detours and because there are more time penalties given fewer detour options will be available. This would cancel out the effect of the time penalty. This leads to the 95% IC-Threshold being the best value.

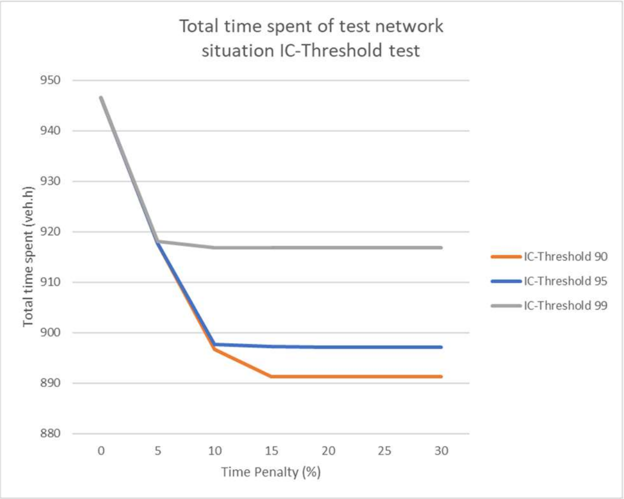


Figure 17 IC-Threshold test with example network with 50% habitual drivers and 50% time penalty users

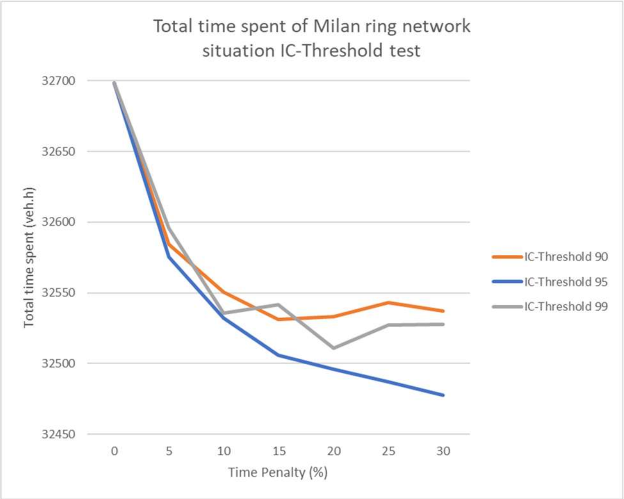


Figure 18 IC-Threshold test with Milan ring network with 50% habitual drivers and 50% time penalty users

5.2.4 Time penalty values

For the time penalty, only steps of a 5% difference are considered. There are two main reasons for this. Because user classes are rounded to full percentages, smaller steps will not always lead to a change in the distribution. This would lead to an overestimation of a certain time penalty and because the ConvErr of 1% in MARPLE results would not be consistent. The second reason is that the average travel time for the Milan ring network is between 21,5 and 22 minutes. By observing the Dutch highway road network, comparable values are observed. This leads to a change in time penalty on average of one minute when the penalty parameter is changed. This has a more significant effect than a change of 1% that lead to only 13 seconds change on average. By simulating every time penalty between 0% and 40% for the .10 scenarios, the scenario's witch 100% penetration rate of automated vehicles, the optimal time penalty is determined. The founded optimum applied to the other scenarios as optimum and this is verified by simulating 5% above and below the assumed optimum. When both verification results are below the expected optimum, the assumed optimum is the optimum for that scenario.

The results of the test network in Figure 19 show that a time penalty of above 12% leads to the most optimal solution. In this case, more than 40% of the road users avoid congestion. The compliance decreases while the time penalty increases. For scenario 4.10, this means that a time penalty of above 30% leads to a situation that there are too few participants to achieve the optimum. For scenarios with less than 40% congestion avoiders, the optimum will be narrower and the optimum shifts eventually to lower time penalties. Because a larger time penalty is perceived negatively by users, the lowest possible time penalty that (almost) lead to the optimum will be used. For example, the results in Figure 19 for the test network indicates 10% as optimal time penalty for scenario 5.10 and not 15 of 20 that have a slight advance of 1 or 2 vehicle hours. The optimal situation differs from network to network but can be determined using this approach.

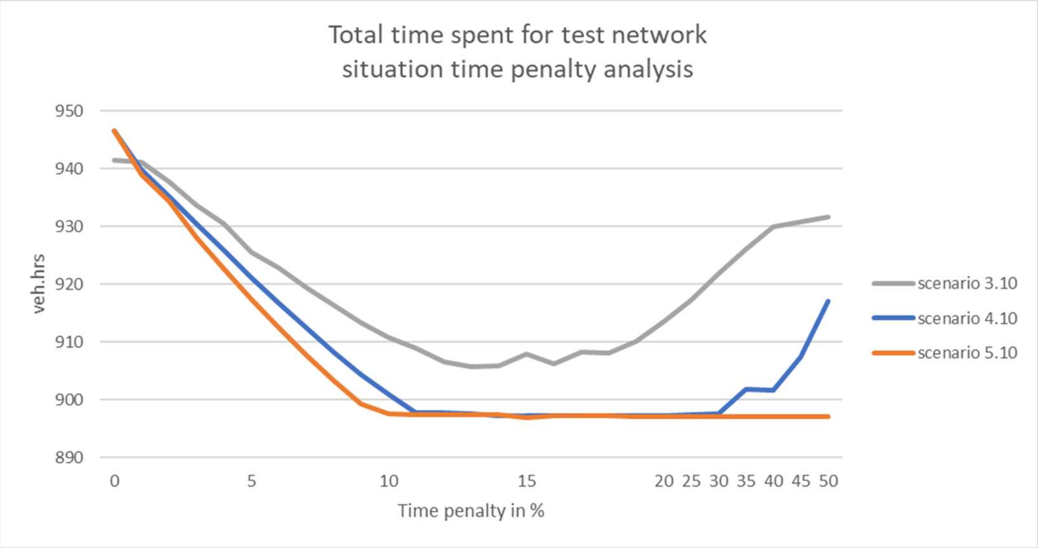


Figure 19 Time penalty analysis test network

5.2.5 Number of iterations with a time penalty

In MARPLE, the number of iterations after the application of the time penalty can be chosen. The centralised route guidance system is assumed to have almost perfect information about the network state. Because routing is centrally managed, the centralised system will balance traffic to the new optimal equilibrium. For this reason, the maximum number of iterations with the time penalty is set to 20 iterations which means that in practice MARPLE iterates until the convergence error is reached.

5.3 Scenarios

This subparagraph describes the scenarios that are simulated. Tlhe first subparagraph describes all variables in the scenario table, that are related to Figure 15, in 5 sets of 11 simulations each. In the second subparagraph, the scenario table is performed according to Figure 15 and the optimal time penalty is determined by the test runs. This results in the input variables for the user class distribution presented in Table 12.

5.3.1 Scenario table

This paragraph presents all variables of the simulation scheme to allocate drivers and vehicles to the four user classes per scenario in Table 11. This table should read as follows. The scenario number consists of two parts. The main number corresponds to the policy strategy as labelled below:

1) Do nothing;
2) A regulated intermediary, free of obligations, only used for data sharing;
3) A regulated intermediary, free of obligations, partial commitment;
4) Obligated use of intermediary services, but voluntary use for road users;
5) Obligated use of intermediary services and mandatory use for road users.

The number after de delimiter corresponds to the percentage of automated vehicles in the scenario where 01 stands for 10% and 10 for 100%. The letters in the table represent the distribution of vehicles on the specific position in the simulation scheme of Figure 15. Compliance has alg. if the algorithm is active and 100 while every vehicle is forced to comply. The time penalty is determined by test runs in the next step and for that reason variable. The regulation parameters represent if 1 the regulation is active and if 0 the regulation is not active.

Table 11 Scenario table

	Percentage									Time penalty	Regulation parameters		
			Human drivers cannot be influenced	Human drivers influenced by TMC	Human drivers influenced by SP	SP approach user optimum limited data	SP approach User optimum shared data	SP approach Congestion avoidance			Implementation of the intermediary	Obligation of intermediary services	Obligation of compliance
Scenario	Human	Automated	A	B	C	F	G	H	Compl.	%	Ω_1	Ω_2	Ω_3
Do nothing													
1.00	100	0	70	10	20	0	0	100	alg.	var.	0	0	0
1.01	90	10											
⋮	⋮	⋮											
⋮	⋮	⋮											
1.09	10	90											
1.10	0	100											
A regulated intermediary, free of obligations, only used for data sharing;													
2.00	100	0	70	10	20	0	100	0	alg.	var.	1	0	0
2.01	90	10											
⋮	⋮	⋮											
⋮	⋮	⋮											
2.09	10	90											
2.10	0	100											
A regulated intermediary, free of obligations, partial commitment;													
3.00	100	0	70	10	20	50	25	25	alg.	var.	1	0	0
3.01	90	10											
⋮	⋮	⋮											
⋮	⋮	⋮											
3.09	10	90											
3.10	0	100											
Obligated use of intermediary services, but voluntary use for road users;													
4.00	100	0	70	10	20	100	0	0	alg.	var.	1	1	0
4.01	90	10											
⋮	⋮	⋮											
⋮	⋮	⋮											
4.09	10	90											
4.10	0	100											
Obligated use of intermediary services and mandatory use for road users.													
5.00	100	0	70	10	20	100	0	0	100	var.	1	1	1
5.01	90	10											
⋮	⋮	⋮											
⋮	⋮	⋮											
5.09	10	90											
5.10	0	100											

5.3.2 Input of user class distribution

The scenario table presented in Table 11 shows a variable time penalty. By searching for the most optimal time penalty by the approach described in subparagraph 5.2.4, the user class distribution is defined as presented in Table 12. More findings of the variable of the time penalty will be discussed in paragraph 5.4 Results. The user class distribution is determined based on the schema of Figure 15 with the percentages presented in Table 11 and the compliance algorithm of Equation 14, Equation 15 and Equation 16.

Table 12 User class distribution based on the optimal time penalty

Do nothing						A regulated intermediary, free of obligations, only used for data sharing						A regulated intermediary, free of obligations, partial commitment					
Scenario	Time penalty	user class				Scenario	Time penalty	user class				Scenario	Time penalty	user class			
		1	2	3	4			1	2	3	4			1	2	3	4
1.00	10	70	20	3	7	2.00	10	70	0	23	7	3.00	10	70	5	12	13
1.01		63	28	3	6	2.01		63	0	31	6	3.01		63	7	15	15
1.02		56	36	3	5	2.02		56	0	39	5	3.02		56	9	18	17
1.03		49	44	2	5	2.03		49	0	46	5	3.03		49	11	21	19
1.04		42	52	2	4	2.04		42	0	54	4	3.04	15	42	13	26	19
1.05		35	60	2	3	2.05		35	0	62	3	3.05		35	15	29	21
1.06		28	68	1	3	2.06		28	0	69	3	3.06		28	17	33	22
1.07		21	76	1	2	2.07		21	0	77	2	3.07		21	19	36	24
1.08		14	84	1	1	2.08		14	0	85	1	3.08		14	21	39	26
1.09		7	92	0	1	2.09		7	0	92	1	3.09		7	23	42	28
1.10	N/A	0	100	0	0	2.10	N/A	0	0	100	0	3.10		0	25	45	30

Obligated use of intermediary services, but voluntary use for road users						Obligated use of intermediary services and mandatory use for road users					
Scenario	Time penalty	user class				Scenario	Time penalty	user class			
		1	2	3	4			1	2	3	4
4.00	15	70	0	12	18	5.00	25	70	0	0	30
4.01		63	0	15	22	5.01		63	0	0	37
4.02		56	0	18	26	5.02		56	0	0	44
4.03		49	0	21	30	5.03		49	0	0	51
4.04		42	0	24	34	5.04		42	0	0	58
4.05		35	0	27	38	5.05		35	0	0	65
4.06		28	0	29	43	5.06		28	0	0	72
4.07		21	0	32	47	5.07		21	0	0	79
4.08		14	0	35	51	5.08		14	0	0	86
4.09		7	0	38	55	5.09		7	0	0	93
4.10		0	0	41	59	5.10		0	0	0	100

User class 1: No assignment
User class 2: SUE with $\theta = 2$
User class 3: SUE with $\theta = 10$
User class 4: SUE with $\theta = 10$
+ time penalty

5.4 Results

The MARPLE model produces results on multiple levels of detail. These are on the level of links, routes, OD pairs, network sections and the entire network. The level of detail of links is used to analyse the locations and differences of traffic jams in the network. The routes are analysed on differences in travel time to determine which routes will benefit and which will be affected by the centralised route guidance system. The same is performed on the level of OD pairs. The most important level of detail is the entire network. On this level of detail, the performance of the entire traffic flow is analysed based on the total time spent, the total delay, the total distance travelled and the average speed.

5.4.1 Traffic flow performances

In this subparagraph, the three most important network performance indicators that are measured by MARPLE are presented. These are total time spent, total network delay and total distance travelled. The network performance indicator of the average speed is only included in the summary of subparagraph 5.4.5 because this indicator does not give additional insights compared with the other network performance indicators.

Total time spent

The results of the total time spent for the Milan ring network, presented in Figure 20, show that the regulations work for the improvement of the traffic flow. However, it also shows that the current implementation of the intermediary without commitment leads to only 0,1% improvement and finally to an improvement with automated vehicles of 0,3%. It also shows that more regulations lead to better traffic performances. Table 13 shows the percentage improvement compared with the Do nothing scenario with the same number of automated vehicles. This table shows the effect of the regulation with that specific penetration rate of automated vehicles.

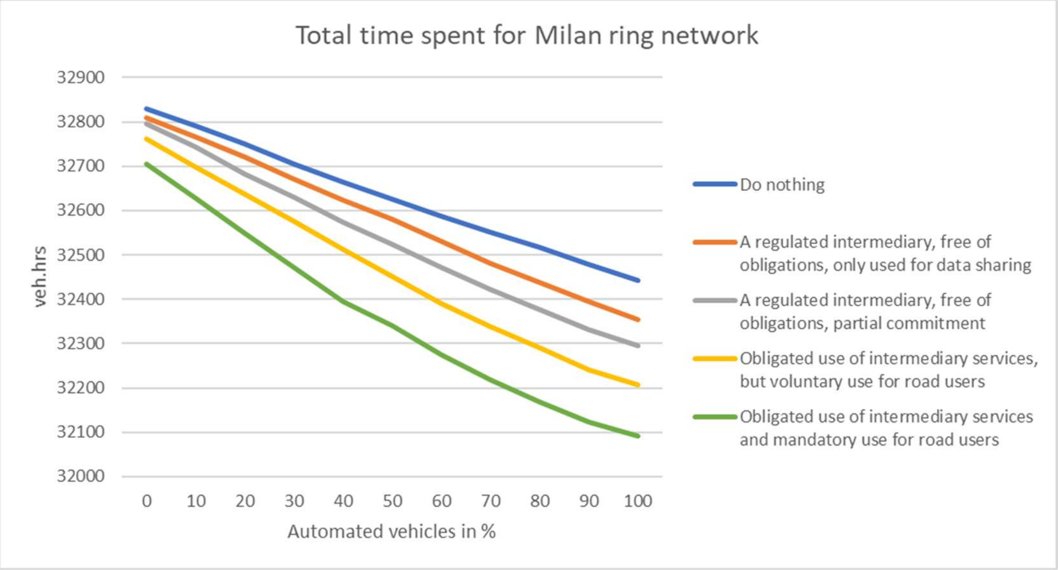


Figure 20 Total time spent for Milan ring network

Table 13 Percentages of total time spent savings per scenario for the Milan ring network

	Percentage of total time spent savings per regulation for the Milan ring network				
Scenario	1	2	3	4	5
.00	0,0%	0,1%	0,1%	0,2%	0,4%
.01	0,0%	0,1%	0,1%	0,3%	0,5%
.02	0,0%	0,1%	0,2%	0,3%	0,6%
.03	0,0%	0,1%	0,2%	0,4%	0,7%
.04	0,0%	0,1%	0,3%	0,5%	0,8%
.05	0,0%	0,1%	0,3%	0,5%	0,9%
.06	0,0%	0,2%	0,4%	0,6%	1,0%
.07	0,0%	0,2%	0,4%	0,7%	1,0%
.08	0,0%	0,2%	0,4%	0,7%	1,1%
.09	0,0%	0,3%	0,5%	0,7%	1,1%
.10	0,0%	0,3%	0,4%	0,7%	1,1%

Total delay

Figure 21 presents the total delay in the Milan ring network. The results have the same pattern as the total time spent. However, for the delay in the network, the results become more significant. An important notion to make is that these results directly show that if the intermediary is only used for data sharing, the congestions are hardly reduced compared with the Do nothing scenario. The relative improvements are presented in Table 14 in percentages compared with the Do nothing scenario. This table shows that regulations for service providers can eventually reduce the total network delay by 7,3% and when the road users are regulated as well, the reduction can be increased up to 12,4%.

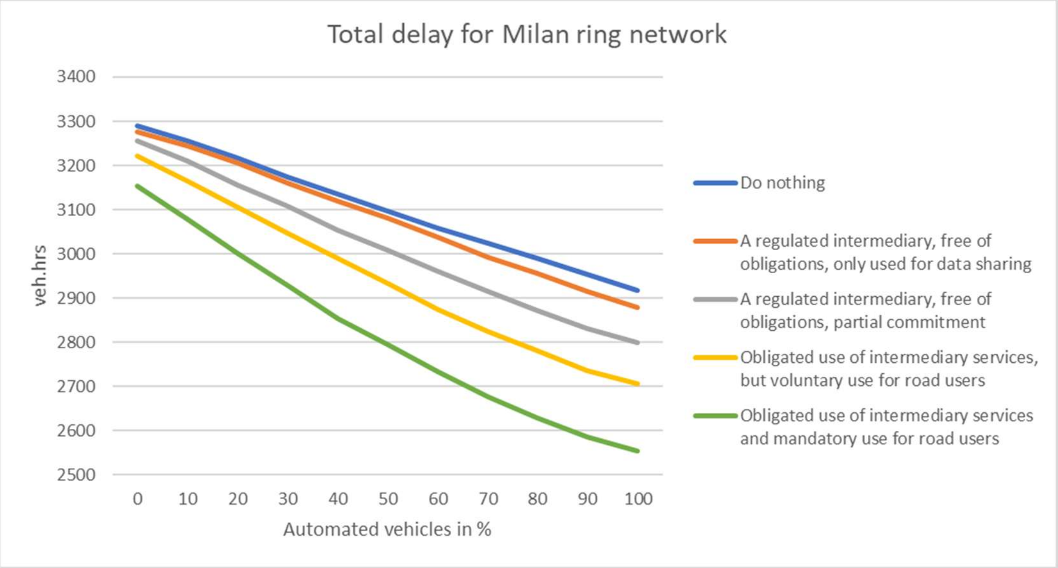


Figure 21 Total delay for Milan ring network

Table 14 Percentages of total delay savings per regulation for the Milan ring network

	Percentage of total delay savings per regulation for the Milan ring network				
Scenario	1	2	3	4	5
.00	0,0%	0,4%	1,0%	2,1%	4,1%
.01	0,0%	0,4%	1,4%	2,8%	5,4%
.02	0,0%	0,4%	1,9%	3,4%	6,7%
.03	0,0%	0,5%	2,1%	4,0%	7,8%
.04	0,0%	0,5%	2,6%	4,7%	9,0%
.05	0,0%	0,5%	2,9%	5,3%	9,8%
.06	0,0%	0,7%	3,2%	6,0%	10,6%
.07	0,0%	1,0%	3,6%	6,6%	11,5%
.08	0,0%	1,1%	4,0%	7,0%	12,1%
.09	0,0%	1,3%	4,2%	7,4%	12,5%
.10	0,0%	1,4%	4,1%	7,3%	12,4%

Total distance travelled

Compared with the other results, the results of Figure 22, which presents the total distance travelled, are less in line with the other results that could be expected based on previous studies. However, the change in results can be clarified by the addition of traffic information and the habitual behaviour of human drivers. While subtracting scenario 2, the effect of automated vehicles and traffic information, from the others in Figure 23, continuous relative growth in travel distance is observed. This is in line with previous studies (Houshmand, Wollenstein-Betech, & Cassandras, 2019) and line with the expected results. Because vehicles that avoid congestion make a detour, this growth in travel distance was expected. The result is an additional 7000 vehicle kilometres to reduce the total delay in the network. Because the average speed increases, the extra distance travelled does not outweigh the faster driving and leads to an improvement of the total time spent. In the data of scenario 2 with only data sharing, seems to have an incongruous kink in the graph between 80 and 90% automated vehicles. Deeper analysis shows already a small kink between 60 and 70% automated vehicles. In both points the simulation got an additional iteration to reach the convergence error. This means that a small over- or underestimation based on the convergence error turns into the reverse. This explains the kinks in the results.

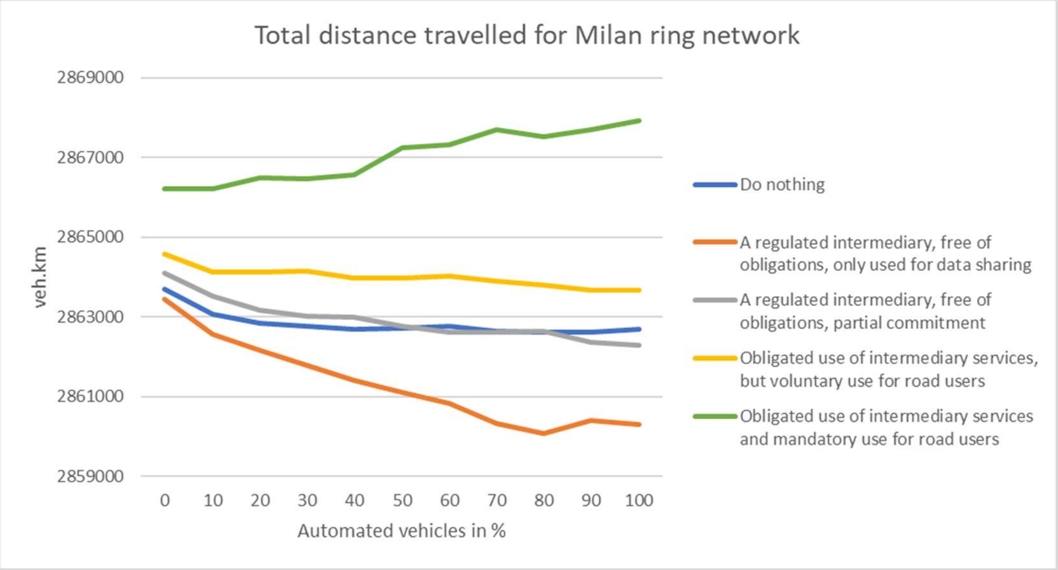


Figure 22 Total distance travelled for Milan ring network

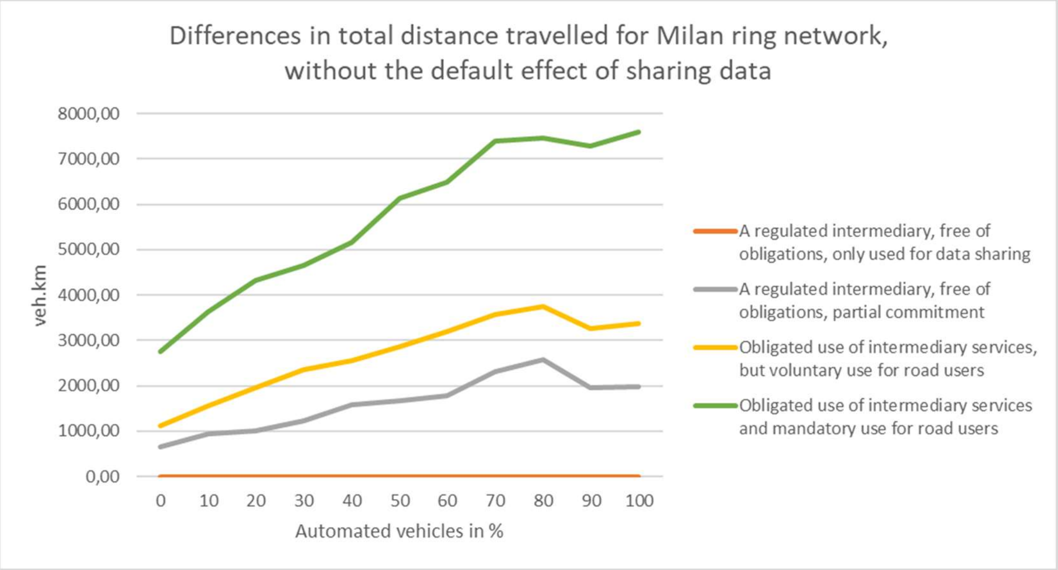


Figure 23 Differences in total distance travelled for Milan ring network, without the default effect of automated vehicles

5.4.2 Time penalty effects

Figure 24 presents the relative effect of the time penalty in total time spent compared with the outcome of a time penalty of 0%. The selection of scenarios is varied in the number of participators with congestion avoiding routing. The number of participants is presented in Figure 25. With more participators, the optimum of the time penalty shifts toward larger time penalties and the result becomes more sensitive if the penalty is set too high. The explanation for the sensitivity is the change in the actual number of vehicles that avoid congestions. If this change becomes larger, the effect becomes more significant because more road users switch to a user optimum routing. The reason for the shift in optimal time penalty can be explained by the reason that with fewer participating vehicles, the potential of the scenario is reached faster. For example, consider an ideal situation where 20% of the vehicles must make a detour to avoid congestion with a time penalty of 20%. While only 10% of the vehicles participate, the congestion will not be solved. This means that the difference in travel time between the congested route and the detour route is smaller. With a smaller difference, it is beneficial to lower the time penalty until not all the participating vehicles make the detour to increase compliance.

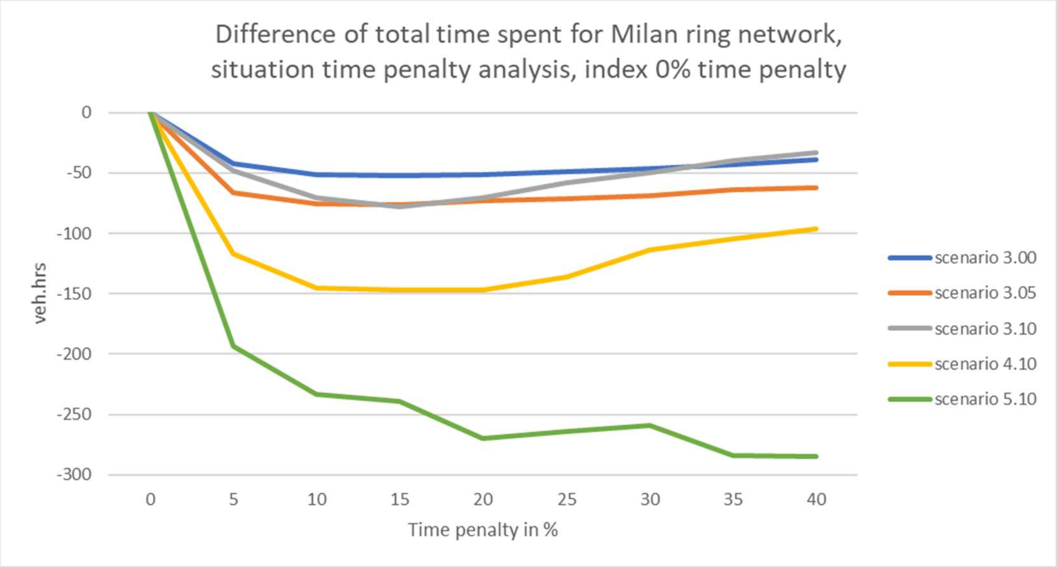


Figure 24 Relative effect of the time penalty per regulated scenario

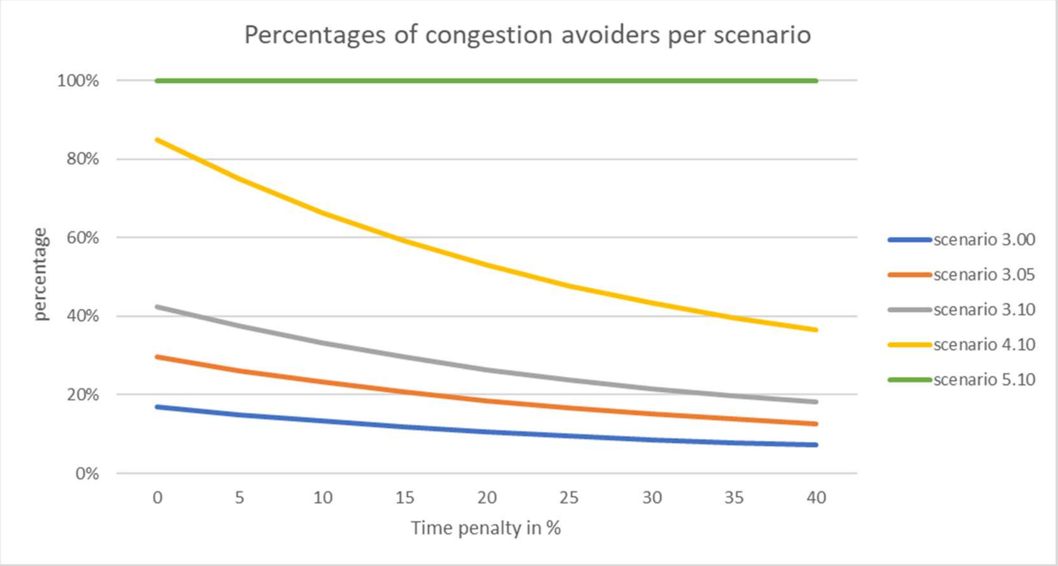


Figure 25 Percentages of congestion avoiders by certain time penalty

5.4.3 Congestion analysis

For the Milan ring network, the concept of a centralised route guidance system by avoiding congestion has been proven to be effective to reduce the amount of congestion in the network. Figure 26 presents the total queue length of the time step with the most vehicles in the network. In today's traffic, the regulated intermediary with obligations for service providers will reduce congestion by 2,5% (237m) and with obligations for road users even more with 4,7% (456m). While the network is fully penetrated with automated vehicles, these results will increase to 7,3% (592m) and 13,1% (1056m). However, it is notable that not every congestion will shrink by this approach. Figure 27 visualises the changes in queue lengths of Table 15 and shows that the concept does not affect the congestion of the South-East routes to the centre ring. Explanations can be found in the fact that destinations in the centre of Milan cannot be reached by other non-congested routes and destinations outside the ring would be faster anyway by taking the outer ring because of these congestions. On the other hand, the concept significantly reduces congestion on four positions and solves it for link 617.

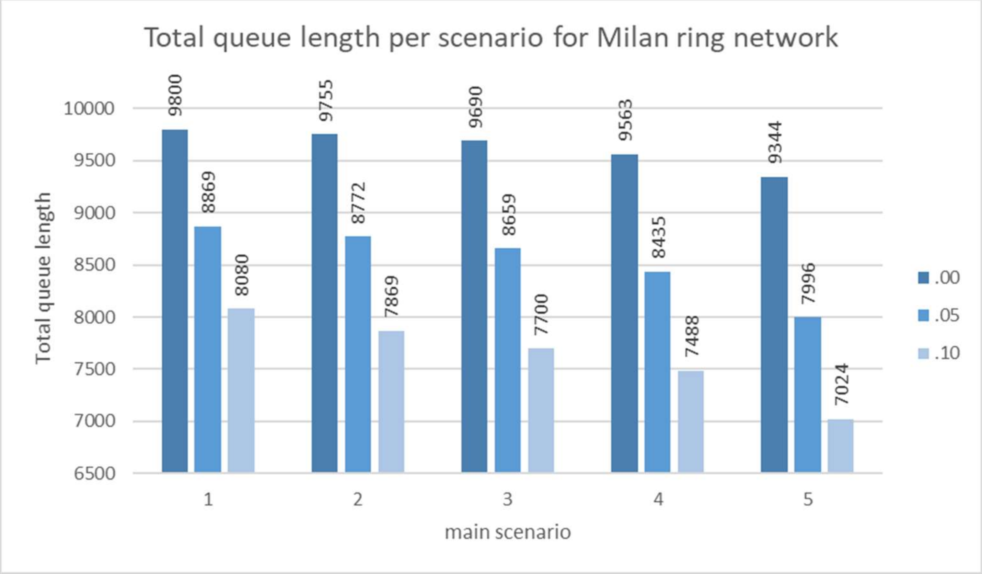


Figure 26 Queue lengths per scenario for time step 11 (8:30)

Table 15 Changes in the queue length for congested links at time step 11 (8:30) compared with the most potential scenario

link nr	1.00	5.00		1.10	5.10
57	185	171		177	111
100	762	758		228	241
101	1401	1400		1400	1399
106	1385	1385		1385	1385
461	225	180		210	69
465	193	162		184	177
477	670	652		68	56
478	1538	1538		1477	1472
586	631	493		398	144
617	189	107		189	0
620	663	671		659	659
621	569	441		410	16
761	98	93		0	0
825	1291	1293		1295	1295

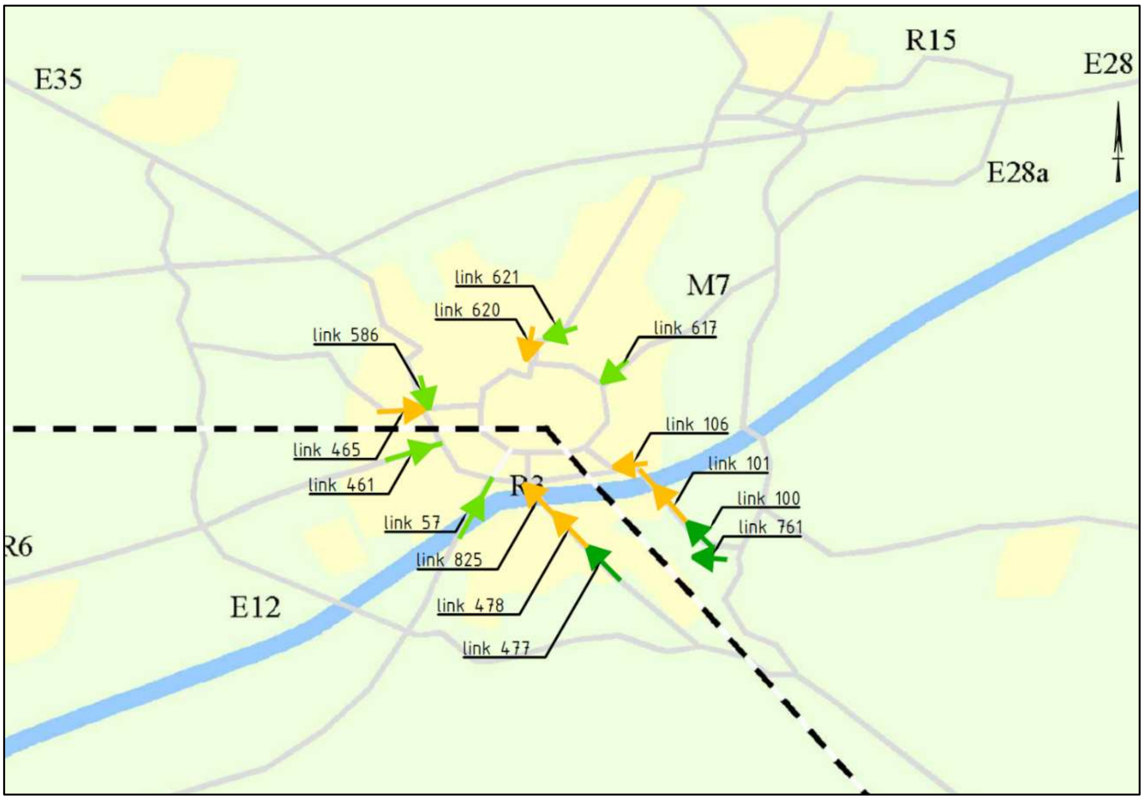


Figure 27 Map with congested links at time step 11 (8:30), orange: no improvement, dark green: improved by automated vehicles and light green: improved by regulations

5.4.4 Origin-Destination improvements

On the level of origin-destination, the results of travel time differences are quite similar compared with those of route travel time differences. The difference that can be observed is that in Figure 28 ratio of benefits and losses is not as good. Explanations can be found in the fact that several routes belong to the same group. This means that while a certain OD profits from the regulation, it obtains the profit for multiple routes. Figure 29 shows that no OD experience disadvantages of more than half a minute on average and some of the OD pairs benefit almost 3 minutes on average. OD pairs that benefit and those that lag can geographically be grouped. Origins on the West side of Milan experience a disadvantage while travelling to the North-East area. This is explained by avoidance of routes through the inner ring of Milan and the increase in traffic on the Northern outer ring. For the same reason, almost all origins outside of Milan benefit from their trips to the destinations around the inner ring of Milan. In conclusion, fewer people take the short route and thus relieve the inner ring road which improves the accessibility and liveability of the inner city.

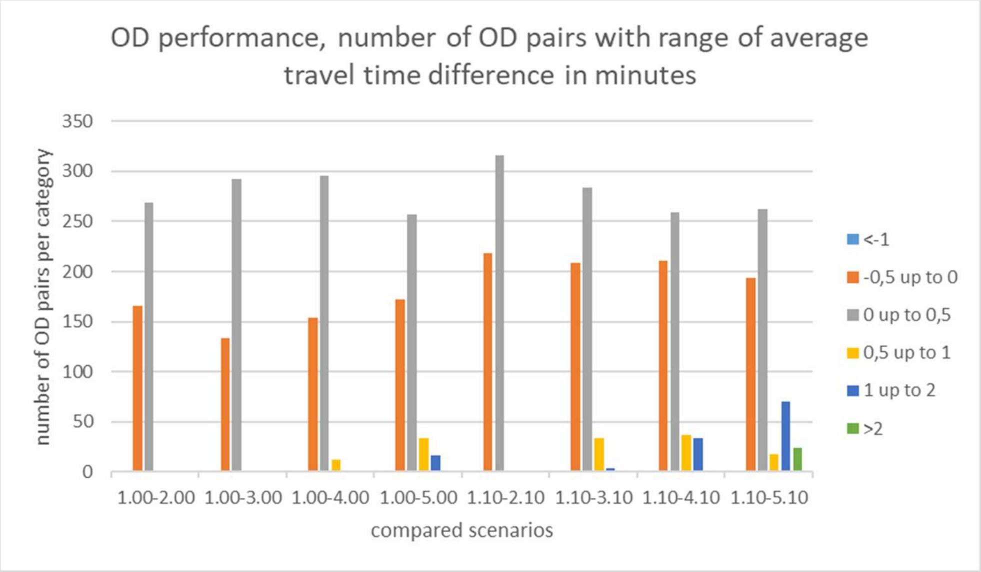


Figure 28 Overview of differences in average OD travel time

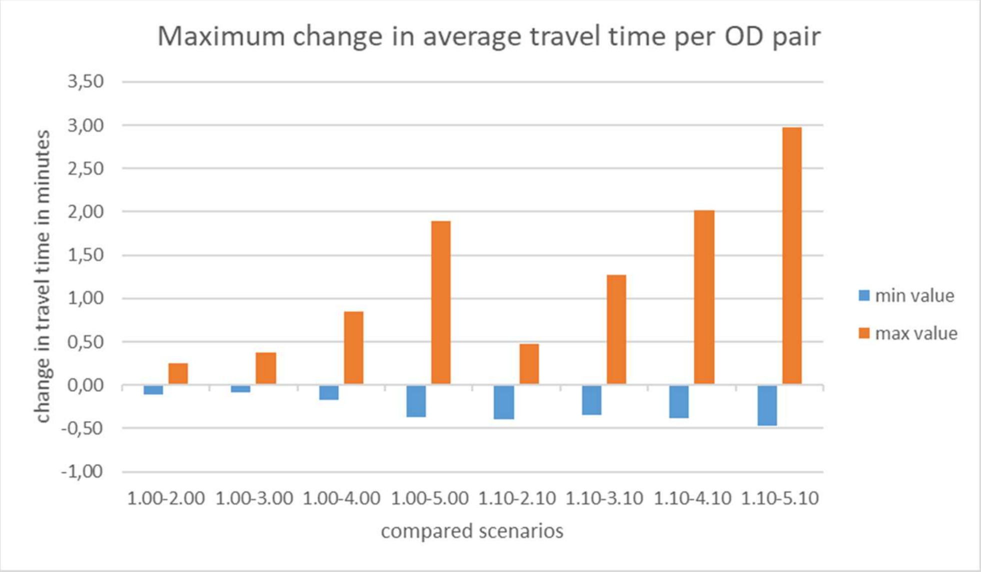


Figure 29 Overview of extreme values for travel time changes per OD

5.4.5 Summary of the results

The previous subparagraphs show all the results in detail. In this subparagraph, the results are summarised in two tables. Table 16 shows the impact of the centralised route guidance system for the current situation without automated vehicles. Table 17 shows the impact of the centralised route guidance system for the future situation when the penetration rate of automated vehicles reached 100%. On average can be seen that the impact of the centralised route guidance system is approximately three times larger in the future situation with automated vehicles compared with the current situation without automated vehicles.

Table 16 Summary results current situation without automated vehicles

	Do nothing	A regulated intermediary, free of obligations, only used for data sharing	A regulated intermediary, free of obligations, partial commitment	Obligated use of intermediary services, but voluntary use for road users	Obligated use of intermediary services and mandatory use for road users
Total time spent	32.830 veh.hrs	32.809 veh.hrs	32.795 veh.hrs	32.762 veh.hrs	32.705 veh.hrs
	0,0 %	-0,1 %	-0,1 %	-0,2 %	-0,4 %
Total network delay	3289 veh.hrs	3277 veh.hrs	3256 veh.hrs	3221 veh.hrs	3152 veh.hrs
	0,0 %	-0,4 %	-1,0 %	-2,1 %	-4,1 %
Average speed	87,23 km/h	87,28 km/h	87,33 km/h	87,44 km/h	87,64 km/h
	0,0 %	0,1 %	0,1 %	0,2 %	0,5 %
Total distance travelled	2.863.705 km	2.863.446 km	2.864.101 km	2.864.571 km	2.866.208 km
	0,0 %	0,0 %	0,0 %	0,0 %	0,1 %
Queue lengths	9800 m	9755 m	9690 m	9563 m	9344 m
	0,0 %	-0,5 %	-1,1 %	-2,4 %	-4,7 %

Table 17 Summary results future situation with only automated vehicles

	Do nothing	A regulated intermediary, free of obligations, only used for data sharing	A regulated intermediary, free of obligations, partial commitment	Obligated use of intermediary services, but voluntary use for road users	Obligated use of intermediary services and mandatory use for road users
Total time spent	32.442 veh.hrs	32.355 veh.hrs	32.296 veh.hrs	32.208 veh.hrs	32.091 veh.hrs
	0,0 %	-0,3 %	-0,4 %	-0,7 %	-1,1 %
Total network delay	2917 veh.hrs	2878 veh.hrs	2799 veh.hrs	2705 veh.hrs	2554 veh.hrs
	0,0 %	-1,4 %	-4,1 %	-7,3 %	-12,4 %
Average speed	88,24 km/h	88,40 km/h	88,63 km/h	88,91 km/h	89,37 km/h
	0,0 %	0,2 %	0,4 %	0,8 %	1,3 %
Total distance travelled	2.862.692 km	2.860.309 km	2.862.289 km	2.863.674 km	2.867.914 km
	0,0 %	-0,1 %	0,0 %	0,0 %	0,2 %
Queue lengths	8080 m	7869 m	7700 m	7488 m	7024 m
	0,0 %	-2,6 %	-4,7 %	-7,3 %	-13,1 %

5.5 Discussion

This paragraph discusses the results of paragraph 5.4. The first two subparagraphs explain differences in results compared with expectations and previous work. The following two subparagraphs discuss the distribution of benefits and losses with different perspectives. In 5.5.4 the effect of traffic information in the model will be discussed because this is a special characteristic of MARPLE. After that, the generalisability of the results will be discussed and this paragraph ends with the strengths and weaknesses of the model.

5.5.1 Explanation of the difference between scenarios four and five

As seen in Figure 19, it was expected, based on the test network, that scenarios four and five would lead to the same traffic flow performance if the time penalty was right. Unfortunately, Figure 24 shows that scenario four did not reach the same effect as scenario five in the Milan ring network. This can be explained by the complexity of the network of the Milan ring. In the test network, a road user that routes user optimum would be compensated by a road user that avoids congestion by switching to the detour route if another road user changes to the fastest route. However, this is in the real network not always possible. Figure 30 will be used to explain this phenomenon. For the Origin-Destination (OD) pair B-D, the demand will be distributed to equalise the travel time of the middle and right route. OD pairs A-C and B-C have no alternative routes and must take the middle route. OD pair A-D can choose between the fastest middle route and the detour left route. In this case, the most optimal traffic state is that all the demand on A-D would take the left (detour) route. If one vehicle chooses the faster congested middle route, all other traffic will experience a disadvantage from this decision. For this reason, every vehicle must participate to reach the potential of the centralised route guidance system. In the Milan ring network, these routes can be found in all OD pairs outside the ring that can be reached faster through the centre of Milan instead of the detour over the outer ring.

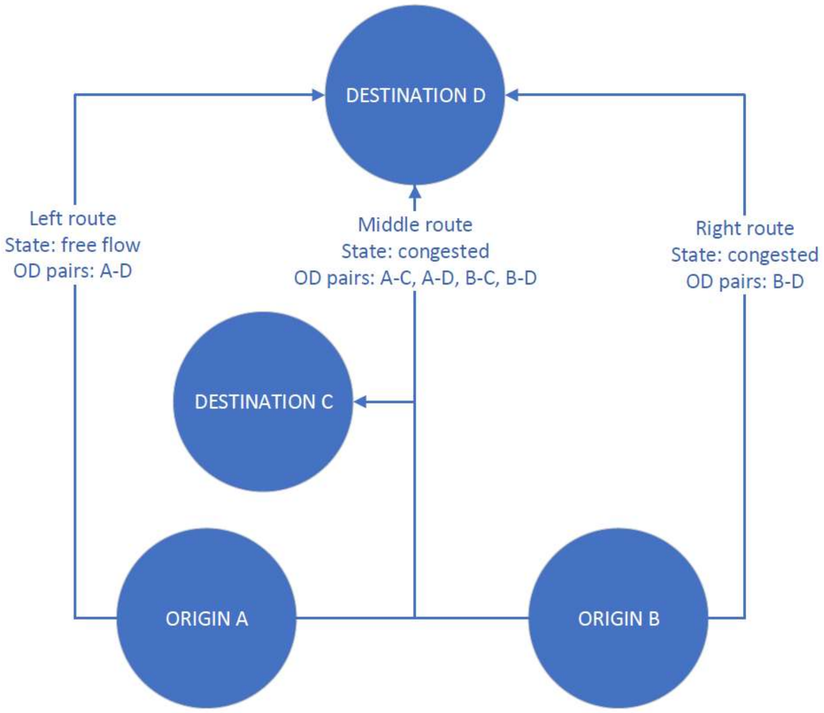


Figure 30 Sketch to explain why scenarios 4 and 5 do not have the same effect

5.5.2 Explanation of continuous improvement by more automated vehicles

Figure 20 shows that the traffic flow performance continuously improves while more automated vehicles are involved. In literature was found that the higher the participation rate, the less impact the additional participating rate would have. However, these studies were less complex and addressed fewer different concepts in the simulation. For example, the study of Arian Housamand et al. in 2019 assumed that human drivers drive according to a perfect user optimum routing (Houshmand, Wollenstein-Betech, & Cassandras, 2019). Figure 31 subtracts the habitual routing behaviour from the data by subtracting the Do nothing scenario from the others. This shows that the results flatten after 80% of automated vehicles. While also subtracting the data issue by scenario 2, the flattening starts at 60% which is comparable with the results of Houshmand et al. In conclusion, the results show that the habitual routing behaviour is not optimised and user optimum routing by automated vehicles will improve the traffic flow performance regardless of the level of information.

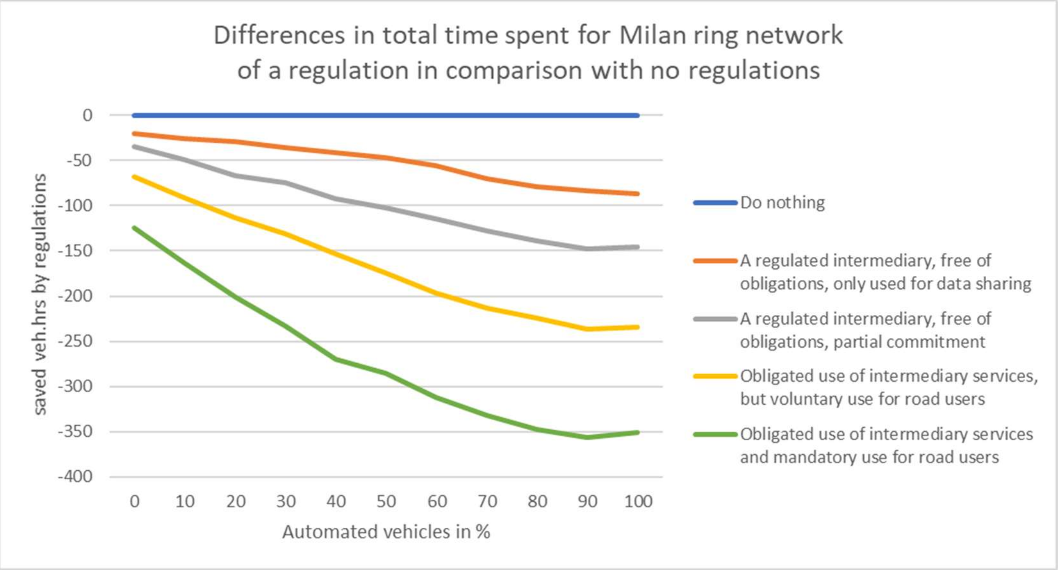


Figure 31 Differences in traffic flow performance without effect of automated vehicles

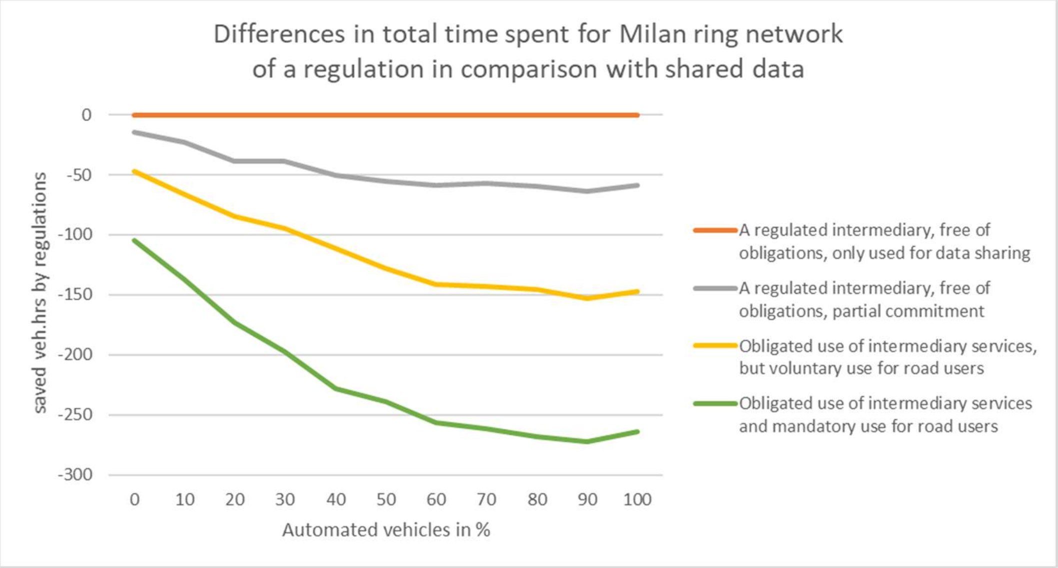


Figure 32 Differences in traffic flow performance without effect of data and automated vehicles

5.5.3 Distribution of travel time benefits and losses

As can be seen in the results of paragraph 5.4.4 Origin-Destination improvements, in every scenario no OD has to a disadvantage of more than 45 seconds on average. However, the perceived additional travel time of the detour might be larger because of the new traffic state. Compared to the situation without any regulations, road users will experience a disadvantage of no more than 30 seconds on average from the regulation. Compared to the new traffic state, people could choose to change their route for their benefit. This route change might result in a larger travel time benefit than the described 30 seconds. Because multiple road users avoid congestion, congestions reduce and the difference with the detour increases. This might result in a larger perceived sacrifice of travel time by the detour. A useful tool for policymakers to reduce the perceived travel time suffering is the adjustment of the maximum time penalty. In every situation, this percentage is the maximum perceived additional travel time by the detour compared with the possibilities of the current traffic state. Policymakers may decide to reduce the time penalty to increase the acceptance of strict regulations. Because for the Milan ring network most benefits are reached within the time penalty boundaries of 10%, a slightly less effective time penalty may be preferable. Table 18 shows the effect of the different time penalties and shows that for 4.10 a reduction of the time penalty from 15% to 10% will only harm the total delay and not the total time spent. For 5.10 a reduction from 25% to 20% leads to almost equal results. The more violent reduction to 10% will reduce the effect of the regulation more serious with 13% (0,11% of the total travel time). However, despite the reduction of effectiveness, it is still the most effective policy strategy.

Table 18 Effect of strong regulations per time penalty (TTS Total Time Spent, TD Total Delay)

Effect of strong regulations per time penalty				
	4.10		5.10	
	TTS	TD	TTS	TD
0	0	0	0	0
5	0,4%	4,7%	0,6%	7,3%
10	0,4%	5,8%	0,7%	9,3%
15	0,5%	6,0%	0,7%	9,9%
20	x	x	0,8%	11,2%
25	x	x	0,8%	11,2%

5.5.4 Effect of information in traffic

The effect of information in traffic can be extracted from the difference of scenario sets one and two. The difference in performance is presented in Table 13 and Table 14. It shows that the total time spent reduces by 0,3% and the total network delay by 1,4% in the future situation with only automated vehicles. In the simulation, this is taken care of by making the route choices less random. In the results, this can be observed by the fact that almost all flows on routes below one vehicle per hour in scenario 1.10 converge to zero. Information makes incorrect estimations of the travel time less likely and vehicles will always choose the fastest route. The simulations shows that a lack of information leads to an efficiency error of 0,1% to 0,3% which is so small that it is hardly possible to measure an effect. An important note is that this error is only plausible for usual traffic conditions. The impact during network disruptions has already been shown to be larger (Taale, 2020).

5.5.5 Effect of automated vehicles

In the current situation where all vehicles are human-driven, the number of vehicles that can be influenced during regular daily traffic operations is, with 30%, limited. With the future introduction of automated vehicles, the routing of vehicles will eventually be controlled by service providers. It is estimated that highly automated vehicles will have a share of the vehicles fleet somewhere between 2025 and 2030 (Calvert, Schakel, & van Lint, 2017). It is expected that in 2025 this share is still below 1% and grow to 6% in 2035. Highly automated vehicles may drive autonomously on the highway and the routing algorithm of the service provider may take the routing decisions. This makes these newly introduced vehicles influenceable and that increases the impact of the centralised route guidance system. The implementation of the intermediary may take years. All subsystems must be aligned before the intermediary can be implemented and implementing new policies may take some time. The results without any automated vehicles in the network underestimates the effect of the centralised route guidance system when finally implemented. In the results, the share of complying vehicles grows from 18% without automated vehicles to 59% with the obligation to participate for service providers with a time penalty of 15%. For this reason, the results with a limited share of automated vehicles must be considered to observe the effect of the centralised route guidance system.

5.5.6 Generalisability of results

The result of this study shows that when a network has some residual capacity, the centralised route guidance system improves the traffic flow. When a network has no or too little residual capacity left, there will be no congestion-free alternatives left and all routes will receive a time penalty which cancels out the effect of the time penalty. For this reason, the flows of the Milan ring network were lowered to 80% to test this concept. Compared with the initial network choice of the Rotterdam ring network, which contains only highways, the level of the time penalties seems also to be applicable. Because of congestion, travel time increases and a small time penalty tempt people to choose the other route already. With a larger time penalty, it seems possible to solve congestions because the second-best route alternative, when reasonably available, usually differs in 10 to 25% travel time in free-flow conditions. Because every network is different, the absolute impact of the regulation could differ significantly per situation that is considered. For example, the result for the test network, presented in Appendix E, shows that the regulation to force road users to comply compared with only regulations for the service providers would not lead to a better result. The simple explanation is that the maximum potential was already reached with the less strict regulations. Because the Milan ring network has shown that real-world networks are more complex than the test network, the results of the Milan ring network are likely to be applicable to other networks. This is in terms of the relative effect because every network with congestion and residual capacity has the potential to improve the traffic flow.

Because the optimal time penalty is not the same for every network, it should be determined per network. With the current approach of the time penalty, the most optimal time penalty can be determined by comparing the results for different time penalties in steps of 5%. As shown in this study, it is expected that the optimal time penalty should be somewhere between 10% and 25%. To investigate the optimum, the span 0% up to 40% should be enough to conclude the most optimal time penalty.

5.5.7 Strengths and weaknesses of the model

The used model for this study allows to combine three concepts. These are the influence of information on routing behaviour, the habitual behaviour of human drivers and the congestion avoiding routing that is centrally controlled. This makes it possible to capture the different routing behaviours of road users in four different user classes. Because the number of interrelated variables between the scenarios is reduced to a minimum, the effect of every variable can be distinguished. In MARPLE the combination of system and user optimum algorithms for different user groups seems to be too complex. The approach with a time penalty for congested routes made these calculations more basic. For that reason, it seems to be more likely that such an approach will be used in the future with more complex real-world applications. The counter side of this approach is that it might be too simplistic and there is too little distinction between routes with only one link with congestion and routes with multiple links with congestion. For this reason, an improvement in the application of a time penalty could lead to an even better result and might work also in highly dense networks. However, the generic approach makes the application clear and reduces discussions about compliance. Because it is expected that the results underestimate the effect, the results of the simulation are still reliable for policymakers to take decisions.

Compared with a microscopic simulation more details could be included in de model and this could improve the results. However, the strength of the macroscopic model is that the driving behaviour on a microscopic model is excluded from the model. How automated vehicles would interact with other traffic is still uncertain and is not part of this research. The macroscopic model allows considering only the effect of routing behaviour which makes the effect clearer without too much noise.

6 Conclusions and recommendations

This chapter concludes the study with the answers to the research questions, the limitations of this study, the scientific contribution and the recommendations for future research and policymakers.

6.1 Answer to the research question

In this paragraph, the conclusions of chapters two and three are used to answer the sub-questions in the first two subparagraphs. In the last subparagraph, the main research question of the research is answered with the results that were found during this research.

6.1.1 Sub-question 1

The first sub-question: *How can road authorities and service providers work together in a coordinated approach to give route advice and what do they want to achieve?* is answered in chapter two. The base to answer this question is the critical review of the SOCRATES$^{2.0}$ project. This is performed by the framework for regulation and liberalization in network industries (Jaag & Trinkner, 2011) complemented with additional other literature. Cooperation between road authorities and service providers takes place through an intermediary. The intermediary vertically segregates the network management tasks from participating actors and gives them the information to execute their measures. This leads to the following workflow. Every actor collects its data, the intermediary combines this information, it executes the commonly agreed strategy table, it gives instructions to all actors and those actors perform these instructions with the available measures. However, as shown in Figure 11, service providers can bypass the system and may abuse the services of the intermediary. The service providers can be categorised based on their behaviour into three groups. Those who commit to the services, those who only share data and those who do not connect with the intermediary. The achievements of the cooperation are the improvement of the traffic flow by reducing travel time and the improvement of the quality of the service in terms of the manoeuvrability in the network indicated by the total network delay and the average speed in the network.

6.1.2 Sub-question 2

The set of regulation strategies to answer the second sub-question: *What are possible policy regulations for a centralised route guidance policy to guide cooperative vehicles to increase the impact on the traffic flow?* are formulated in chapter three. The regulation strategies consist of the following three measures. The implementation of an intermediary, the obligation of service providers to participate and the obligation of road users to comply with the system. Combined, these measures resulted in four regulation strategies to prevent service providers and road users to circumvent the services of the intermediary. These strategies are:

- **Do nothing**;
  In this strategy, no regulations are implemented and eventually, all vehicles will drive user optimum without perfect knowledge of the network.
- **A regulated intermediary, free of obligations;**
  In this strategy, an independent intermediary is established which makes cooperation possible. The intermediary will aggregate the data of all participating actors and determines the optimal set of measures based on a commonly agreed strategy table.
- **Obligated use of intermediary services, but voluntary use for road users;**
  In this strategy, in addition to the previous strategy, all actors are forced to use the services of the intermediary.
- **Obligated use of intermediary services and mandatory use for road users.**
  In this strategy, in addition to the previous strategy, also the road users are forced to comply with the system.

6.1.3 Main research question

Prior to the simulation, the sub-questions investigated how road authorities and service providers could work together in a coordinated approach for route guidance and how this cooperation could be regulated. With an intermediary that takes over the tasks of traffic management, all data can be combined to improve the knowledge of the system to improve route guidance for a better traffic flow performance for the entire network. With different regulation strategies, the commitment to the intermediary services can be increased to reach the maximum potential of the traffic flow performance. With three levels of regulation, the services of the intermediary could be voluntary, mandatory for service providers or even mandatory for road users. These strategies are translated to scenarios for simulation to finally answer the main research question:

What is and will be in the future the impact on the daily traffic flow performance of different regulation strategies for a centralised congestion avoiding route guidance system where road authorities and service providers work together in a coordinated approach?

In the current traffic situation without and in the future with automated vehicles, the commitment of service providers is required to achieve an effect of the centralised route guidance system. This study shows that an intermediary that is only be used for data sharing will not improve the traffic flow performance under usual traffic conditions. With only the commitment of part of the service providers, the effect remains limited. This study shows that the centralised route guidance system only shows significant positive effects when all service providers commit to the system. Because of the complexity of real-world networks, the maximum potential of the system can only be reached when all vehicles participate with the centralised route guidance system in highly dense networks. When networks are less dense or less complex, less strict regulations may also reach the maximum potential of the system. The number of vehicles that can be influenced is in the current traffic situation is limited. The automated vehicles in the future allow increase the impact of the system. Automated vehicles will route by a system that can be instructed by the intermediary. The impact of the centralised route guidance system increases approximately three times with a penetration rate of automated vehicles of more than 70% compared with the current situation without automated vehicles. In conclusion, the impact is without commitment (almost) zero, it reduces/solves congestion with the (regulated) commitment of service providers and reaches its maximum potential with the regulation of the compliance of road users.

6.2 Limitations of the study

Besides the weaknesses of the model described in subparagraph 5.5.7, there are some other limitations. This research focuses on daily traffic operations without disruptions. This means that in this case, the scenario for data sharing does not lead to less congestion. However, it could be beneficial during disruptions in the network like H. Taale has proven before (Taale, 2020). The results are valid for the investigated situation but more traffic situations are possible. Next, this study focuses on route guidance as the only measure to be taken. Currently, multiple other measures are applied to improve the traffic flow. These measures could strengthen or weaken each other. Because the effect of the single measure was unknown this must be investigated first. The effect of multiple measures is out of the scope of this research but could influence the potential of a centralised route guidance system. The used model for this research was the ring network of Milan and the example network of two routes for one OD pair. More network variations are possible like grid structures which were not included in this study. In addition, the Milan ring network was with the origin of 2002 outdated and the example network was very basic. Because of the dependency of the DiTTlab for the network model and the limited time available for this research, it was not possible to obtain a more recent operating network for MARPLE. However, this study shows with the available network that the potential of the system is promising and the potential differs from situation to situation.

Limitations for the execution of this project were the adjustments to MARPLE. Because further developments of the software MARPLE were outside the scope of this thesis, only the provided update with the time penalty approach for congested routes in MARPLE version 3.6.1 was available. This means that the implementation of a time penalty approach for congested routes is not further optimised. Another limitation related to the software were the problems with embedding the data from MARPLE in OmniTRANS. Because this did not work after several attempts, the graphical representation of the data in the network could not be generated. The most important network data is visualised manually. Another limitation in the generated data was the missing network indicators per user class or type of routing behaviour. To convince service providers to participate, this data could be very useful because it only contains their users and ignores others. However, the presented data in this research shows that hardly any road users experience serious disadvantages from the centralised route guidance system and the system significantly improves on average. That also applies to the service providers.

6.3 Scientific contribution

No previous study is found that combines a centralised route guidance system with realistic current and future traffic. There is also no study found that evaluates the impact on the traffic flow with different sets of policy regulations. For this reason, it was not known if a lack of political/societal acceptability would lead to efficiency problems for the implementation of such a system. The result of this research shows the impact of a centralised congestion avoiding route guidance system with different scenarios of acceptability of service providers and political regulations with an implemented algorithm for the compliance of road users.

Compared with previous studies, this research combines habitual routing behaviour with user optimum routing behaviour and congestion avoiding routing behaviour. This is a more realistic approach than a combination of user and system optimum routing. The assumption that all human drivers will adapt their routing to the user optimum is proven by literature to be untrue. People usually do not know the current traffic state and are not willing to change their route for small travel time benefits. The first evaluation of the impact seems to be larger than in the previous approach. Next, the congestion avoiding algorithm is a simpler approach and calculations cost less calculation power compared with the system optimum algorithms. This makes the applied algorithm more likeable to be implemented in real-world situations. With the applied time penalty approach with a maximum, the issue of previous studies with too long unlikely detours is eliminated.

Lastly, this research brings an initial opening for the discussion to what extent a new centralised route guidance system should be regulated. Strict regulations have proven to be the most effective. However, policymakers may be satisfied with the presented results of less effective regulations in favour of their preferred regulation strategy and the support of their policy. Another discussion arises to implement the maximum time penalty. With the results of this study, policymakers will have insights into the effect of lower time penalties and more strict regulations to combine some elements to determine what scenario is preferred.

6.4 Recommendations for future research

To complement the limitations of this study, this paragraph gives some recommendations for future research. As explained, the time penalty approach is implemented for all routes that include a link with more intensity than the IC-Threshold and it does not distinguish in the severity of the congestion. To make this possible, the option to implement the time penalty per link should be considered. This means that the additional perceived travel time for routes with multiple (nearly) congested links is larger than for routes with only one (nearly) congested link. This can make the time penalty also valuable for OD pairs where all routes have at least one (nearly) congested link. The second recommendation to improve the application of the time penalty is to calculate the optimum by the model and adapt the compliance automatically. In the used model, the time penalty was for every OD the same. Because some ODs just needed a smaller time penalty to reach the optimum, multiple road users have dropped out due to the higher time penalty that was required in other ODs to reach the optimum. If this would not be technically feasible, the possibility of modifying the time penalty per zone in the network can still be considered to make the time penalty more precise to achieve a maximum number of users that comply with the system.

Another limitation of this study was omitting the other measures to improve the traffic flow. For example, among others, the combination with ramp metering should be considered to check if these measures would strengthen each other or not. Because both systems aim to prevent congestion, it could be expected that these two can strengthen each other a lot. Because this combination will likely prevent/solve more congestions, the used model should also include the capacity drop. With multiple prevented congestions and the capacity drop which included 5% to 30% of the capacity (Yuan, Laval, Knoop, Jiang, & Hoogendoorn, 2018), this will have a significant impact on the results.

The last recommendation for future research is to examine how all network indicators can be distinguished per user class. This can help in the discussion with policymakers and service providers to commit with the intermediary. Service providers may be afraid that their users must take the detour disproportionately often and they may search for alternative services. Insights into how the travel time is distributed over the different user classes may be helpful to convince service providers to participate.

6.5 Recommendations for policymakers

Regulations are not the preferred alternative for policymakers. However, this research shows that without commitment for the intermediary, the additional information will hardly improve the traffic flow performance. As a recommendation out of this research, at least the commitment of service providers must be guaranteed by the policymakers to reach a significant improvement on the traffic flow. Discussions with the largest service providers should show whether participation must be regulated or if service providers would participate voluntarily. It may also be beneficial to determine the level of regulation per area in the network instead of for the total network. This could lead to strict regulations in areas like the Milan ring network and softer regulations in less dense networks. For the use of the time penalty, most gains are to be made in the lower ranges of the time penalty. This means that policymakers should consider if small benefits for the traffic flow are worth it to lose support for the system. A time penalty of 10% may be unnoticeable for a large part of traffic and lead to the majority of the benefits. Considering a silent implementation could lead to more participants and for that reason to a better traffic flow performance. The last recommendation for policymakers is the moment of action. Currently, automated vehicles are in development. When policymakers do not act, these developments may make it more difficult or even impossible to implement the centralised route guidance system later. In addition, the more advanced route navigation systems that are currently used can also be used to improve the traffic flow. In combination with the results, when data is shared during disruption management, it is worth considering the implementation of a centralised route guidance system and to further optimise the algorithm.

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Appendix

A. Scientific paper

As part of the graduation process, a research paper for this study is written. The research paper is an abbreviated version of the entire report where most details and reasoning are omitted.

The impact of regulations for a centralised route guidance system with different penetration rates of automated vehicles

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TIL thesis, Faculty of Civil Engineering and Geosciences, TU Delft

Abstract. This study aims to quantify the impact on the traffic flow performance of different regulation strategies for a centralised route guidance system where road authorities and service providers work together in a coordinated approach. Previous research concentrates on the effect of a centralised route guidance system when every vehicle participates and all vehicles have perfect knowledge of the traffic state. This is not the real case with human drivers and multiple service providers and the impact of cooperation may be limited. This study combines habitual driving behaviour, the effect of the quality of information and a congestion avoiding user optimum algorithm to quantify the impact of a centralised route guidance system. The congestion avoiding user optimum algorithm will add a perceived time penalty to all routes with links above a certain intensity/capacity ratio to avoid choosing the congested route. The cooperation is described by the coordinated approach model of the SOCRATES$^{2.0}$ project. In this model, the cooperation is organised by an intermediary who takes on the management tasks. Because a lack of commitment could be a problem for the success of the system, the services of the intermediary can be regulated with four regulation strategies starting with no regulation to regulation for both service providers and road users. The impact is determined with the dynamic macroscopic traffic model MARPLE. The result shows that without commitment the system does not improve the traffic state. For the maximum potential of the system, it must be fully regulated for both service providers and road users. Although with only the commitment of service providers, there is already a positive impact on the traffic flow and in less complex networks it can already solve all congestion.

Keywords: Centralised route guidance, Congestion avoiding, Traffic simulation, MARPLE, Connected vehicles, Cooperative traffic management, Social routing

Introduction

Nowadays around 91% of the people have navigation equipment available and 80% of the people who travel for business or who go for a day out uses a navigation application (KiM, 2017). Of those people, 35% receive online congestion updates (KiM, 2017) and will be able to change route based on real-time traffic conditions. The percentage of road users with real-time updates will continue to grow with the future cooperative automated vehicles. Route guidance software will be included in automated vehicles and may automatically be followed up. This means that the information given by the traffic management centres to the road users by Dynamic Route Information Panels (DRIP's) might be less effective to influence the route choice of drivers. With the expectation that in 2035 already 6% of the vehicles is highly automated (Calvert, Schakel, & van Lint, 2017). This means that the possibilities to influence route behaviour shift from road authorities to service providers. These service providers do not work together with the traffic management centre of the government. They base their route advice on real-time data and only consider the travel time of the users of their services (Bilali, Isaax, Amini, & Motamedidehkordi, 2019). This means that service providers use a user optimum approach to guide vehicles through the network. If too many drivers use this user optimum approach this can lead to an inefficient network performance which will increase the travel time of a lot of the travellers (Boyce & Xiong, 2004). The traffic management centre of road authorities and the service providers might work together to reach common network-wide traffic management goals to prevent inefficient network performances in the future. Cooperation can take place as described in the concept of the coordinated approach (for smart routing) of the SOCRATES cooperation framework (SOCRATES$^{2.0}$, 2020). The SOCRATES$^{2.0}$ project is a European project that is initiated to bring road authorities, service providers and car manufacturers together to improve car mobility. The SOCRATES$^{2.0}$ project suggests, among other things, that this coordinated approach can lead to more optimal use of the network and more satisfied road users by implementing an intermediary structure to perform the network management tasks. However, there are some concerns about the commitment of such an approach by service providers and road users (Koller-Matschke, 2018). A large field study with 20.000 participants in the region of Amsterdam did not lead to a significant improvement of the traffic flow performance (Wilmink, Jonkers, Snelder, & Klunder, 2017). This indicates that the commitment for such a system should be large to reach any improvements to the traffic flow. The possibility that service providers and road users would not use the services of the intermediary is strengthened because most benefits of system optimum routing are mostly obtained by non-participating vehicles. This makes participating service providers less competitive compared with non-participating service providers (Houshmand, Wollenstein-Betech, & Cassandras, 2019). Because there is no insight into whether road users would accept this kind of route guidance and what the benefits would be for the network performance, service providers may not be willing to participate. Regulations may solve the lack of compliance but are not the preferred alternative of policymakers and may even not be necessary.

Previous studies show the full potential of the situation where every vehicle participates in the centralised system optimum route guidance system (El Hamdani & Benamar, 2018; Kuru & Khan, 2020). However, many road users are not influenced by traffic information (Gan & Chen, 2013; Iraganaboina, Bhowmik, Yasmin, Eluru, & Abdel-Aty, 2021; Reinolsmann, et al., 2020; Rijkswaterstaat, 2015; KiM, 2017) and not everyone is willing to accept it voluntarily (Mariotte, Leclercq, Ramirez, Krug, & Becarie, 2021; Bonsall & Joint, 1991). This makes the studied scenarios not relevant to the current and future traffic situations. Multiple regulation strategies with voluntary and mandatory elements were suggested to research to improve the impact of the centralised route guidance system (Bagloee, Tavana, Asadi, & Oliver, 2016). With the knowledge that almost all effect of automated vehicles is reached in the first 50% (Houshmand, Wollenstein-Betech, & Cassandras, 2019), a moderately strict regulation strategy might be very effective and satisfy road users, policymakers and service providers. The aim of this study is to quantify the impact on the traffic flow performance of different regulation strategies for a centralised route guidance system where road authorities and service providers work together in a coordinated approach.

Cooperation between road authorities and service providers

The cooperation framework of the SOCRATES$^{2.0}$ project describes the coordinated approach for smart route advice. In this approach, four intermediary roles are established to make coordinated end-user services possible as presented in Figure 1. The network monitor combines the data collected by the service providers to create a commonly agreed view of the network. The strategy table describes how this data is processed, what measures should be taken in certain situations and which objective is pursued. The network manager will perform the strategy table and the assessor will verify if the network manager is doing its job correctly. The implementation of these roles is not part of this study. During this study, it is assumed that all roles are implemented properly and when this study mentions the intermediary it means the combination of these separated roles.

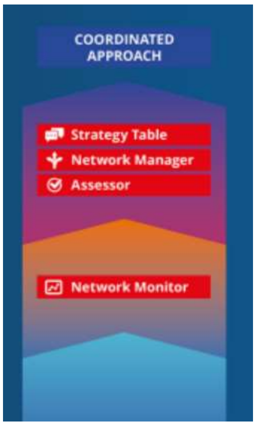
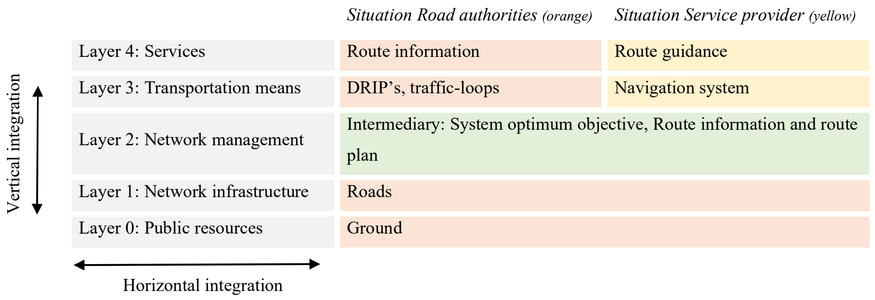


Figure 1 Coordinated approach (SOCRATES$^{2.0}$, 2020)

The concept of separating the network management tasks by implementing an intermediary is a well-known principle in network industries (Jaag & Trinkner, 2011). The intermediary will vertically segregate the network management tasks of all actors and integrate these tasks horizontally. Figure 2 presents how the new situation will be with the implemented intermediary. Besides this concept makes cooperation possible, it could lead to some undesirable side effects. Especially while multiple coordination centres emerge, unbundling may lead to flawed coordination (Brunekreeft, 2015). Because a small country like The Netherlands has already five regional traffic centres to control the highway network (Rijkswaterstaat, Verkeerscentrum Nederland, 2021), this could lead to an issue in the future. As only a single region is considered in this study, flawed coordination is not a concern. Another consideration to be taken is the potential lack of competitive incentives (Jaag & Trinkner, 2011; Armstrong & Sappington, 2006). Because the intermediary takes overall network management tasks, service providers cannot compete with providing the fastest route. This may lead to a reduction of investments in the future because investments do not lead to exclusive rights to harvest the benefits of the investment.



	Situation Road authorities (orange)	*Situation Service provider (yellow)*
Layer 4: Services	Route information	Route guidance
Layer 3: Transportation means	DRIP's, traffic-loops	Navigation system
Layer 2: Network management	Intermediary: System optimum objective, Route information and route plan	
Layer 1: Network infrastructure	Roads	
Layer 0: Public resources	Ground	

Figure 2 Segregation of Network layers vertical integrations per actor, suggested situation road network with in green the new intermediary, based on (Jaag & Trinkner, 2011)

Figure 3 shows how cooperation can occur with an implemented intermediary. With this figure, the last issue that service providers may bypass the intermediary will be addressed. In Figure 3, SP1 stands for the group of service providers which behave exemplarily. With only this kind of service provider, the process will be as follow. All actors have data sensors and obtain their data. Actors aggregate their data and share their data with the intermediary which aggregate all available data to one data set which presents the common truth about the network state. The intermediary calculates the optimum routing and instructs all actors with the measures to be taken. The actors actuate the measures and the road users obtain the routing information. This is how cooperation with an intermediary is meant to work. However, as can be seen in Figure 3, SP2 and SP3 do not act like that. SP2 stands for the service providers that only share data. This group uses the data of all actors to improve their service to offer the fastest routing for their users. This group does not execute the measures of the intermediary and will not offer a routing that is best for the system. The last group, SP3, are the service providers that act independently. This group does not connect with the intermediary and continues to act as they do nowadays. Because the intermediary structure would be set up by the government, the TMC, Traffic Management Centres, are assumed to behave exemplary and no behavioural variations will be observed.

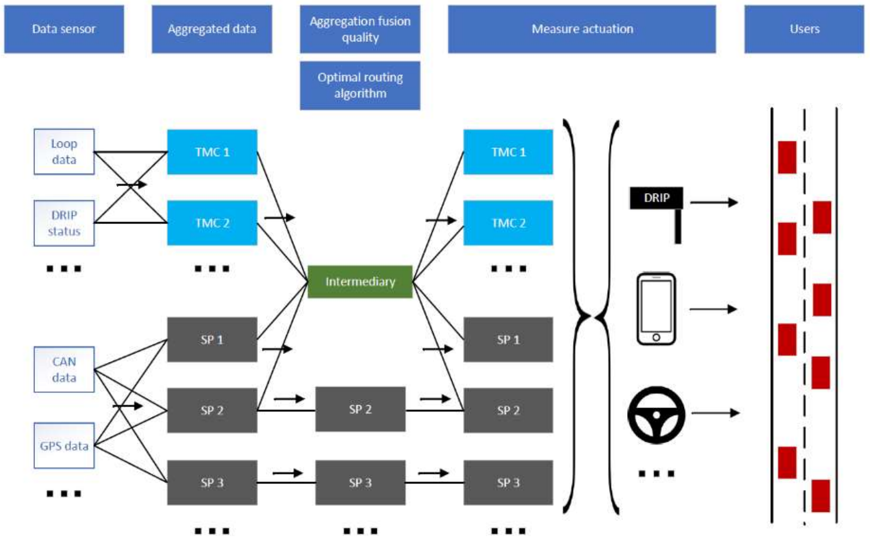


Figure 3 Interaction scheme with voluntary use of an intermediary with bypass behaviour, based on intermediary option three from proposed cooperation framework SOCRATES$^{2.0}$ *(Koller-Matschke, 2018)*

With the cooperation model defined, the cooperation needs a commonly agreed objective as would be described in the strategy table. The SOCRATES$^{2.0}$ project described four objectives (Koller-Matschke, 2018). A safer, cleaner and more efficient traffic flow and optimum use of the road capacity, Better services to the road users and better quality of life for citizens, More cost-effective traffic management by optimising the use of existing road capacity and Economic growth and the creation of more jobs by reducing traffic problems and by creating new business opportunities. The common denominator of these objectives is the reduction of congestion. Congestions lead to more unsafe situations, lead to more pollution, lead to less efficient traffic flows and is seen as a traffic problem. Reducing or solving congestions would be a logical objective for the cooperation. However, this objective should not be done at any cost. To prevent excessive detours to reduce congestion, the reduction of the total travel time should be considered as the objective of the cooperation for smart routing. Because congestion leads to a longer travel time, the reduction of congestion is also included in the objective to minimise the total travel time.

Policy regulations for route guidance

To prevent unwanted behaviour of service providers and to force road users to comply with the services, three measures are formulated which lead to four potential routing strategies.

Measures

The measures are indicated with the Greek letter omega. This letter recurs in Figure 5 where this letter represents the enabling or blocking of a route in the scheme for assigning traffic to a specific group of routing behaviour.

Ω_1: Implementation of the intermediary

The first regulation, named Omega 1, is the implementation of the intermediary. The intermediary makes the path to congestion avoiding user optimum routing for service providers possible. This is presented with the dashed line, with the Omega 1 sign, in Figure 12. Next, this regulation also makes it possible for service providers possible to exchange data to improve their user optimum algorithm. For this reason, the Omega 1 sign is added to the user optimum algorithm. The distinction between different user optimum algorithms will be made later.

Ω_2: Regulation that forces service providers to participate with the services of the intermediary

The second regulation, named Omega 2, forces service providers to use the services of the intermediary. When this regulation is active, service providers cannot directly offer user optimum route suggestions to their users. Service providers are obligated to execute the instructions of the intermediary and offer the congestion avoiding user optimum routing to their users.

Ω_3: Regulation that forces road users to accept the route guidance

With the third regulation, named Omega 3, the option to reject the congestion avoiding algorithm is blocked. Road users will be forced to comply with the congestion avoiding user optimum routing. In this case, all guided vehicles will avoid congestion to improve traffic performance.

Policy strategies

While these policy measures are combined, four policy strategies can be formulated.

- **Do nothing;**
  In this strategy, no regulations are implemented and eventually, all vehicles will drive user optimum without perfect knowledge of the network.
- **A regulated intermediary, free of obligations;**
  In this strategy, an independent intermediary is established which makes cooperation possible. The intermediary will aggregate the data of all participating actors and determines the optimal set of measures based on a commonly agreed strategy table.
- **Obligated use of intermediary services, but voluntary use for road users;**
  In this strategy, in addition to the previous strategy, all actors are forced to use the services of the intermediary.
- **Obligated use of intermediary services and mandatory use for road users.**
  In this strategy, in addition to the previous strategy, also the road users are forced to comply with the system.

Method and Material

Model and network choice

To perform the simulation, the simulation package Model for Assignment and Regional Policy Evaluation (MARPLE) is used. MARPLE is a dynamic macroscopic simulation package that works with user classes. A user class represents a group of road users with the same routing behaviour. With the update of MARPLE to version 3.6.1, distinctions can be made between the knowledge of the network, whether information matters for routing and if road users avoid congestion. With these distinctions, the current routing behaviour and the routing behaviour after the implementation of the intermediary can be described. The network that will be used during the simulation is the Milan ring network from the year 2002 and is presented in Figure 4. A ring structured network is suitable for this study because it provides multiple route options for many origin-destination pairs. This makes rerouting possible and non-congested route alternatives more likely to exist. Because this study focuses on the impact on the traffic flow with a centralised route guidance system, the age of the network does not matter. Results of the simulation are used to draw general conclusions and not to draw region-specific conclusions for Milan. The Milan ring network has turned out to be the most appropriate available workable network because of the number of route options.

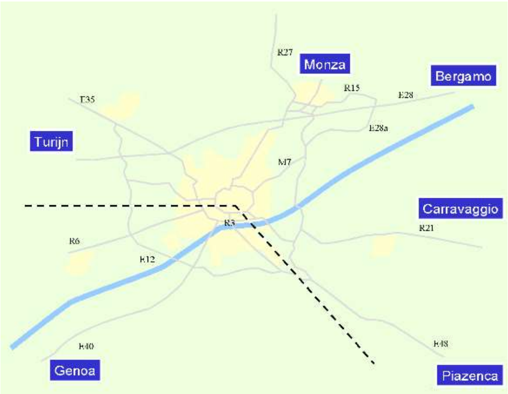


Figure 4 Milan ring network in 2002

Algorithms

There are five well-known algorithms for the assignment of traffic available in the transportation research field. These are All or Nothing Assignment, Capacity Restrained Assignment, Incremental Assignment, User Equilibrium Assignment and System Optimum Assignment (Saw, Katti, & Joshi, 2015). However, MARPLE does not provide all algorithms. MARPLE uses an initial allocation for its first initial allocation and has two user optimum optimisation algorithms available that can be performed to reallocate traffic. Next to these algorithms in MARPLE, an algorithm to determine the compliance rate will be performed before the simulation takes place. A description of all algorithms used will now be provided.

Initial allocation

MARPLE uses an initial allocation based on the C-logit model and the free flow travel times or the shortest path to route habitual routing behaviour (Taale, 2020). Habitual routing behaviour consists mostly of previous experiences of the driver (Bogers, Bierlaire, & Hoogendoorn, 2014). Because traffic is not always congested, it is assumed that habitual drivers, that cannot be influenced by traffic information, will route to their perceived fastest route according to the uncongested traffic condition. The fastest route method is chosen because the shortest path may result in excessive use of the underlying road network which is expected to be not the fastest route.

User optimum algorithm

MARPLE has two User Equilibrium Assignment algorithms means Stochastic User Equilibrium (SUE) and Deterministic User Equilibrium (DUE) (Taale, MARPLE, beschrijving en handleiding, 2020). For the DUE it is assumed that drivers have perfect information over the network and chooses the actual fastest route. The SUE is used while the information over the network is incomplete and drivers choose their perceived fastest route. The completeness or quality of the knowledge of the traffic state can be varied with the parameter teta. Teta changes the size of the stochastic uncertainty for the SUE assignment which indicates the chance that the chosen route is the fastest. The SUE algorithm uses the C-Logit route choice algorithm to consider the overlap of routes. To flatten route intensity to ensure that the simulation converts, the Multiple Successive Average method (MSA) is used. For this study, only the SUE algorithm is used and the teta is specified per user class. Because in almost every situation there are still human drivers involved, the information would never be perfect like in the DUE and the SUE algorithm with a large teta is more suitable.

Congestion avoiding user optimum algorithm

In this study, cooperative vehicles route with a congestion avoiding user optimum algorithm. A congestion avoiding approach has proved to have a positive effect on the traffic flow performance in literature (Summerflied, Deokar, Xu, & Zhu, 2020). In this study, congestion avoiding will be regulated with a perceived time penalty for links above a certain intensity/capacity threshold. With this time penalty, participating road users will avoid routes with a (nearly) congested link. This will reduce congestion and for that reason the average travel time. In the best-case scenario, it also prevents congestion with the associated capacity drop. Unfortunately, the effect of the capacity drop is not included in this study.

The principle to use congestion avoidance to achieve a better traffic performance will work as follow. In case of congestion on a single lane link, all routes containing that link will have a perceived additional travel time in terms of a percentage of the total travel time. The congestion avoiding vehicles will prefer the detour while the additional travel time is shorter than the time penalty and that will reduce the inflow on the congested link. With a capacity of 1800 vehicles per hour, this would mean that every vehicle that takes a detour of x seconds will reduce the queue by 2 seconds. This means that the travel time of all passing vehicles will be reduced by 2 seconds by the offer of x seconds of the vehicle that makes the detour till the moment the congestion would be solved without the detour. A previous study shows that avoiding all congestion can lead to excessive detours which could lead to a reduced effect on the total travel time (Summerflied, Deokar, Xu, & Zhu, 2020). The chosen time penalty approach will prevent this because the time penalty value is the longest additional travel time that would be accepted which prevents excessive detours to occur.

Algorithm for compliance

Not every road user is willing to accept a social routing like the congestion avoiding approach. Initially, about 80% of the people are willing to accept the social routing and this decreases to under 40% while the additional travel time increases (Mariotte, Leclercq, Ramirez, Krug, & Becarie, 2021; Bonsall & Joint, 1991). Recent studies show that social demographic attributes have an influence on compliance (Mariotte, Leclercq, Ramirez, Krug, & Becarie, 2021; van Essen, Thomas, van Berkum, & Chorus, 2020). However, in a macro simulation, these attributes are averaged out. A variable that will be considered is the number of participators. In general, while people have the feeling that others make the social choice, they are more willing to accept the social alternative (Pruitt & Kimmel, 1977; Bonsall & Joint, 1991). Because it is not known in a MARPLE whether a road user had a detour before, it is assumed that below 10% participation rate every participator previously had the detour and it turns to always had the fastest route while reaching 100% participation rate. To formulate the algorithm to determine the compliance rate, the results of two studies (Bonsall & Joint, 1991; Mariotte, Leclercq, Ramirez, Krug, & Becarie, 2021) are used and the participation rate is implemented as described before. The algorithm used for this study to determine the compliance rate is described with Equation 1, Equation 2 and Equation 3.

Parameters:
C = Compliance in percentage [%]
t = Value of time penalty [%]
p = Participation rate [%]

$$C = 20 + 65 * 0{,}97^{t}$$
$$Domain: \{p \geq 0 | p < 10\}$$

Equation 1 Compliance function for participation rates till 10%

$$C = 20 + 15\frac{p-10}{90} + \left(65 - 15\frac{p-10}{90}\right) * (0{,}97 + 0{,}0225 * \frac{p-10}{90})^{t}$$
$$Domain: \{p \geq 10 | p \leq 100\}$$

Equation 2 Compliance function for participation rates between 10% and 100%

$$C = 35 + 50 * 0{,}9925^{t}$$
$$Domain: \{p = 100\}$$

Equation 3 Simplified compliance function for participation of 100%

Mathematical description MARPLE

The mathematical description of the MARPLE model is taken from the study of Taale (2008) and adapted, if necessary, to the situation of this study. MARPLE is a dynamic deterministic traffic assignment model. For this study, the stochastic dynamic user optimal assignment (SDUE), see Figure 5, that is implemented in MARPLE, is used to perform the simulation. The model uses the Dijkstra algorithm to generate routes. To assign traffic to these routes, a stochastic user equilibrium where the random error with parameter θ can be adjusted to represent the information knowledge of the network is used. With the C-logit model overlap in routes are considered by assigning traffic. To load this traffic, MARPLE uses a dynamic network loading model which includes congestion spillback. To smooth route flows the method of successive averages (MSA) is included and the model stops the simulation when the convergence criterion is reached.

```
Algorithm Stochastic dynamic user optimal assignment (Taale, 2008)
Step 1:    Construct a set of routes between every OD pair with Dijkstra algorithm.
Step 2:    For each time period $k$ determine an initial route flow solution $f_k^{(0)} \in \Omega$.
           Set $j := 1$.
Step 3:    Calculate route cost $c_k^{(j)}(f^{(j-1)})$ using the dynamic network loading model.
Step 4:    Calculate new route flows $f_k^{(j)} \in \Omega$ with the C-logit model.
Step 5:    Smooth route flows with $f_k^{(j)} = f_k^{(j-1)} + \zeta^j (f_k^{(j)} - f_k^{(j-1)})$ (MSA)
Step 6:    If convergence criterion is met, then stop.
           Otherwise, set $j := j + 1$ and return to step 3.
```

Figure 5 Algorithm Stochastic dynamic user optimal assignment

Because of the new programmed time penalty, the calculation of the perceived route costs $\hat{c}_k^{rod}$ for OD pair od, route r and time period k are different calculated than in the original MARPLE model. In Equation 4, two additional parameters are adjusted. tpb_k stands for the binary value which is 1 if a link on the route exceeds the I/C-Threshold value and 0 if not for time period k. tpp stands for the percentage of the time penalty and ε_k^{rod} is the random component for route r for origin o and destination d. The travel costs c_k^{rod} for route r of OD pair od at time period k is the sum of all travel times τ_{at} of the links that are included in route r on the corresponding time step t. The travel time τ_{at} is dependent in the saturation flow φ_{at} which means that the travel time increases when the capacity is nearly reached. Other variables in Equation 5 are the queue length κ_{at}, the parameter related to the initial queue z_{at}, the link independent parameter k_{at}, the length of the link l_a, the length of the analysis for time period h Δ_h and the capacity at the end of the link Q_a''.

$$\hat{c}_k^{rod} = c_k^{rod} + tpb_k^{rod} * tpp * c_k^{rod} + \varepsilon_k^{rod}$$

Equation 4 Calculation of perceived route costs

$$\tau_{at} = \tilde{\tau}_{at} + 0{,}9 l_a \Delta_h \left(z_{at} + \sqrt{z_{at}^2 + \frac{8k_a\varphi_{at}}{Q_a''\Delta_h} + \frac{16k_a\kappa_{at}}{(Q_a''\Delta_h)^2}} \right), \forall a \in A, t$$

Equation 5 Travel time calculation

To obtain information about the resulting link indicators, congestion in the network and travel times, the route flows are loaded onto the network with the deterministic dynamic network loading (DNL) model (Taale, 2008) presented in Figure 6. The model is deterministic and dynamic because there are no random components and the loading of the network evolves over time. The model can be described in general according to the following steps. Traffic is loaded according to the demand profile. The traffic propagates link by link from origin to destination. The travel time on the link is based on the travel time function, described in Equation 5. At decision nodes, nodes with multiple directions, flows are distributed according to the proportion of the route flows. The model checks if there is enough space available on the next link Ψ_{at}. The total space on a link is determined by the length of the link l_a multiplied by the number of lanes p_a which is divided by the average space occupied by a vehicle l^{-veh}. The available space Ψ_{at} is determined by subtracting the number of vehicles on the link χ_{at} from the total space of the link, see Equation 6. If Ψ_{at} is smaller than the inflow u_{at}, the inflow u_{at} is reduced to meet the constraints of Equation 6 indicated with u'_{at}. The queue will be stored upstream and the length of the queue κ_{at} is defined by Equation 7. Here is $\tilde{v}_{at}$ the unconstrained outflow of link a at time step t and v'_{at} the corrected outflow. In the situation that the queue occupies all space on the link, it will spill back to the previous link.

```
Algorithm Dynamic network loading model (Taale, 2008)
Step 1:   Initialise all variables needed.
Step 2:   Calculate splitting rates for every node and time period.
Step 3:   Propagate traffic through the network using the following steps:
          Determine the initial flows per link.
          Determine free flow travel time and capacity per link and time period.
          Divide each time period in a number of time steps.
          For every time step $t$:
            • Determine delay and travel time per link.
            • Calculate the outflow per link.
            • For every node determine the inflow.
            • Calculate the available space for every link.
            • For every node determine the outflow with the splitting rates.
            • Determine the inflow for every link.
            • Determine links with blocking back and adjust the outflow for those links.
            • Calculate link indicators.
Step 4:   Calculate delay and travel costs $c_k^{rod}$ for every $r$, $o$, $d$ and $k$.
```

Figure 6 Algorithm Dynamic network loading model

$$\Psi_{at} = \frac{l_a p_a}{l^{-veh}} - \chi_{at}, \forall a \in A, t$$

Equation 6 Calculation of length of the queue

$$u_{at} \leq \Psi_{at}$$
$$u_{at} \leq Q'_a$$

Equation 7 Constraints for the inflow of a link

$$\kappa_{at} = \tilde{v}_{at} - v'_{at}, \forall a \in A, t$$

Equation 8 Calculation of the queue length

Conversion to simulation

To translate the cooperation model with the specified regulations to a simulatable input, the Scheme for assigning traffic to specific groups of routing behaviour, presented in Figure 5, is developed. The scheme divides road users in two groups of human drivers and automated vehicles based on the input variable of the scenario. All automated vehicles are influenced by service providers and human drivers can be influenced by service providers, the traffic management centre or are not influenceable at all. For this study, human drivers are divided according to the following percentages. Parameter A is set to 70% because research show that somewhere between 30% to 35% of the traffic is influenceable by traffic information (Gan & Chen, 2013; Iraganaboina, Bhowmik, Yasmin, Eluru, & Abdel-Aty, 2021; Reinolsmann, et al., 2020; Rijkswaterstaat, 2015; KiM, 2017). The mean measure for routing traffic by the traffic management centre is the dynamic route information panel (DRIP). Unfortunately, this information is only relevant for only 30% to 40% of the road users (KiM, 2017) and only 5% to 6% of the road users is willing to change route for small travel time benefits (Wardman, Bonsall, & Shires, 1996; Rijkswaterstaat, 2015). This assumes that parameter B is set to 10%. This left parameter C to be 20%. Since 91% of the road users have navigation equipment available (KiM, 2017) and 25% of all road users using it on a regular basis (KiM, 2017; Knapper, van Nes, Christoph, & Hagenzieker, 2015), this assumption is also valid. The distribution of the group which is influenced by the service providers depends on the scenario. Without implementing the intermediary, parameter H is set to 100% because no data is shared. While Ω_1 is active, F, G and H can all be non-zero and the values depends on the scenario. With the regulation Ω_2 active, parameters G and H will be forced to be zero and F becomes 100% which lead to the situation where all road users influenced by the service providers uses the congestion avoiding routing. If road users comply this routing depends on the compliance algorithm described by Equation 1, Equation 2 and Equation 3. Only in the situation where Ω_3 is active, the compliance will be 100%. In all other situations, vehicles who decline the congestion avoiding routing will route according to the user optimum algorithm with good knowledge of the network.

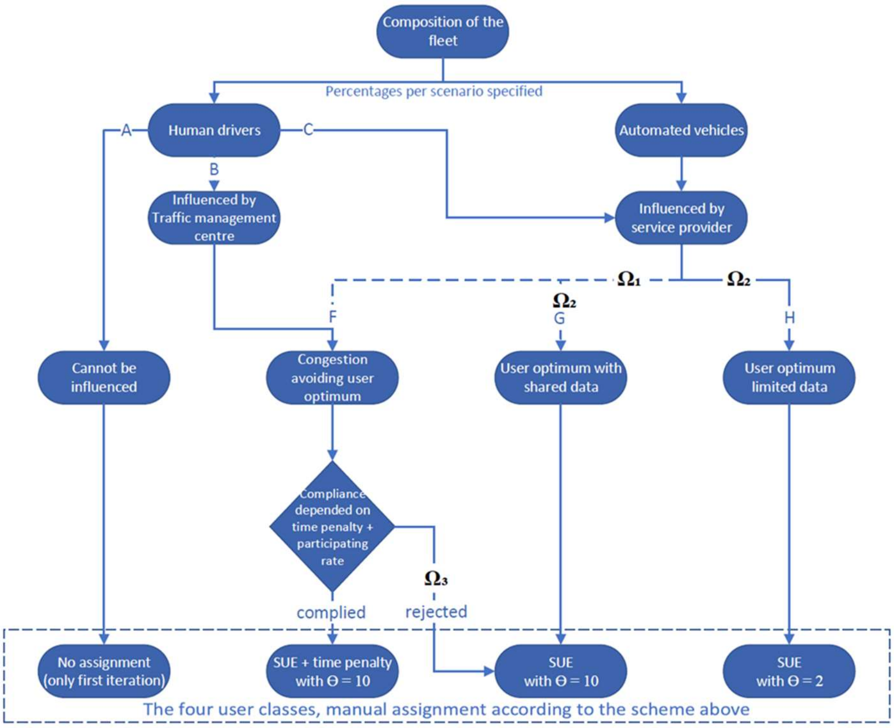


Figure 7 Scheme for assigning traffic to specific groups of routing behaviour

User classes

The parameters of the four user classes, resulting from Scheme for assigning traffic to specific groups of routing behaviour, are described below per user class.

1) No assignment (only first iteration)

According to the manual of MARPLE, a teta value of 0 means that drivers show habitual behaviour and that they are not influenced by traffic information (Taale, MARPLE, beschrijving en handleiding, 2020). Routes are determined by the initial iteration of the simulation and route choices are not changed during the trip. For this group, the time penalty is not included.

2) SUE + time penalty with $\Theta = 10$

This group will avoid congestion. To avoid congestion a time penalty is included for routes with (nearly) congested links. The size of this time penalty depends on the simulation itself and is not determined in advance. This group is connected with the intermediary and shares data which means that the quality of traffic information is increased. In the case of perfect information, the value of teta should be infinity. However, with changing traffic states, data errors and human drivers the perfect information will never be perfect. For this reason, the teta value will be set to 10 which was also indicated as complete information in a study of the developer of MARPLE (Taale, 2020).

3) SUE with $\Theta = 10$

This group only considers their travel time and uses the data of the intermediary to achieve this. This means that there is no time penalty included and the teta is at the same level as the group that avoid congestion.

4) SUE with $\Theta = 2$

The last group is the group of service providers that act independently. Because a service provider represents a group of individual vehicles there is some information available about the current traffic state. According to the manual of MARPLE, a teta value of 0 means poor informed and 3 good informed (Taale, MARPLE, beschrijving en handleiding, 2020). Because information is far from complete and some vehicles may not have an updated system, the value 2 is chosen for the teta of the independent acting service providers group.

Scenarios

There are four regulation strategies to perform in the simulation. However, for one of the regulation strategies, the outcome is not certain. In the strategy A regulated intermediary, free of obligations, three situations can occur. The first is that the data is only shared and the service is abused for its own benefit. The second one is that only a part of the service providers will participate. The last scenario is that every service provider uses the service voluntarily and the result would be the same are the regulation where all service providers are forced to use the services of the intermediary. This leads to five scenarios. The variables to allocate road users to groups of routing behaviour are presented in Table 1.

Scenarios:

1) Do nothing
2) A regulated intermediary, free of obligations, only used for data sharing
3) A regulated intermediary, free of obligations, partial commitment
4) Obligated use of intermediary services, but voluntary use for road users
5) Obligated use of intermediary services and mandatory use for road users

Table 1 Variables for allocating traffic to groups of routing behaviour

	Percentage							Regulation parameters		
Scenario	A	B	C	F	G	H	Compl.	Ω_1	Ω_2	Ω_3
1	70	10	20	0	0	100	alg.	0	0	0
2	70	10	20	0	100	0	alg.	1	0	0
3	70	10	20	50	25	25	alg.	1	0	0
4	70	10	20	100	0	0	alg.	1	1	0
5	70	10	20	100	0	0	100	1	1	1

After executing the scheme for assigning traffic to specific groups of routing behaviour the input variables for MARPLE are determined. The input variables are presented in Table 2. For the time penalty, only steps of 5% difference are considered. This leads to an on average minute difference in travel time. Because some values are rounded and the converge error of 1%, a more specific time penalty could lead to non-existent local optima which could lead to wrong conclusions. Another problem that would occur is that the optimal time penalty would not be consistent and vary with a few percentages. To determine the optimum, the .10 scenarios are simulated for time penalties between 0% and 40%. The most optimum time penalty is taken for the other scenarios and for every scenario is checked with two simulations + and -5% to check if the optimum is still optimal.

Table 2 MARPLE input per scenario

Do nothing						A regulated intermediary, free of obligations, only used for data sharing						A regulated intermediary, free of obligations, partial commitment					
Scenario	Time penalty	user class				Scenario	Time penalty	user class				Scenario	Time penalty	user class			
		1	2	3	4			1	2	3	4			1	2	3	4
1.00	10	70	20	3	7	2.00	10	70	0	23	7	3.00	10	70	5	12	13
1.01		63	28	3	6	2.01		63	0	31	6	3.01		63	7	15	15
1.02		56	36	3	5	2.02		56	0	39	5	3.02		56	9	18	17
1.03		49	44	2	5	2.03		49	0	46	5	3.03		49	11	21	19
1.04		42	52	2	4	2.04		42	0	54	4	3.04	15	42	13	26	19
1.05		35	60	2	3	2.05		35	0	62	3	3.05		35	15	29	21
1.06		28	68	1	3	2.06		28	0	69	3	3.06		28	17	33	22
1.07		21	76	1	2	2.07		21	0	77	2	3.07		21	19	36	24
1.08		14	84	1	1	2.08		14	0	85	1	3.08		14	21	39	26
1.09		7	92	0	1	2.09		7	0	92	1	3.09		7	23	42	28
1.10	N/A	0	100	0	0	2.10	N/A	0	0	100	0	3.10		0	25	45	30

Obligated use of intermediary services, but voluntary use for road users						Obligated use of intermediary services and mandatory use for road users					
Scenario	Time penalty	user class				Scenario	Time penalty	user class			
		1	2	3	4			1	2	3	4
4.00	15	70	0	12	18	5.00	25	70	0	0	30
4.01		63	0	15	22	5.01		63	0	0	37
4.02		56	0	18	26	5.02		56	0	0	44
4.03		49	0	21	30	5.03		49	0	0	51
4.04		42	0	24	34	5.04		42	0	0	58
4.05		35	0	27	38	5.05		35	0	0	65
4.06		28	0	29	43	5.06		28	0	0	72
4.07		21	0	32	47	5.07		21	0	0	79
4.08		14	0	35	51	5.08		14	0	0	86
4.09		7	0	38	55	5.09		7	0	0	93
4.10		0	0	41	59	5.10		0	0	0	100

User class 1: No assignment
User class 2: SUE with Θ = 2
User class 3: SUE with Θ = 10
User class 4: SUE with Θ = 10
+ time penalty

Assumptions

In addition to the researched assumptions for the routing behaviour of human drivers and the teta values, some key assumptions for the simulation must be addressed. These key-assumptions are the parameter for the IC-Threshold and the number of iterations when the time penalty is active. For the IC-Threshold an experiment with 50% habitual drivers and 50% time penalty users is performed to determine which time penalty is optimal. This is done for 99%, 95% and 90%. During the experiment, the 95% IC-Threshold was the most optimal solution and the 99% led to an error in the data. The results are shown in Figure 6 IC-Threshold test Milan ring network. The reason that the 95% IC-Threshold has shown to be the most effective is that the 90% leaves too much capacity unused and the 99% will still lead to congestion because flows are not completely consistent and the link may be unfairly denied a time penalty. The second key-assumption is the number of iterations after the time penalty is used. For this study, it is assumed to continue iterating until the converge error is reached. Because the intermediary has good information about the network state, it could instruct all vehicles to the most optimal routing. This makes it valid to iterate until the converge error is reached.

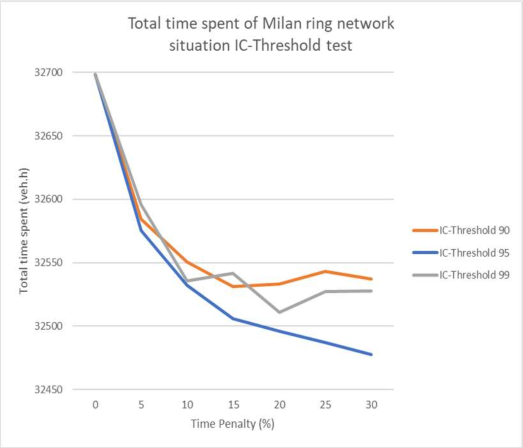


Figure 8 IC-Threshold test Milan ring network

Results

The results show that the centralised route guidance system, that let road users avoid congestion, has a positive impact on the traffic flow when the commitment of service providers is guaranteed. For the current situation, the results are summarised in Table 3. For the future situation with automated vehicles that can, in potential, all be guided by the system the results are summarised in Table 4. Compared with the Do nothing scenario, hardly any effect is observed when the intermediary is only used to share data. Currently, the effect is limited with a reduction of approximately 5% of the queues when the system is fully regulated. However, the result shows that the impact grows approximately to 13% when all vehicles are automated. Figure 9 shows that in the future with the different routing behaviour of automated vehicles, the effect of route choices will improve anyway. However, as can be seen in the same figure, the intermediary can strengthen the effect.

Table 3 Summary results current situation without automated vehicles, percentages are compared with the do nothing scenario

	Do nothing	A regulated intermediary, free of obligations, only used for data sharing	A regulated intermediary, free of obligations, partial commitment	Obligated use of intermediary services, but voluntary use for road users	Obligated use of intermediary services and mandatory use for road users
Total time spent	32.830 veh.hrs	32.809 veh.hrs	32.795 veh.hrs	32.762 veh.hrs	32.705 veh.hrs
	0,0 %	-0,1 %	-0,1 %	-0,2 %	-0,4 %
Total network delay	3289 veh.hrs	3277 veh.hrs	3256 veh.hrs	3221 veh.hrs	3152 veh.hrs
	0,0 %	-0,4 %	-1,0 %	-2,1 %	-4,1 %
Average speed	87,23 km/h	87,28 km/h	87,33 km/h	87,44 km/h	87,64 km/h
	0,0 %	0,1 %	0,1 %	0,2 %	0,5 %
Total distance travelled	2.863.705 km	2.863.446 km	2.864.101 km	2.864.571 km	2.866.208 km
	0,0 %	0,0 %	0,0 %	0,0 %	0,1 %
Queue lengths	9800 m	9755 m	9690 m	9563 m	9344 m
	0,0 %	-0,5 %	-1,1 %	-2,4 %	-4,7 %

Table 4 Summary results future situation with only automated vehicles, percentages are compared with the do nothing scenario

	Do nothing	A regulated intermediary, free of obligations, only used for data sharing	A regulated intermediary, free of obligations, partial commitment	Obligated use of intermediary services, but voluntary use for road users	Obligated use of intermediary services and mandatory use for road users
Total time spent	32.442 veh.hrs	32.355 veh.hrs	32.296 veh.hrs	32.208 veh.hrs	32.091 veh.hrs
	0,0 %	-0,3 %	-0,4 %	-0,7 %	-1,1 %
Total network delay	2917 veh.hrs	2878 veh.hrs	2799 veh.hrs	2705 veh.hrs	2554 veh.hrs
	0,0 %	-1,4 %	-4,1 %	-7,3 %	-12,4 %
Average speed	88,24 km/h	88,40 km/h	88,63 km/h	88,91 km/h	89,37 km/h
	0,0 %	0,2 %	0,4 %	0,8 %	1,3 %
Total distance travelled	2.862.692 km	2.860.309 km	2.862.289 km	2.863.674 km	2.867.914 km
	0,0 %	-0,1 %	0,0 %	0,0 %	0,2 %
Queue lengths	8080 m	7869 m	7700 m	7488 m	7024 m
	0,0 %	-2,6 %	-4,7 %	-7,3 %	-13,1 %

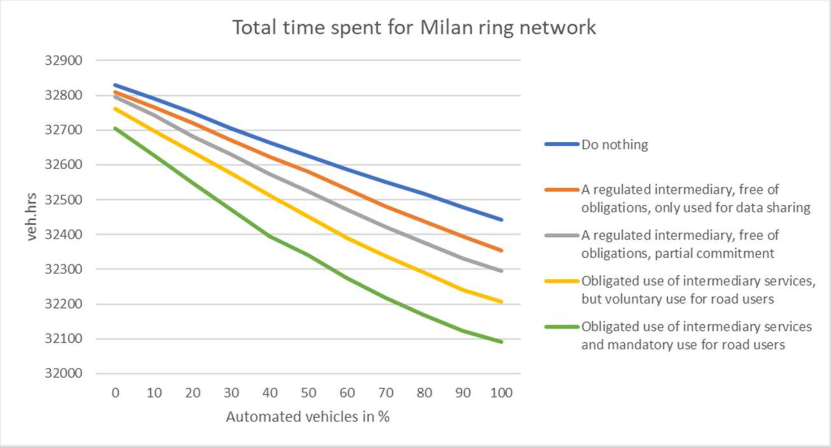


Figure 9 Total time spent for Milan ring network

OD effects

The detour should not disproportionately be distributed. To analyse if this happens, the OD results are presented. Figure 10 shows that no OD pair is more than 30 seconds worse on average compared with the situation without regulation. The OD pairs that notice a slight delay are those who drive from the North-West to North-East. The reason for the slight delay is the increased density on the outer ring which slightly lowers the speed a bit and this tour might be a bit longer. The additional traffic is used to drive on the inner ring road. This relieves the traffic pressure on the inner ring road and leads to travel time benefits for almost all OD pairs that have a destination inside the centre of Milan. Because the studied network has an average travel time of approximately 22 minutes, people suffer, with a maximum of 30 seconds, at most 2,3% of their travel time on average and others have, with more than 2 minutes reduction, benefits up to 10% of their travel time.

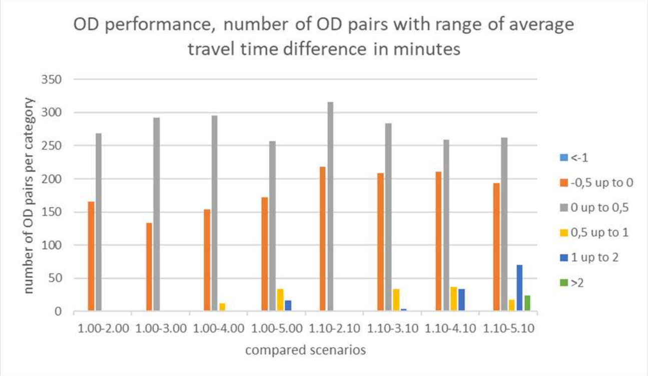


Figure 12 Amount of OD pairs with travel time changes on average

Sensitivity time penalty

Figure 11 presents the relative effect of the time penalty in total time spent compared with the outcome of a time penalty of 0%. The selection of scenarios is varied in the number of participators with congestion avoiding routing. With more participators, the optimum of the time penalty shifts toward larger time penalties and the result becomes more sensitive if the penalty is set to high. The explanation for the sensitivity is the change in the actual number of vehicles that avoid congestions. If this change becomes larger, the effect becomes more significant because more road users switch to a user optimum routing. The reason for the shift in optimal time penalty can be explained by the reason that with fewer participating vehicles the potential of the scenario is reached faster. For example, consider an ideal situation where 20% of the vehicles must make a detour to avoid congestion with a time penalty of 20%. While only 10% of the vehicles participate, the congestion will not be solved. This means that the difference in travel time between the congested route and the detour route is smaller. With a smaller difference, it is beneficial to lower the time penalty until not all the participating vehicles make the detour to increase compliance.

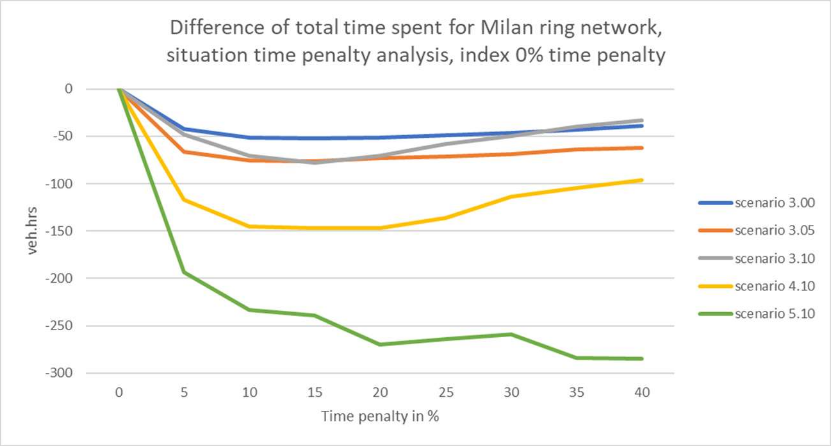


Figure 13 Relative effect of the time penalty per regulated scenario

Effect of traffic information and automated vehicles

Figure 7 shows that the traffic flow performance continuously improves while more automated vehicles are involved. In literature was found that the higher the participation rate, the less impact the additional participating rate would have. However, these studies were less complex and addressed fewer different concepts in the simulation. Figure 12 subtracts the habitual routing behaviour from the data by subtracting the Do nothing scenario from the others. This shows that the results flatten after 80% of automated vehicles. While also subtracting the data issue by scenario 2, presented in Figure 13, the flattening starts at 60% which is comparable with previous results. In conclusion, the results show that the habitual routing behaviour is not optimised and user optimum routing by automated vehicles will improve the traffic flow performance regardless of the level of information.

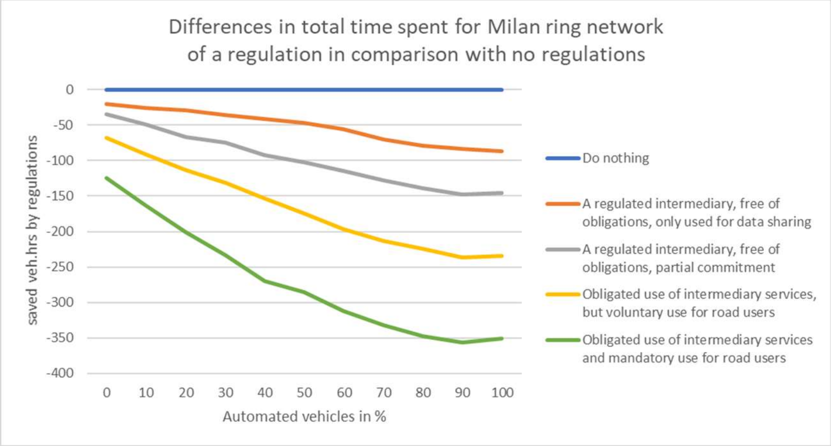


Figure 14 Differences in traffic flow performance without effect of automated vehicles

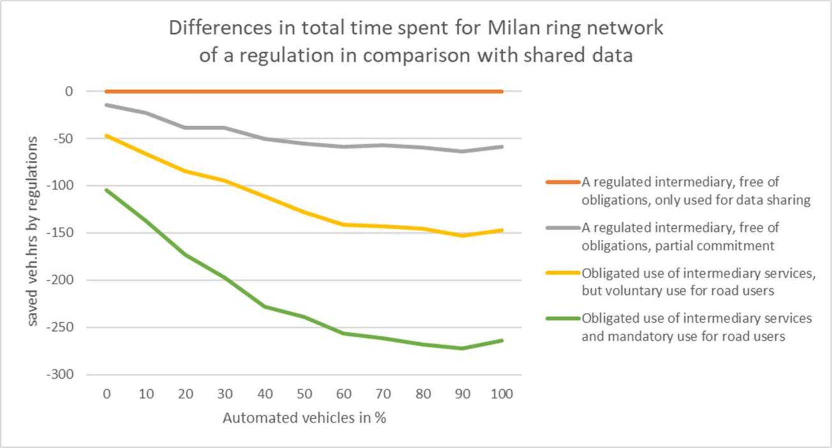


Figure 15 Differences in traffic flow performance without effect of data and automated vehicles

Discussion, conclusion & recommendations

Discussions

The results are clear but the interpretation of the results can differ. Based on previous studies it was expected that strict regulations would not be necessary and the full potential would already be reached while all service providers participate. Because of the high dense network and the complexity of the network, all traffic of multiple OD pairs should make a detour to reach full potential. Other OD pairs will always have a congested link and those OD pairs will not perceive the time penalty and cannot avoid congestion. For this reason, the impact of the fully regulated scenario is larger compared with the less strict regulations. This study also shows that information alone does not have an impact on the daily traffic situation. The total network delay will be reduced by only 1,4% while all vehicles are automated. Information may help with distributions, but for daily operation the impact is not noteworthy. An interesting topic is the application of the time penalty. With the OD pair results, the comparison is made with the Do nothing scenario. However, people will perceive they have a longer detour. The perceived detour depends on the application of the time penalty. With a time penalty of 20%, no one can change route to obtain a travel time benefit of more than 20%. This means that that specific road user will not suffer more than 30 seconds on average compared with the unregulated situation but can perceive a detour of at most 20%. Because people may dislike this, the maximum time penalty can be reduced at the expense of a slightly decreased impact on the system. Table 5 shows the impact of the system with different time penalties. In scenario 4.10 a reduction of the time penalty from 15% to 10% only cost a small reduction of the impact while the compliance of the policy may improve enough to make it acceptable for policymakers. The results for the Milan ring network seem to be applicable to other networks with the notion that while less dense all congestion could be solved. While considering other networks, a time penalty between 10% to 25% seems to cover most of the logical acceptable detour options. This is because this is the difference in travel time in free-flow conditions.

Table 5 Effect of strong regulations per time penalty (TTS Total Time Spent, TD Total Delay)

Effect of strong regulations per time penalty				
	4.10		5.10	
	TTS	TD	TTS	TD
0	0	0	0	0
5	0,4%	4,7%	0,6%	7,3%
10	0,4%	5,8%	0,7%	9,3%
15	0,5%	6,0%	0,7%	9,9%
20	x	x	0,8%	11,2%
25	x	x	0,8%	11,2%

Limitations

In other studies, is instead of a congestion avoiding algorithm a system optimum algorithm used. A system optimum algorithm will achieve the optimum instead of approaching the system optimum state with the congestion optimum algorithm. For this reason, the used algorithm might be too simplistic to investigate the maximum potential of the system. However, because the system optimum algorithm was already too complex for the simulation software, the used approach to avoid congestion could be more realistic to be implemented. The time penalty applies to all routes with a congested link and does not make a distinction between severe and mild congestion. This leads to the situation that when the first link of the route is congested, all routes get the time penalty and no effect is observed. As a result, an opportunity is missed to reroute OD pairs where all alternative routes have a congested link.

This research focuses on daily traffic operations without disruptions. This means that in this case, the scenario for data sharing does not lead to less congestion. However, it could be beneficial during disruptions in the network like H. Taale has proven before (Taale, Cooperative Route Guidance - A Simulation Study for Stockholm, 2020). The results are valid for the investigated situation but more traffic situations are possible. Next, this study focuses on route guidance as the only measure to be taken. Currently, multiple other measures are applied to improve the traffic flow. These measures could strengthen or weaken each other. Because the effect of the single measure was unknown this must be investigated first. The effect of multiple measures is out of the scope of this research but could influence the potential of a centralised route guidance system. The used model for this research was the ring network of Milan and the example network of two routes for one OD pair. More network variations are possible like grid structures which were not included in this study. In addition, the Milan ring network was with the origin of 2002 outdated and the example network was very basic. Because of the dependency of available network models and the limited time available for this research, it was not possible to obtain a more recent operating network for MARPLE. However, this study shows with the available network that the potential of the system is promising and the potential differs from situation to situation.

Conclusions

In the current traffic situation without and in the future with automated vehicles, the commitment of service providers is required to achieve an effect of the centralised route guidance system. This study shows that an intermediary that is only be used for data sharing will not improve the traffic flow performance under usual traffic conditions. With only the commitment of part of the service providers, the effect remains limited. This study shows that the centralised route guidance system only shows significant positive effects when all service providers commit to the system. Because of the complexity of real-world networks, the maximum potential of the system can only be reached when all vehicles participate with the centralised route guidance system in highly dense networks. When networks are less dense or less complex, less strict regulations may also reach the maximum potential of the system. The number of vehicles that can be influenced is in the current traffic situation is limited. The automated vehicles in the future allow increase the impact of the system. Automated vehicles will route by a system that can be instructed by the intermediary. The impact of the centralised route guidance system increases approximately three times with a penetration rate of automated vehicles of more than 70% compared with the current situation without automated vehicles. In conclusion, the impact is without commitment (almost) zero, it reduces/solves congestion with the (regulated) commitment of service providers and reaches its maximum potential with the regulation of the compliance of road users.

Recommendations

As explained, the time penalty approach is implemented for all routes that include a link with more intensity than the IC-Threshold and it does not distinguish in the severity of the congestion. To make this possible, the option to implement the time penalty per link should be considered. This means that the additional perceived travel time for routes with multiple (nearly) congested links is larger than for routes with only one (nearly) congested link. This can make the time penalty also valuable for OD pairs where all routes have at least one (nearly) congested link. The second recommendation to improve the application of the time penalty is to calculate the optimum by the model and adapt the compliance automatically. In the used model, the time penalty was for every OD the same. Because some ODs just needed a smaller time penalty to reach the optimum, multiple road users have dropped out due to the higher time penalty that was required in other ODs to reach the optimum. If this would not be technically feasible, the possibility of modifying the time penalty per zone in the network can still be considered to make the time penalty more precise to achieve a maximum number of users that comply with the system.

For policymakers are regulations not the preferred alternative. However, this research shows that without commitment for the intermediary, the additional information will hardly improve the traffic flow performance. As a recommendation out of this research, at least the commitment of service providers must be guaranteed by the policymakers to reach a significant improvement on the traffic flow. Discussions with the largest service providers should show whether participation must be regulated or if service providers would participate voluntarily. For the use of the time penalty, most gains are to be made in the lower ranges of the time penalty. This means that policymakers should consider if small benefits for the traffic flow are worth it to lose support for the system. A time penalty of 10% may be unnoticeable for a large part of traffic and lead to the majority of the benefits. Considering a silent implementation could lead to more participants and for that reason to a better traffic flow performance. The last recommendation for policymakers is the moment of action. Currently, automated vehicles are in development. When policymakers do not act, these developments may make it more difficult or even impossible to implement the centralised route guidance system later. In combination with the results, when data is shared during disruption management, it is worth considering the implementation of a centralised route guidance system and to further optimise the algorithm.

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B. Files for verification MARPLE update (test network)

Verification-MARPLEparm.txt

```
//Title
Simulation Parameters

//General
;Assign Optimization Metering SmoothG SmoothFlow DelayType InitialFlow ThresFlow ConvError minCounter maxCounter
   2          0          0        0        1          0          1          1        0.05        5          30

//Assignment
;  rho   beta gamma Kirchhoff initialAssign
   10     1     2      0          1

//LocalControl
;LContrMethod LOptPeriod
         1         60

//AntControl
;nrAssign nRTperiods optCriterium LTimeStepOpt
      1          1          1          60

//Routes
;nrRoutes nrRand scaleFac linkCost linkEqual junctionDelay ODdist
    4        50     0.66     1       0.85         0           1

//VehPar
;VehLen  TruckV  minV1  minV2  Ja1  Ja2  Ja3  Ja4  Ja5  Ja6  Ja7  Ja8  Ja9
  7.5       80      10      10     85   75   60   50   40   20   15   10   10

//TollPar
;TollType  ValTime1  ValTime2  ValTime3  ValTime4
    0          10.0       15.0        8.5        24.6

//TimePenaltyPar
;TimePenaltyType IC-threshold PenaltyNrIter
          1            95.00          30              (IC-threshold is varied in different tests)

//EventSimPar
;EventSimType  EventSimAssign  EventSimNrIter
         0                2                3

//PlotPar
;MFDplot  MFDperiod  ContourPlot  StartTime  FlowPlot  SpeedPlot  ControlPlot  TravelTimePlot
     0          5               0           7          0          0            0              0

//Output
;outputflag  binary  emissions
        1         0         0

//EmissionPar
;truckperc  excelout  binout
      0          0         0
```

Verification-Network.txt

```
//Title
Example network with one controlled intersection and two metered ramps

//Parameters
;nrTimePeriods LengthTim LTimeStep ScaleFlow ScaleCap ScaleSpeed DemandPar
    13               900         20          1.00      1.00       1.00       1

//Links
;linknr nettype length nrlanes satflow   speed  type CTR  nrSG  Signal(s) nrCL ConfLinks
;              (m)         (veh/hr) (km/hr)
   1     1    5000    2     4000    120    0
   2     1    2500    1     4000    120    0
   3     1    6500    1     2000    120    0
   4     1    2500    1     2000    120    0

//Nodes
;nodenr type nIn  links      nOut  links     AllowedTurns
  1              1    0           1    1
  2              0    1   1       2    2 3
  3              2    2   3 4     0
  4              0    1   2       1    4

//Origins
;nrOrigins nodenrs
   1      1

//Destinations
;nrDestinations nodenrs
    1         3

//OD table
;origin destination nRoutes Routenrs.   timeperiod 1 - timeperiod n
  1     3        2      1 2      3000 3000 3000 3000 3000 3000 3000 3000 3000 3000 3000 3000 3000

//Routes
;Routenr nrLinksRoute Links
   1      3       1  2 4
   2      2       1  3

//UserClasses
;userclass percentage teta
   1      50       0.0
   2       0       2.0
   3       0      10.0
   4      50      10.0

//UserClassTP
;userclass time penalty (% of travel time)
   1      0.0
   2      0.0
   3      0.0
   4     25.0    (is varied in different tests)

//SelectedLinks
;selected links  perc change
   1                  0
   2                  0
```

C. Parameters of the Milan ring network

```
//Title
Simulation Parameters

//General
;Assign Optimization Metering SmoothG SmoothFlow DelayType InitialFlow ThresFlow ConvError minCounter maxCounter
   2         0           0        0         1          0          0          1         1          5          30

//Assignment
;  rho   beta gamma Kirchhoff initialAssign mobscan
   10     1     2       0          1          0

//AntControl
;nrAssign nRTperiods optCriterium LTimeStepOpt
    1          1           1           60

//VehPar
;VehLen TruckV minV1 minV2 Ja1 Ja2 Ja3 Ja4 Ja5 Ja6 Ja7 Ja8 Ja9
   7.5     80    10     10   85  75  60  50  40  20  15  10  10

//EventSimPar
;EventType EventSimAssign EventSimNrIter
     0            0             0

//TollPar
;TollType ValTime1 ValTime2 ValTime3 ValTime4
    0        0        0        0        0

//TimePenaltyPar
;TimePenaltyType IC-threshold PenaltyNrIter
        1            95            20

//LocalControl
;LContrMethod LOptPeriod
      1           1

//Routes
;nrRoutes nrRand scaleFac linkCost linkEqual junctionDelay ODdist
     8       50   1.660000     1       0.60         1           0

//PlotPar
;MFDplot MFDperiod ContourPlot StartTime FlowPlot SpeedPlot ControlPlot TravTimPlot
    0         0          0       0.000000     0        0          0           0

//Output
;outputflag BinaryOutput
      2          1
```

D. Comprehensive description model choice

This appendix describes the process of model choice for this research comprehensive in addition to paragraph 4.1. First, an overview of existing model types is given with a brief explanation. In the second subsection, the usefulness of the model types is researched based on what the model type is capable of and what it can predict. The resulting model types are ranked based on computational time and data requirements. This led to a chosen model type of which an overview of available simulation packages is given in the next subsection. This list will be further scoped to the most promising packages, the availability of those software packages is checked at the DiTTlab, a software package is chosen and it ends with the selection of the network in the software package.

D.1) Overview of the existing type of models

There are three main types of traffic flow models which all relate to the fundamental relation (or fundamental diagram) (van Wageningen-Kessels, van Lint, Vuik, & Hoogendoorn, 2015). These types are micro-, meso- and macroscopic-model. The model categories have their level of aggregation with the macroscopic model as the most aggregated and the microscopic the less aggregated. Next to these three types, others specified additional model types like the demand models and the data-driven models and made a distinction between static and dynamic macroscopic models (Calvert, Minderhoud, Taale, Wilmink, & Knoop, 2015). Below all these types of models are shortly introduced.

- **Demand models**
  Demand models derive the demand for transportation on the demand for activities (Ben-Akivai, Bowman, & Gopinath, 1996). In most cases, this kind of model is part of the four-step urban transportation planning modelling approach (Calvert, Minderhoud, Taale, Wilmink, & Knoop, 2015).
- **Macroscopic models** (static and dynamic)
  The macroscopic model represents the traffic flow in the aggregated measured terms flow, speed and density (Azlan & Rohani, 2018; Barcelo, 2010). The difference between static and dynamic models is that the dynamic models consider time dynamics (Calvert, Minderhoud, Taale, Wilmink, & Knoop, 2015).
- **Mesoscopic models**
  Mesoscopic models simplify the dynamics of individual vehicles, compared with microscopic models, for computational benefits. Mesoscopic models are categorised in between micro- and macroscopic models because of their aggregation level (van Wageningen-Kessels, van Lint, Vuik, & Hoogendoorn, 2015). There are two types of mesoscopic models. The first group simplifies the model by grouping vehicles to describes the analysed transportation elements and the second group simplifies the dynamics of individual vehicles (Azlan & Rohani, 2018; Barcelo, 2010).
- **Microscopic models**
  Microscopic modelling is based on the characteristics of various vehicle movements. The driver behaviour plays a more prominent part in these models (Calvert, Minderhoud, Taale, Wilmink, & Knoop, 2015; Barcelo, 2010). There are three types of microsimulation models. These are the car-following model, the lane changing models and gaps of the individual drivers (Azlan & Rohani, 2018).
- **Data-driven models**
  Data-driven models are models that use data to predict short term traffic states (Vlahogianni, Karlaftis, & Golias, 2014). This type of model is often used by route-planner websites and some satellite navigation systems (Calvert, Minderhoud, Taale, Wilmink, & Knoop, 2015).

D.2) Selection of useful model types

As described in the previous subsections, five types of models are available. In this subsection, all model types are filtered on the needed model capabilities and predictions. Based on computational time, the requirements of data and the possibilities for larger network sizes, the remaining model types are ranked. This result in the chosen model type for this research.

What should the model be capable of?

The model should be able to reallocate traffic based on different algorithms. This led to different route choices for vehicles that the model has to process. The trip/destination and departure time is data input and has not to be determined by the model. There is no mode choice to be made because only road traffic is considered during this study. The speed of vehicles in the network will be monitored. However, differences in speed choice of vehicles on the same route are not important and would be averaged out. Lane choice and headway choice are on a high level of detail and could lead to variations in the capacity of a road. Because these phenomena are not included in the scope of this study, this would lead to unnecessarily longer computation times. Table 19 shows all types of models with the behavioural choices they are able to deal with. The route choice is highlighted because this is what the model should do. This means that the demand model is discarded.

Table 19 Types of models and behavioural choices they are able to deal with (Calvert, Minderhoud, Taale, Wilmink, & Knoop, 2015)

	Trip / destination	Mode of travel	Departure time	Route choice	Speed choice	Lane choice	Headway choice
Demand model	x	x	x	-	-	-	-
Macro-model (static)	-	-	x	x	-	-	-
Macro-model (dynamic)	-	-	x/-	x	x	-	-
Meso-model	-	-	-	x	x	x/-	-
Micro-model	-	-	-	x	x	x	x
Data-driven model	x	x	x	x	-	-	-

What should the model predict?

Paragraph 2.4.5 gave a summary of the KPIs that the model should be able to predict. These KPIs are travel time, travel speed and intensity/density ratios. Because only road traffic is considered, there is no need to determine the modal split. Also, the lane distribution is not important, because only the full capacity of the road is of interest. What is left are the route proportions, travel time/average speed and volumes. The route proportion might be useful to determine the impact per sub-group, the travel time/average speed is a specified indicator and the volumes will be used to determine the intensity/density ratio of different roads. Table 20 shows the variables that the different model types can predict. This shows that the static macro-model is less suitable and that the data-driven model is not useful because that model cannot determine the route proportions and the most important variables of travel time and speed are not in the strength of this type of model. This means that the dynamic macro-model, the meso-model and the micro-model are useful for this study.

Table 20 Types of models and traffic flow variables that can be predicted (Calvert, Minderhoud, Taale, Wilmink, & Knoop, 2015)

	Modal split	Route proportions	Travel time / average speed	Lane distribution	Volumes
Demand model	x	-	-	-	-
Macro-model (static)	-	x/-	x/-	-	x
Macro-model (dynamic)	-	x/-	X	-	x
Meso-model	-	x/-	X	x/-	x
Micro-model	-	x/-	X	x	x
Data-driven model	-	-	x/-	x/-	x/-

Computation times and data requirements

Three of the six model categories are useful for the simulation task. These categories are the dynamic macro-model, the meso-model and the micro-model. However, not every type of model is appropriate for this simulation task because of the differences in computation time and the amount of needed data. More detailed models like micro-models need more data as input, are stochastic and have longer computation times in comparison with less detailed models like the macroscopic models (Wegener, 2011). Wegener shows that in larger networks with many alternatives the number of choices should be extremely large to reduce the standard error of the computation. This makes microscopic models less suitable for simulations with many alternatives like network studies. Macroscopic models are in most cases not stochastic (Khoshyaran & Lebacque, 2009). This means that a single run of a scenario would be enough because every run lead to the same results. This means that the computational time with a macroscopic model is limited. Table 11 shows that for this study, four main scenarios with each eleven sub scenarios must be simulated. With the expected size of the network to make route choice relevant, it can be expected that a micro-simulation model would take too much computational time. Because there is no specified need for detailed and stochastic driver behaviour, there is no need to simplify the micro-model to a meso-model. For this reason, a dynamic macroscopic model is chosen for this research. A summary of the ranking information of relevant model types is presented in Table 21.

Table 21 The ranking information of relevant model types

	Network size	Stochastic	Input data	Computation time
Macro-model (dynamic)	Suits in particular larger networks	In most cases not	Mainly origin-destination	Fastest
Meso-model	Suits all sizes	Has stochastic variation	Depends on simplifications	In between
Micro-model	Suits in particular small models	Large stochastic variation	Up to socio-economic data	Longest

D.3) Overview of relevant simulation packages

Based on four studies that gave an overview of available software packages for traffic simulation, a list of software packages is made (Calvert, Minderhoud, Taale, Wilmink, & Knoop, 2015; Kotusevski & Hawick, 2009; Ratrout & Rahman, 2008; Ejercito, Nebrija, Feria, & Lara-Figueroa, 2017). This resulted in a list of 25 software packages. A full elaboration of all these software packages would be undoable. To reduce the amount of work, software packages that are not satisfactory are not further explained and only the reason why is given. Promising packages will be explained in more detail and based on this information a selection is made to check availability at the DiTTlab.

OmniTRANS StreamLine

OmniTRANS Streamline is an additional module to the commercial package OmniTRANS to upgrade the static macroscopic model to a dynamic macroscopic model (Dat.mobility, 2021). Even though it is a commercial package, it claims to have a flexible and modular framework that allows users to add or replace algorithms. The main attributes of OmniTRANS are that it is multimodal and have a flexible architecture.

MARPLE

MARPLE is a dynamic traffic assignment (DTA) package that stands for Model for Assignment and Regional Policy Evaluation. It is a macroscopic dynamic allocation model that can be used to determine the effects of traffic management measures in regional networks (TrafficQuest, 2021). The main attribute is that it works with different user classes which allow giving different properties to different groups of road users.

DynusT

DynusT is a widely used simulation-based DTA model and stands for Dynamic Urban Systems for Transportation (DynusT, 2021). Engineers or planners can use the software to assess the impacts of intelligent transportation system technologies, such as dynamic message signs, ramp meters, and in-vehicle guidance systems. The purpose of this software package is in line with the goal of this research, however, it is not known if it is possible to implement other algorithms like those for compliance. This software originated at a university but is now commercialised.

INDY

INDY is a DTA package that stands for Interactive Dynamic assignment model. It is a route-based analytical multiclass dynamic traffic assignment model (Bliemer, Versteegt, & Castenmiller, 2004). The focus of this software package is on large scale networks where it aims to reduce computation time. INDY seems to be a suitable package for this research, however, there is not much recent literature available about this software package and it seems that it has no website and it is already offline.

PTV Visum

Visum is the macroscopic travel-demand modelling software of PTV. It is a full commercial package that has all functionalities for consultancies (PTVgroup, 2021). The software is comprehensive, however, because of the commercial background, it is not possible to change the software to implement algorithms that do not exist in the program.

Aimsun

Aimsun is a software package that includes all types of models. It is a commercial program with a user-friendly user face. Because it is comprehensive for consultancies it is not possible to change all pre-programmed codes. This makes it less suitable for this specific research.

Other non-relevant simulation packages

- SUMO: Microsimulation
- Simtraffic: Microsimulation
- DRACULA: Microsimulation
- TSIS/CORSIM: Microsimulation
- Paramics modeller: 3D microsimulation
- MATSim: Agent based
- TransCAD: Specialism GIS
- Synchro: Specialism intersections
- Other PTV software: Specialism divers
- EMME: Specialism multimodal urban planning
- PELOPS: Specialism longitudinal processes
- CORFLO: Specialism corridors
- MASSVAC: Specialism evacuations
- DynaMIT Specialism real-time
- INTEGRATION: No recent literature
- KRONOS: No recent literature
- KWaves: No recent literature
- DYNASMART: Website offline

Selection of software packages

Based on the research of 25 software packages, a selection of the three most promising software packages can be made. These are DynusT, MARPLE, OmniTRANS StreamLine. MARPLE is the only non-commercial package that has the advantage of a more open code. However, DynusT and OmniTRANS StreamLine are commercial and by that reason further developed. When the custom algorithm for compliance can be applied in the commercial packages, these packages have the advantages of the smooth output and a graphical user interface.

D.4) Availability and choice of software package

The availability of the selection of software packages of the previous subsection was requested from Simeon Calvert, co-director of the DiTTlab (S. Calvert, personal communication, May 7, 2021). He told that OmniTRANS Streamline is not available for the DiTTlab unless a new license would be bought. This means that this package is not available. DynusT is a software package that Simeon Calvert is not familiar with, so it is likely that the DiTTlab has no licenses and models available. This means that MARPLE is the only model left. This software package is without restrictions available on the website of TrafficQuest (TrafficQuest, 2021) and because the external supervisor for this thesis, Henk Taale, is the developer of this packages support for this package is available.

MARPLE

The most important attribute of MARPLE is that it works with user classes which makes it possible to distinguish between the routing behaviour of various subgroups. These could be the following behavioural groups from Figure 12. However, MARPLE does not provide a congestion avoiding user optimum algorithm by default and the options should be future researched. A system optimum algorithm is possible and has been done before with MARPLE (H. Taale, personal communication, May 12, 2021). However, this has never been done in combination with a user optimum user class and adjustment of the model was still needed. This has resulted in version 3.6.0. Next, MARPLE has a special attribute that allows simulating different levels of information quality. This makes it possible to make a distinction between user optimum routing without data sharing and with data sharing. This attribute of MARPLE makes it possible to review Figure 12 to add a user class for user optimum to make the distinction between the user optimum algorithm of service providers who share data and those who do not. For this reason, MARPLE is a suitable package to simulate the impact of the policy strategies.

E. Results of test network

This appendix presents the results from the test network on the highest level of detail.

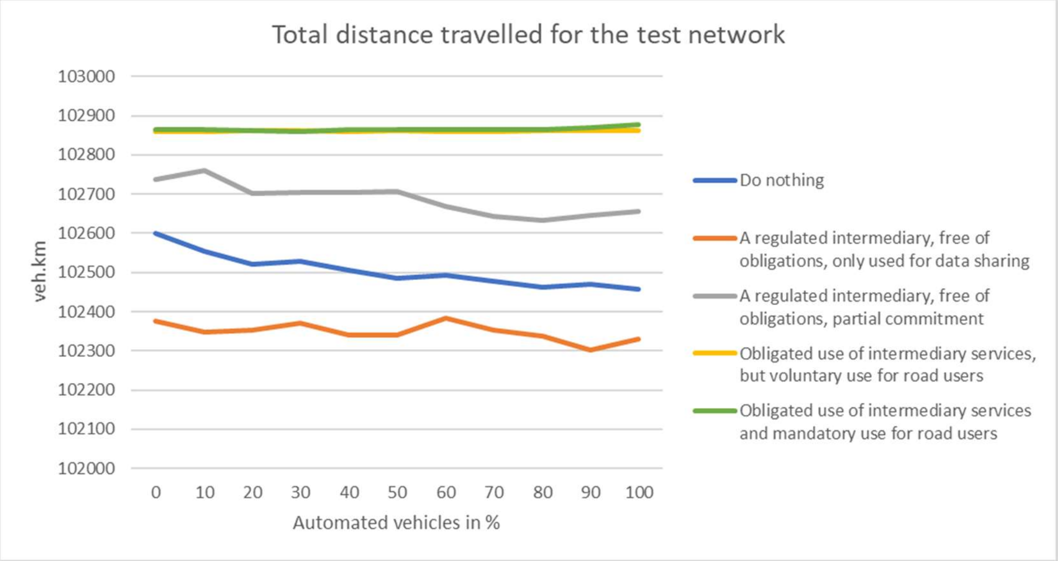

Figure 33 Total distance travelled for the test network

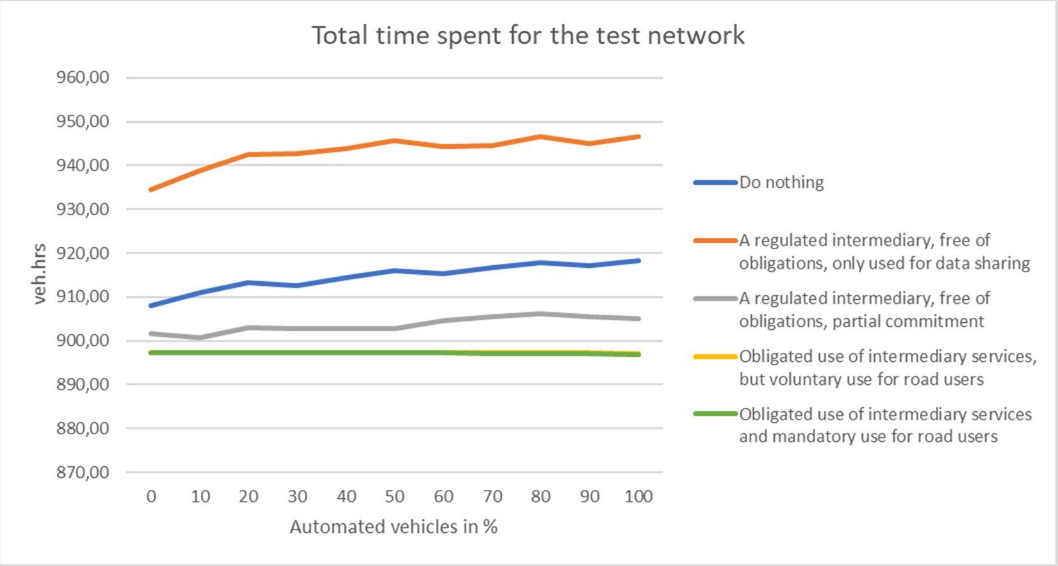

Figure 34 Total time spent for the test network

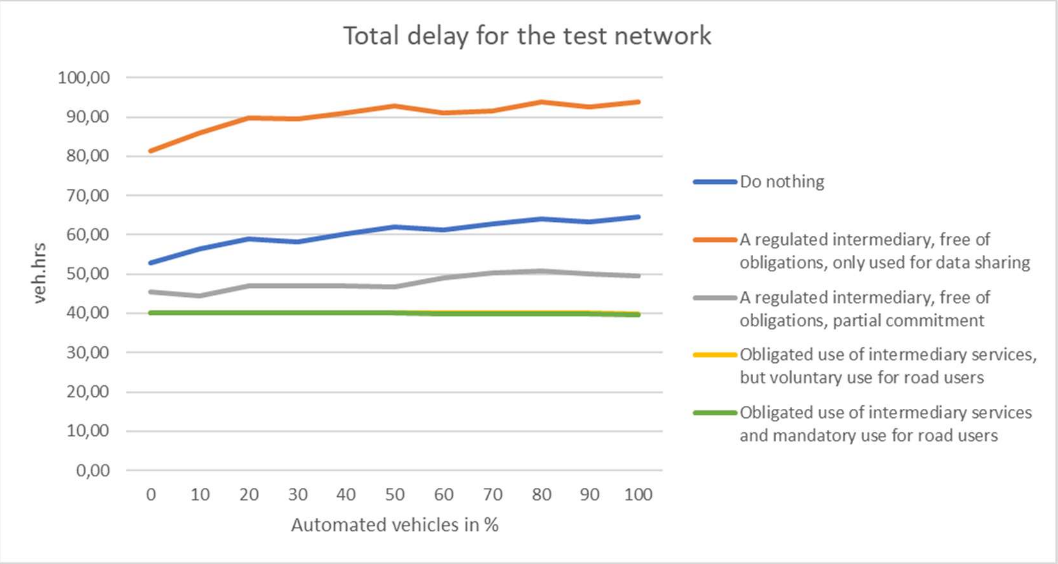

Figure 35 Total delay for the test network

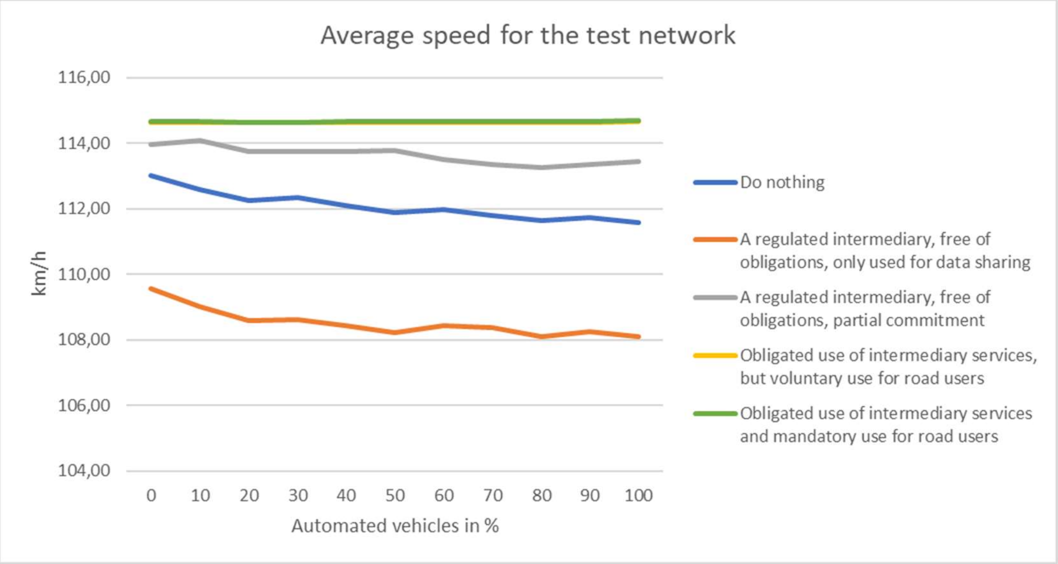

Figure 36 Average speed for the test network

F. Notations mathematical description of the model MARPLE

In paragraph 4.3 the model of MARPLE is mathematically described. To assist in reading the formulas, this Appendix gives an overview of all notations that are used. The notations and descriptions are taken from the research of Taale (2008) and are complemented with the adjustments of the time penalty.

Indices:
a : index for a link
d : index for a destination
j : index for an iteration in the assignment and for an outgoing link in the DNL model
k : index for a time period
m : index for the random drawings
o : index for an origin
r : index for a route
t : index for a time step

Sets:
A : set of links
$\mathfrak{R}^{od}$: set of feasible routes between origin o and destination d
Ω : space of feasible route flows

DTA model variables:
β : positive parameter
γ : positive parameter
c_k^{rod} : travel costs of traffic departing during time period k form origin o to destination d using route r [s]
$\hat{c}_k^{rod}$: perceived travel costs of traffic departing during time period k form origin o to destination d using route r [s]
ε^* : threshold value for the convergence error
ε_k^{rod} : random component of the travel costs of traffic departing during time period k from origin o to destination d using route r [s]
$\zeta^{(j)}$: parameter to smooth the flows for iteration j
$\Lambda^{(m)}$: matrix with elements following the standardised normal distribution $N(0,1)$
q_k^{od} : demand departing during time period k from origin o to destination d [veh/h]
θ : parameter for uncertainty in the knowledge of the travel time
ω : scaling factor
C : link cost matrix
CF_k^{rod} : commonality (overlap) factor for route r of OD pair od and time period k
$f_k^{(o)}$: initial route flow [veh/h]
f_k^{-rod} : flow rate departing during time period k from origin o to destination d using route r [veh/h]
L_r : Length of route r [m]
L_{rs} : common length of routes r and s [m]
L_s : Length of route s [m]
P_k^{rod} : probability to choose route r of OD pair od during time period k
r^{odm} : generated route for origin o and destination d with index of random drawing m
tpb_k^{rod} : a binary value to determine if the time penalty is applied for route r of OD pair od during time period k
tpp : the percentage of the time penalty

DNL model variables:

υ_a^f : free flow speed for link a [km/h]
υ_a^c : speed at congestion for link a [km/h]
k_{at} : link dependent parameter for link a at time step t
κ_{at} : queue length on link a for time step t [veh]
l_a : length of link a [m]
l^{-veh} : the average length a vehicle occupies, including space between vehicles [m]
p_a : number of lanes for link a
τ_{at} : travel time on link a at time step t [s]
$\tilde{\tau}_a$: free flow travel time for link a [s]
φ_{at} : degree of saturation on link a at time step t
u_{at} : inflow for link a at time step t [veh]
u'_{at} : restricted inflow for link a at time step t [veh]
v'_{at} : corrected outflow for link a at time step t [veh]
$\tilde{v}_{at}$: uncorrected outflow for link a at time step t [veh]
Ψ_{at} : available space on link a at time step t [veh]
χ_{at} : number of vehicles on link a at time step t [veh]
z_{at} : parameter related to the initial queue for link a at time step t
Δ_h : length of the time step in hours [h]
Q'_a : capacity at the beginning of link a for time period k [veh/h]
Q''_a : capacity at the end of link a for time period k [veh/h]