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

Bastiaan Daniël van den Burg

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.

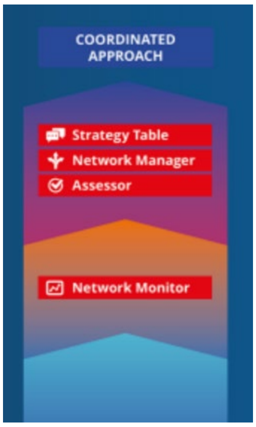

Figure 1 Coordinated approach (SOCRATES$^{2.0}$, 2020)

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.

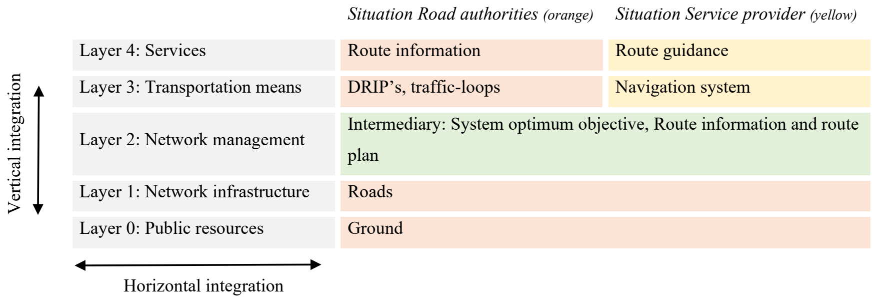

Figure 2 Segregation of Network layers vertical integrations per actor, suggested situation road network with in green the new intermediary, based on (Jaag & Trinkner, 2011)

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.

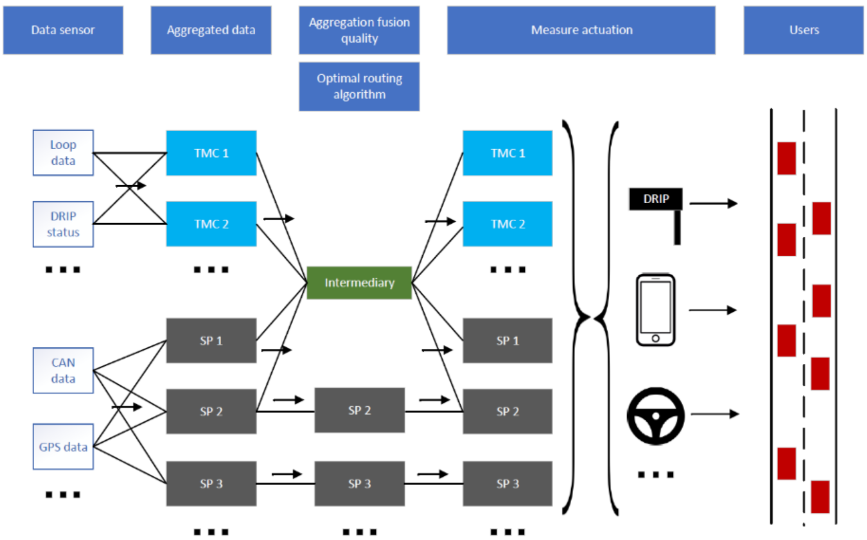

Figure 3 Interaction scheme with voluntary use of an intermediary with bypass behaviour, based on intermediary option three from proposed cooperation framework SOCRATES$^{2.0}$ (Koller-Matschke, 2018)

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 $j \coloneqq 1$.*
Step 3:	*Calculate route cost $c_k^{(j)}\left(f^{(j-1)}\right)$ 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 $j \coloneqq j+1$ 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

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

Equation 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.

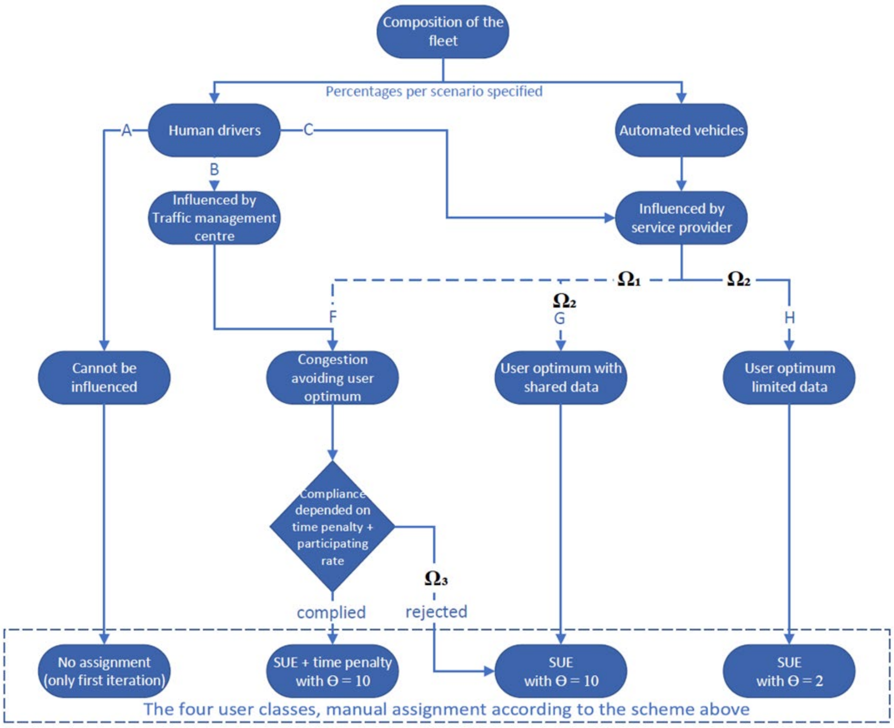

Figure 7 Scheme for assigning traffic to specific groups of routing behaviour

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 Θ = 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 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, 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

Scenario	Time penalty	user class 1	user class 2	user class 3	user class 4
1.00	10	70	20	3	7
1.01		63	28	3	6
1.02		56	36	3	5
1.03		49	44	2	5
1.04		42	52	2	4
1.05		35	60	2	3
1.06		28	68	1	3
1.07		21	76	1	2
1.08		14	84	1	1
1.09		7	92	0	1
1.10	N/A	0	100	0	0

A regulated intermediary, free of obligations, only used for data sharing

Scenario	Time penalty	user class 1	user class 2	user class 3	user class 4
2.00	10	70	0	23	7
2.01		63	0	31	6
2.02		56	0	39	5
2.03		49	0	46	5
2.04		42	0	54	4
2.05		35	0	62	3
2.06		28	0	69	3
2.07		21	0	77	2
2.08		14	0	85	1
2.09		7	0	92	1
2.10	N/A	0	0	100	0

A regulated intermediary, free of obligations, partial commitment

Scenario	Time penalty	user class 1	user class 2	user class 3	user class 4
3.00	10	70	5	12	13
3.01		63	7	15	15
3.02		56	9	18	17
3.03		49	11	21	19
3.04	15	42	13	26	19
3.05		35	15	29	21
3.06		28	17	33	22
3.07		21	19	36	24
3.08		14	21	39	26
3.09		7	23	42	28
3.10		0	25	45	30

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

Scenario	Time penalty	user class 1	user class 2	user class 3	user class 4
4.00	15	70	0	12	18
4.01		63	0	15	22
4.02		56	0	18	26
4.03		49	0	21	30
4.04		42	0	24	34
4.05		35	0	27	38
4.06		28	0	29	43
4.07		21	0	32	47
4.08		14	0	35	51
4.09		7	0	38	55
4.10		0	0	41	59

Obligated use of intermediary services and mandatory use for road users

Scenario	Time penalty	user class 1	user class 2	user class 3	user class 4
5.00	25	70	0	0	30
5.01		63	0	0	37
5.02		56	0	0	44
5.03		49	0	0	51
5.04		42	0	0	58
5.05		35	0	0	65
5.06		28	0	0	72
5.07		21	0	0	79
5.08		14	0	0	86
5.09		7	0	0	93
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

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.

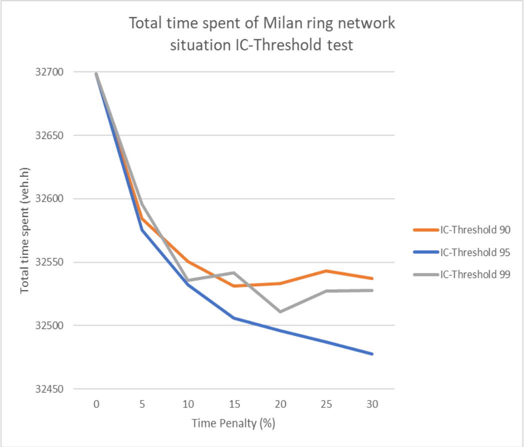

Figure 8 IC-Threshold test Milan ring network

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 %

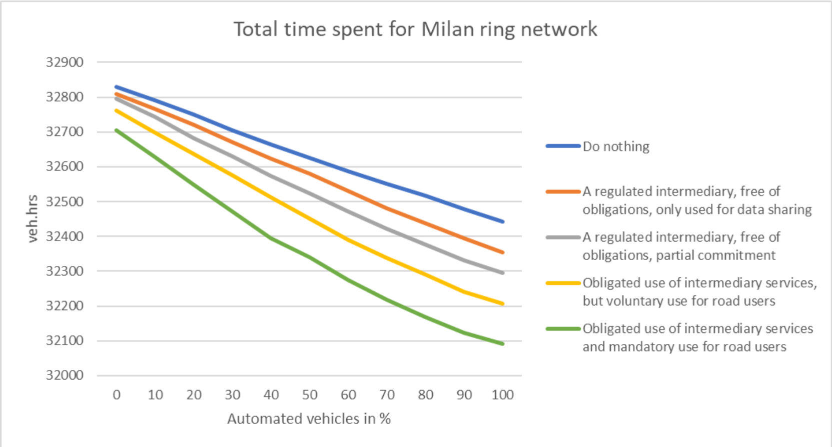

Figure 9 Total time spent for Milan ring network

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.

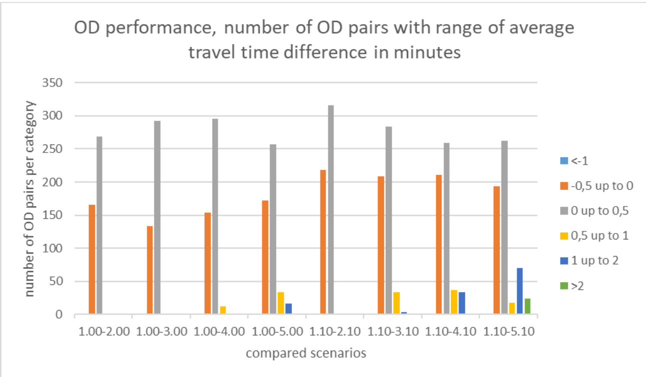

Figure 12 Amount of OD pairs with travel time changes on average

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.

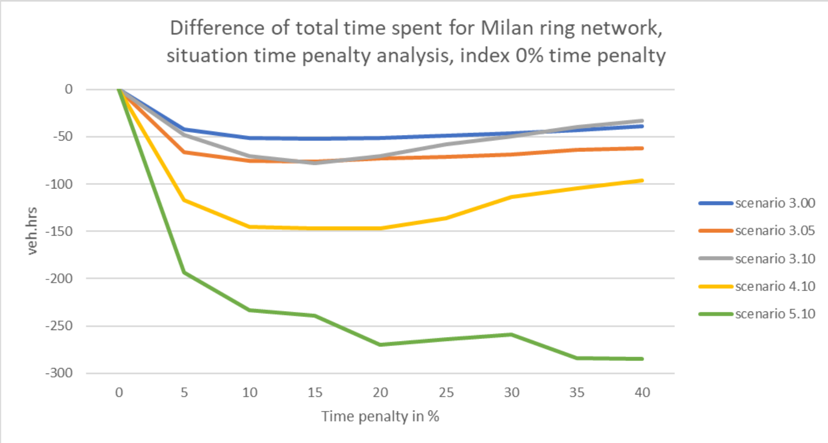

Figure 13 Relative effect of the time penalty per regulated scenario

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.

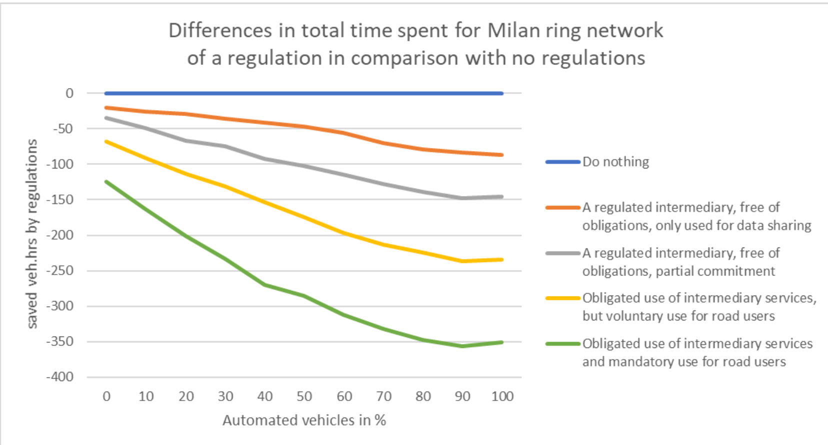

Figure 14 Differences in traffic flow performance without effect of automated vehicles

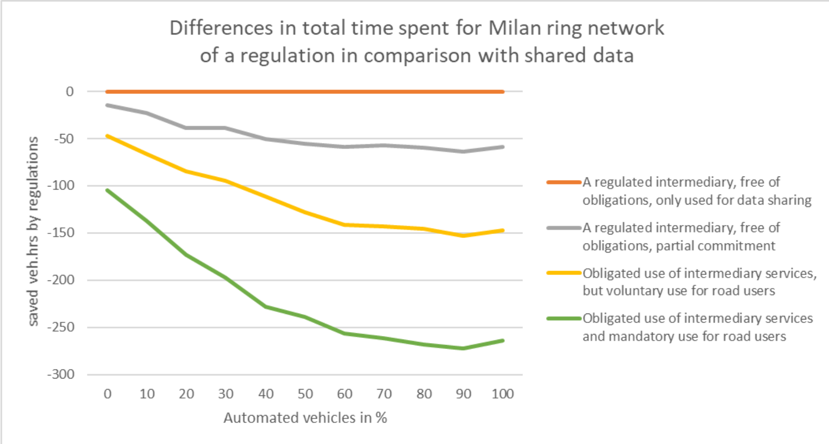

Figure 15 Differences in traffic flow performance without effect of data and automated vehicles

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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