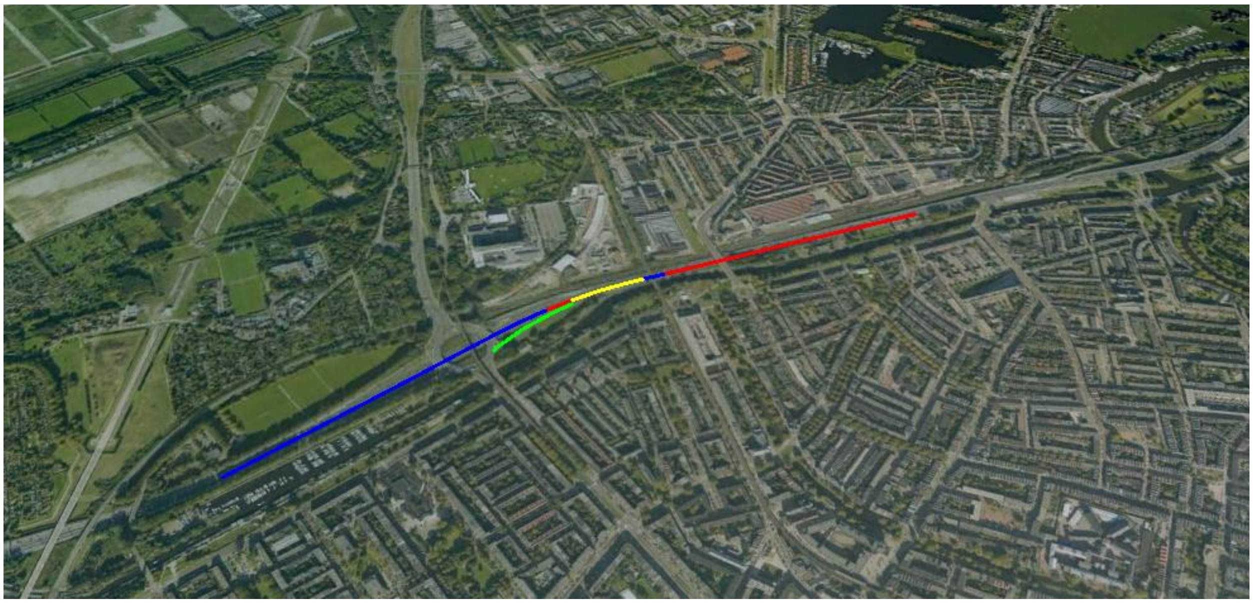
Congestion minimisation by optimising merging behaviour through Intelligent Transportation Systems



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Preface

The word engineer is derived from the word engine and its meaning is: "a person trained and skilled in the design, construction and use of engines or machines or in any of various branches of engineering". Those engines are constructed to make life easier and simpler. Sometimes, they create needs that people never thought they would ever have. Engines do not refer only to solid machines, but also to software and programmes, designed for the solution of everyday problems.

The engine being designed and tested by simulation in this project belongs to the last category. It is a code being created and examined in order to relieve the highways from congestions created at on-ramps. Although the stage is very primary, it can be possibly proven to be a useful tool for future and more detailed research.

At this point, I would like to thank all the people that contributed, more or less, to the completion of this project. First, I would like to thank Prof.Dr.ir Bart van Arem, Dr.ir. Joost de Winter and Drs. Tom Alkim for their useful and always well-intentioned advice and feedback during our meetings. However, among my thesis committee, I would mostly like to thank my daily supervisor, Dr. ir. Wouter Schakel, without whom this thesis would not be the same. His feedback at a weekly basis, his crucial assistance to the code creation, as well as his patience with all my questions played a major role in my thesis completion.

Furthermore, I would like to thank all my friends, both in the Netherlands and in Greece, for giving me courage when I felt anxious and disappointed during the thesis period. Many thanks to my partner in life, Eva and our son, Kyriakos for their patience and support during the 3 years of my studies that we spent away from each other. To end up, above all I would like to thank my parents, Dimitris and Evanthia, for their selfless sacrifices, both financial and emotional, so that I could get properly educated throughout my whole life.

Summary

Congestion is an everyday problem appearing in highways all over the world and in the Netherlands as well. Their cause is the highway demand exceeding the capacity. Especially in bottleneck locations, congestion is more easily formed. On-ramps are among these locations, where merging vehicles and highway ones want to use the same infrastructure. Merging is a sub-component of lane changing; it refers to lane changes but only regarding vehicles entering a new traffic stream. The, not always optimal, interference between merging and highway vehicles results in disturbances at the merging location leading to congestions upstream. Therefore, this is the problem requiring a solution.

The objective of this research is to define which Intelligent Transportation Systems (ITS) are the most suitable for our problem and what their performance will be. Thus, the research question is:

How can the implementation of ITS on highways improve congestion being created at on-ramps?

The sub-research questions are:

- How is congestion currently formed at the on-ramp?
- What measures could be taken to improve the current situation?
- Which ITS are the most appropriate for the problem?
- How can the ITS effects be modelled?
- What are the results obtained after the analysis?

One of the main components of merging is the gap acceptance theory, i.e. the assessment of a provided gap by a merging driver and its acceptance or rejection. After the literature review, the deduction is that much emphasis should be given on this theory. The highway drivers should cooperate and create a gap with the proper length and at the right time so that the merging driver will need less time to assess it and will preferably accept it. In order to make that even more efficient, it is suggested that the merging driver knows upstream of the merging point when and between which vehicles the lane change should be executed. In that way, the driver can be better prepared for the following lane change.

The research is not only theoretical, but mainly practical; an actual on-ramp is examined with data (flows and speeds per minute) obtained from Rijkswaterstaat. The examination site is an on-ramp located on the A20 highway, north of Rotterdam. The road segment has a length of 1.7 km, since it includes the on-ramp and small segments upstream and downstream.

The method with which the ITS performance will be examined is simulation and the programme that will be used is MOTUS. The main advantage of MOTUS is that, since it is developed in Java, it offers the capability of expanding the already existing classes and incorporating new features.

The first step is the design of the examination site. The site is divided in smaller segments. Each segment is divided from its previous and next ones when their characteristics differ, e.g. number of lanes. The site is first designed in Google Earth and then incorporated in MOTUS.

MOTUS consists of two models: the longitudinal (car-following) and the lateral (lane changing). The parameters used in the simulation are divided according to these two models and based on the Lane Change Model with Relaxation and Synchronisation (LMRS). The basic component of LMRS is lane change

desire. However, at a smaller extent it incorporates car following, which is described by the adapted version of the Intelligent Driver Model (IDM+).

In the second step the parameters are calibrated in order for the simulated data to have a good fit with the real data. The calibration did not give a perfect fit. For example, congestion in reality begins at the end of the acceleration lane, while in simulation it begins at the merging point. On the other hand, there is a positive side too. First, the right lane is both in simulation and in reality more congested than the other two lanes. Second, at the merging point, which is a very crucial location, the speeds and flows in simulation have a very good fit with reality.

The next step is the definition of the applied manoeuvres by the drivers. These are the following two:

1) courtesy yielding by reducing speed
2) lane changing towards the left

The aforementioned measures will be applied with the contribution of the merging assistant. This assistant consists of two components:

1) a roadside unit (RSU) located at the merging point. The RSU detects the traffic characteristics at the highway lanes and the on-ramp, processes them and then transmits advice to all drivers
2) Adaptive Cruise Control (ACC) equipped vehicles. A defined percentage of vehicles is ACC-equipped. In those vehicles, drivers can apply the desired (or advised) headway and the ACC will maintain it until the order changes. The instructions transmitted to ACC-equipped vehicles will differ from the ones transmitted to manual vehicles.

Since the applied manoeuvres and ITS are defined, the next step is to decide how the system will work. Its function is described in the next steps:

- The RSU checks the flow at the merging point and on the right lane. When the flow at the right lane exceeds a predefined flow threshold q_{th} for N_{enable} consecutive minutes, the system is activated.
- Next, the RSU detects the next on-ramp vehicle that will reach the merging point. When the vehicle is detected, the RSU calculates which right-lane vehicles will need to either accelerate/decelerate or change lanes. In the latter case, the RSU calculates which middle-lane vehicles will need to perform the same manoeuvres. If a middle lane vehicle has to change lane to the left, the left lane vehicles can only accelerate or decelerate.
- When the right lane flow becomes lower than q_{th} for $N_{disable}$ consecutive minutes, the system is deactivated.

The next step is the simulation beginning. From the obtained data, two days are chosen both during the morning peak (07:00-10:00); 27/10/2015 and 27/11/2015. In order to define the performance of the ITS, three measures of effectiveness are used. These measures are:

- Average travel time
- Average delay
- Vehicle-kilometres travelled

These measures of effectiveness are observed when the different scenarios are run. Those scenarios are the following:

1) Only-controller scenario: during this scenario all vehicles are manual, thus the ACC penetration rate (pACC) is set to 0%. The RSU performs as mentioned above. First, different q_{th} are tested and the most effective is picked. Then, with the chosen q_{th}, different longitudinal and lateral driver compliance rates are tested (comp, lccomp). For simplicity reasons, these rates always have the same values. Exactly like before, the most effective values are chosen.
2) Only-ACC scenario: during this scenario the RSU is never active, therefore q_{th} and (lc)comp are ignored. Different pACC are tested and the most effective is defined.
3) Combination of the above scenarios: during this scenario, only one simulation run is made where both ITS are used and q_{th}, (lc)comp and pACC have the aforementioned values.

On 27/10/2015, on the first scenario there were two different q_{th} with very similar performances, therefore two (lc)comp were found as well. On the contrary, only one pACC value was more effective than the others. The five different scenarios and their performances are shown in the table below.

Scenario	(lc)comp (%)	q_{th} (veh/h)	pACC (%)	Avg. TT change (%)	Delay change (%)	Vehicle-kilometres change (%)
Base case	-	-	-	0	0	0
Only-ACC	-	-	70	-12.3	-35	+5.7
Only-RSU (1)	80	800	-	-2.8	-7.8	+0.7
Only-RSU (2)	50	1200	-	-3.3	-9	+0.8
Combined (1)	80	800	70	-7.7	-22	+3.3
Combined (1)	50	1200	70	-9.1	-25.9	+4.1

The same procedure was made for 27/11/2015. Here, however, only one value per variable was chosen, thus the outcome was three scenarios.

Scenario	(lc)comp (%)	q_{th} (veh/h)	pACC (%)	Avg. TT change (%)	Delay change (%)	Vehicle-kilometres change (%)
Base case	-	-	-	0	0	0
Only-ACC	-	-	40	-4.5	-18.3	+2.7
Only-RSU	80	1200	-	-19.5	-72.6	+2.3
Combined	80	1200	40	-7	-27.5	+2.4

It should be mentioned that on the first day (27/10/2015) the initial delays were a lot higher than in the second one (27/11/2015). Therefore, from the analysis a noteworthy outcome is deduced; when the initial delays are higher, ACC alone outperforms both the RSU alone and the combined scenario. On the contrary, with low initial delays the RSU alone has an outstanding performance, with the delays being almost ¾ reduced. Although when drivers change lanes themselves they can cause congestions, the way the controller imposes lane changes in light congestions result in very positive outcomes.

Despite the positive outcomes of the proposed system, there are still certain aspects that could be improved. For example, it would be better if more days were tested so that the sample would be more robust give more certain results. Furthermore, certain assumptions (e.g. trucks remaining on the right lane) were initially made. These assumptions could be excluded in future research. The last recommendation refers to human behaviour. This is a factor that can never be defined with 100% precision. Even the compliance rate is a very general variable, since a driver may comply with certain instructions, but not all of them. The way to tackle this problem is the maximisation of tests with different input every time in order to obtain results as robust as possible.

Table of Contents

1. Introduction

1.1 General information

Congestion is one of the most common problems taking place in highways, not only in the Netherlands, but worldwide. Among others, merging locations play an important role in this problem. Therefore, dealing with merging, by proposing ways to make the merging process more effective and with fewer disruptions, could result in many highway congestions being alleviated and, perhaps, even disappearing.

At the moment lane changing (part of which is merging) is not a technologically automated procedure. On the contrary, it comes as a result of individual drivers' behaviour. Some steps are made so as to add some automation on this procedure and make it easier and safer.

Lane changing is not just the lane change itself but begins earlier and finishes later than that. First a driver decides whether he/she should change lane and, if it is decided, the lane change is first prepared and then executed. In the target lane, both the vehicle that changed lane and its follower(s) need to gradually increase their headways, since after a lane change they are reduced. This procedure is called relaxation. The moment when the relaxation phase is complete the lane change procedure ends as well.

With regards to merging, drivers are divided in two categories: the ones who want to merge (mergers) and the ones who are already on the stream (mainline drivers). As a result behavioural conflicts may appear. For example the former may be willing to cooperate with the latter but not the other way around. Therefore, the way each driver thinks and moves is one of the main difficulties to be faced, not only in this case but also in other traffic situations.

The reason why merging causes disruptions and, afterwards, congestions is the fact that both mergers and mainline drivers have the desire to use the same infrastructure. In case of high traffic volume this infrastructure may not have enough capacity to accommodate all vehicles combined with free flow speed. This fact, combined with the non-optimised (not direct contact), and sometimes problematic (merge not always allowed by right-lane drivers), communication between the two aforementioned driver categories are responsible for the onset of congestion at on-ramps.

In order to optimise merging behaviour, there are technologies, both in-vehicle and infrastructural, that can be implemented. One scenario that would theoretically solve the arising problems would be the existence of fully automated vehicles. Those vehicles would be able to manoeuvre themselves, as well as communicate with each other at all circumstances with no drivers' intervention. In that case the factor "behaviour" is totally excluded. This is, however, the very last automation level (figure 1) that cannot be made feasible in the near future. Until then, there are lower automation levels (such as driver assistance) where the aforementioned technologies can be incorporated.

Summary of Levels of Driving Automation for On-Road Vehicles

This table summarizes SAE International's levels of *driving* automation for on-road vehicles. Information Report J3016 provides full definitions for these levels and for the italicized terms used therein. The levels are descriptive rather than normative and technical rather than legal. Elements indicate minimum rather than maximum capabilities for each level. "System" refers to the driver assistance system, combination of driver assistance systems, or *automated driving system*, as appropriate.

The table also shows how SAE's levels definitively correspond to those developed by the Germany Federal Highway Research Institute (BASt) and approximately correspond to those described by the US National Highway Traffic Safety Administration (NHTSA) in its "Preliminary Statement of Policy Concerning Automated Vehicles" of May 30, 2013.

Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of *dynamic driving task*	System capability (*driving modes*)	BASt level	NHTSA level
Human driver **monitors the driving environment**								
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a	Driver only	0
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes	Assisted	1
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes	Partially automated	2
Automated driving system **("system") monitors the driving environment**								
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes	Highly automated	3
4	High Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes	Fully automated	3/4
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**	-	

Figure 1 SAE International Levels of Automation

1.2 Problem Definition

As mentioned before, merging at on-ramps is one of the reasons causing the appearance of congestions. This is a traffic problem appearing in highways, the Dutch ones not being an exception. The congestion's head is usually right downstream of the acceleration lane end. When congestion is formed, it starts moving upstream, obstructing both vehicles on the highway and on the acceleration lane. The former cannot move with free flow speed anymore and the latter have difficulties in merging, since the space headways of the highway vehicles are smaller within congestions. Therefore, the problem is that congestion is formed in both the highway and the on-ramp stream and occurs due to the way merging vehicles interfere in the highway stream. The way to tackle it, is to prepare drivers in both streams for the upcoming on-ramp in such a way that they can communicate more efficiently. In that way, congestion will be harder to form. This can be achieved with the provision of ways of communication between them before they actually change lanes, as well as adequate information further upstream. This means that lane changing could be possible with fewer aligning attempts and with both entering and mainline drivers being better prepared and, thus, accelerating and braking less.

1.3 Objective and research question

The objective of the project is to identify which Intelligent Transportation Systems (ITS) could be suitable to reduce congestion resulting from on-ramps and to what extent their implementation will improve the current situation.

The research question is, therefore, the following:

How can the implementation of ITS on highways improve congestion being created at on-ramps?

The sub-research questions are:

- How is congestion currently formed at the on-ramp?
- What measures could be taken to improve the current situation?
- Which ITS are the most appropriate for the problem?
- How can the ITS effects be modelled?
- What are the results obtained after the analysis?

1.4 Scope

Prior to the methodology that will be followed, the scope of the project should be defined. In here, the boundaries of the research are explained and justified.

As it was mentioned earlier in the introduction, merging is not only the lane change of merging vehicles, but goes far beyond that. That should be taken into account regarding the ITS under examination. Therefore, just trying to improve the interaction between merging and mainline vehicles may not be enough itself. For merging to be operated, there need to be acceptable gaps between two main line vehicles on the right lane. These gaps could be created upstream of the merging point. Furthermore, merging affects the right highway lane a lot more than the two others. Therefore, in order to reduce congestion effects it would be possibly beneficial to “switch” congestion more towards the left. Thus, it is possible that drivers upstream of the merging point need guidance in order to leave the right lane and move towards the middle and left ones.

From all the aforementioned, it comes as a result that emphasis should be given to the flow upstream of the merging point. Therefore, the ITS should not necessarily focus only on the interaction between mainline and merging flow, but also on the interaction among mainline vehicles only.

ITS are divided in two categories: vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). V2V communication is ideal for neighbouring vehicles. In cases of direct interaction between vehicles, e.g. lane changing and car-following, V2V communication can assist at a high extent (e.g. CACC). However, as mentioned above, information about the mergers should be provided to the mainline vehicles before the merging point. The merging and mainline vehicles do not share the same infrastructure at all times, but all the drivers need to know well beforehand their next steps even if they are not in direct contact with each other. Therefore, since those vehicles cannot directly communicate with each other, a roadside unit (RSU), similar to the one being mentioned in Pueboobpaphan et al. [1] and Wolterink et al. [2] could be implemented, transmitting information either at variable message signs or at in-vehicle devices, e.g. GPS navigation system. It is still not certain though if one or both of these communication types will be used in the end.

Decision making regards decisions made during driving. With respect to these decisions, the ITS focus on how the driving process will be controlled. According to Michon's hierarchical model [3], there are 3 control levels that determine the driving decisions; strategic, tactical (manoeuvring) and operational (control) (Figure 2). Merging regards the driving procedure and not trip or route planning, thus the research will not focus on the strategic level. Operational level refers to actions taking place within milliseconds, such as reflexing moves executed via steering wheel or pedals. This is also not part of the research since merging is a process consisting of actions that take more time (seconds), including apart from the manoeuvres themselves a certain level of planning. Tactical level regards driving actions and rules, such as steering, braking or overtaking. Since lane changing includes actions such as accelerations and decelerations which, in turn, are composed of the aforementioned tasks, the tactical level is the main part of the research.

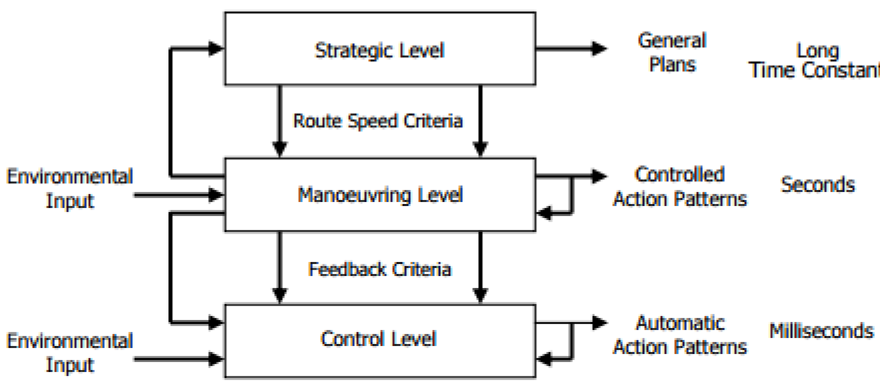


Figure 2 Michon's hierarchical control levels determining drivers' decisions

2. Literature review

2.1 General information on lane changing

In this section the lane changing process is described in more detail. A scheme, based on [4], follows, showing the lane changing process and how its steps are interconnected. The first step is to define when a lane change is desirable. Lane changes can be divided in mandatory and discretionary based on their necessity. Merging is a mandatory lane change, since this is the only manoeuvre the on-ramp traffic can do once it enters the highway. Depending on a driver's route a lane change may also be necessary. Regarding the latter category, lane changes are discretionary when there is a desire for speed increase or a specific lane preference.

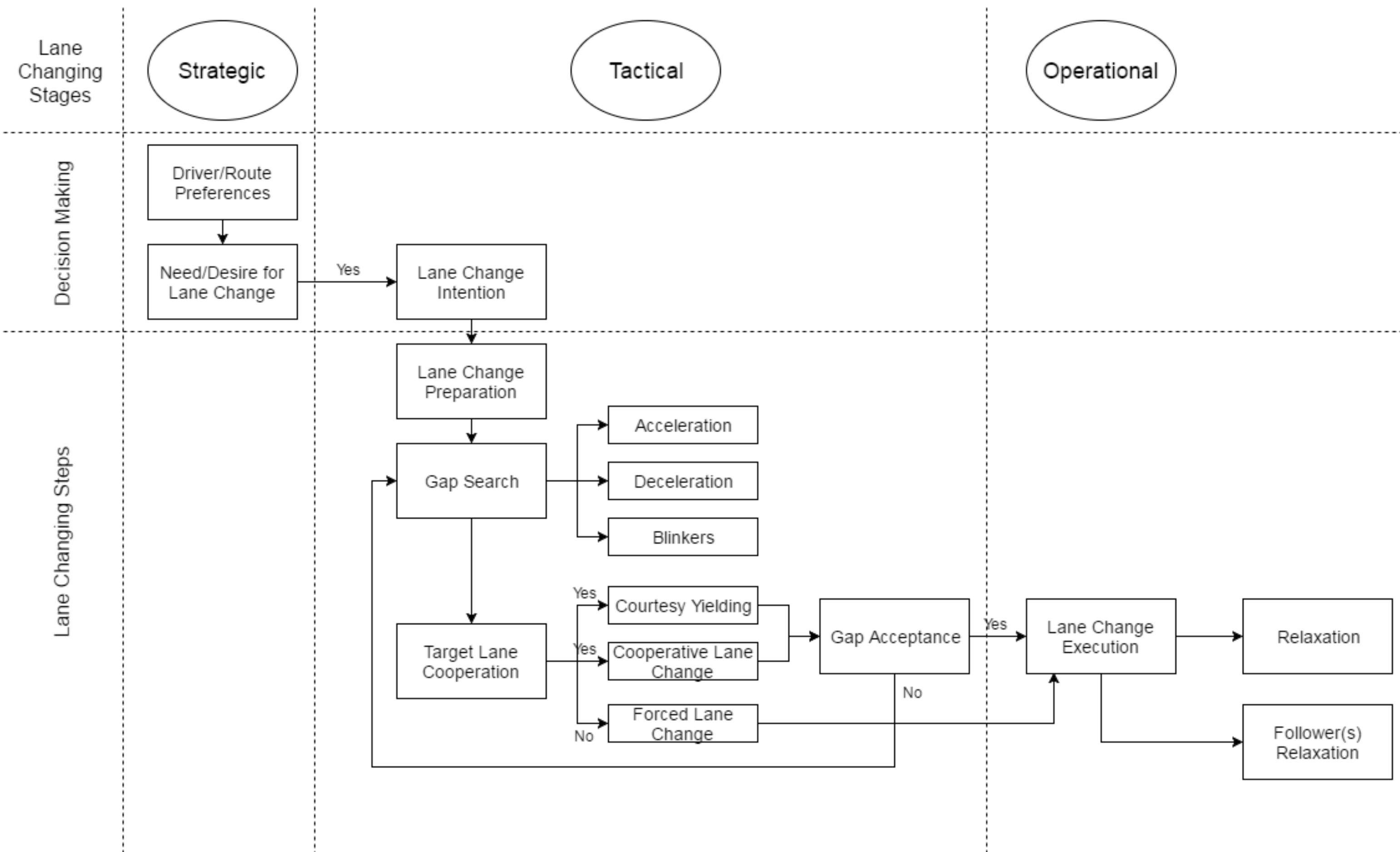


Figure 3 Lane changing preparation and execution

Lane changing is divided in three stages according to Kesting et al. [4]; strategic, tactical and operational. Those stages have general similarities with the aforementioned control levels. In the strategic phase, the driver knows his/her route and, thus makes a lane choice, taking on- and off-ramps into consideration. However, the actions included in the next two levels last more time than in the control levels' description. Especially the operational level actions last some seconds instead of milliseconds.

In the tactical step, the lane change is first intended and then prepared. The preparation is followed by a gap search made by accelerating or decelerating with sometimes simultaneous use of blinkers. A cooperation of drivers in the target lane can be made at the same time. This cooperation can include courtesy yielding (i.e. accelerating or decelerating to create a gap acceptable by the lane changing driver) or cooperative lane changing (i.e. vehicles of the target lane moving to the left in order to create more space). If the gap is accepted the driver will change lanes, otherwise he/she will search for another gap. In case the neighbouring drivers do not cooperate, the lane changing ones will probably need to force a lane change.

In the operational stage, the lane change is executed in a way based on the drivers' safety standards and desire (e.g. more aggressive or more courtesy-based). Right after the lane change is executed, there is a time during which smaller headways are accepted, gradually increasing until they reach the normal headway that is followed by the majority of drivers (relaxation phenomenon). Relaxation affects both the lane changing driver as well as his/her followers.

2.2 General information on merging

Merging manoeuvres occur only at on-ramps and, because of the instability they cause, can result in making these locations bottlenecks. These merging manoeuvres are actually mandatory lane changes made by drivers that need to enter the highway. Those lane changes are performed throughout the whole length of the acceleration lane. When there is free flow on the highway, mergers change lanes more at the beginning of the acceleration lane while in congested highways merging is more distributed along it [5].

The necessity of merges is the actual reason why they are divided from lane changes in general. In Figure 3, in the strategic level it is shown that prior to a lane change a need or a desire is present. The reason why merges are differentiated is the fact that due to this necessity a higher percentage of forced lane changes are possible to occur. Thus, the necessity of these lane changes results in the necessity of them being performed in a smoother way.

One of the most important components of merging is gap acceptance. The gap acceptance theory refers to the fact that a driver assesses a gap (distance or time between two vehicles on the main road). During this assessment, the gap is compared to the critical gap; if the offered gap is larger than the critical gap, it will be accepted, otherwise it is rejected and the driver will move towards another one, either by decelerating or by accelerating. The critical gap is not always the same and differs per driver, vehicle and road [6]. This is the reason why the gap acceptance theory regards both the accepted and rejected gaps as well.

During the merging manoeuvre there are three vehicles participating: the merger, the leader and the follower. According to Hidas [7], based on the gap between the leader and the follower, there are three types of lane changes: free, forced and cooperative. In the first, there is no change in the gap between the leader and the follower when the lane change is prepared. In the second, the gap is either constant or narrowing before the merger's entrance and increases after it, meaning that the follower has (was forced) to brake to allow the new vehicle to merge. In the third, the gap increases before the entrance and decreases afterwards, meaning that the follower slows down to allow the new vehicle to merge.

The merging process (focusing however on lane change only and not in the steps before and after it), including gap acceptance theory, is shown in the figure below. M, F and L are the merger, follower and leader respectively.

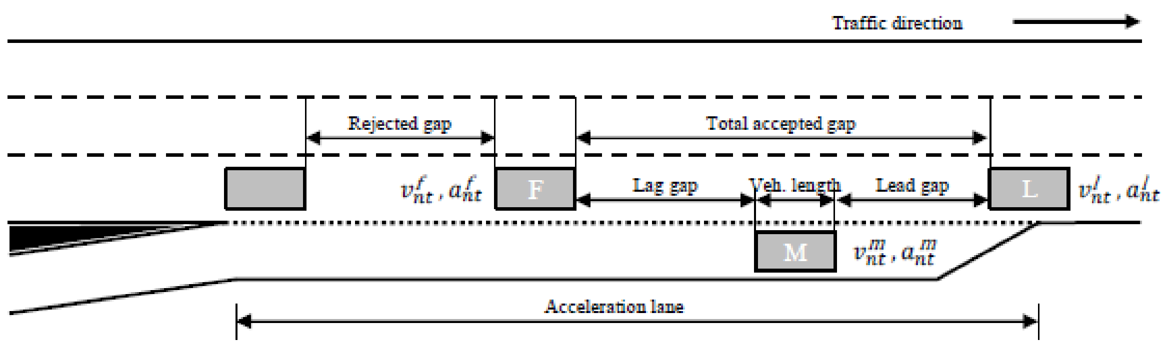


Figure 4 Lane changing process and gap acceptance theory [6]

It can be easily deducted that for the merging procedure to be executed in an optimal way, the three categories of vehicles (merger, follower and leader) should properly communicate in order to cause fewer disturbances with their manoeuvres. However, since merging is not a fully automated procedure, the drivers' individual behaviours should be taken into account. The fact that they can never be totally predictable is a problem that needs to be tackled.

2.3 Research on congestion minimisation at on-ramps

Some research has been made regarding congestion at on-ramps. In Pueboobpaphan et al. [1], it is mentioned how on mixed highway traffic conditions (traffic at the on-ramp is only manual), communication at on-ramps can assist the merging procedure and improve traffic stability by reducing conflicts and speed changes. This merging assistant (MA) is provided to Cooperative Adaptive Cruise Control (CACC) equipped vehicles (being transformed in Adaptive Cruise Control (ACC) when the predecessor of a CACC vehicle is manual) in the form of a roadside unit (RSU).

The RSU detects the on-ramp vehicles and calculates when they will reach the acceleration lane. When the mainline CACC vehicles enter the RSU range this information is transmitted to them. First, it must be ensured that the mainline vehicle will stay outside the safety zone of the ramp vehicle. For this reason, the necessary acceleration rate, in order for the mainline vehicle to be outside the safety zone, will be calculated. Afterwards, it will be compared to a comfortable deceleration rate and the acceleration rate that it already has, and the most restricted one among them will be chosen.

The CACC penetration rates were set to 0%, 50% and 100%, the highway demands was set to 1500 veh/h and 1800 veh/h, the on-ramp demand was 500 veh/h and the merging assistant was either included or not (in the 0% CACC penetration level there is no merging assistant). Also the simulation period was 25 minutes. The simulation outcomes are shown in the table below. The indicators are vehicle-kilometers travelled, average travel time and number of collisions (if deceleration does not exceed a certain threshold, CACC mainline vehicles do not cooperate with merging vehicles and it is possible that a collision can occur, taking into account that merging drivers become more aggressive as they reach the end of the acceleration lane).

Table 1 Outcomes of CACC and merging assistant simulation experiment [1]

Demand (veh/hr)	Cases (%CACC, with or without MA)	VKT (veh-km)	Avg. TT (min)	number of collision
1500	0% (manual)	1389	4.54	3
	50%, with MA	2068	1.89	3
	50%, without MA	2018	1.93	2
	100%, with MA	2045	1.81	13
	100%, without MA	2050	1.81	13
1800	0% (manual)	924	7.54	0
	50%, with MA	2035	3.92	1
	50%, without MA	1993	3.95	3
	100%, with MA	2402	1.85	12
	100%, without MA	2391	1.86	17

As it can be observed, the values of vehicle-kilometres travelled (VKT) and average travel time (TT) are respectively a lot lower and higher in 100% manual vehicles than in vehicles equipped with CACC. In 1500 veh/h demand, there are small differences in VKL and TT but large ones in number of collisions. In 1800 veh/h, VKT are higher in 100% CACC penetration rate and TT is half of the 50% CACC rate. Nevertheless, the collisions are still a lot higher. The most remarkable feature, however, is the fact that the merging assistant is responsible only for very minor differences in the same penetration levels. Therefore, CACC is the main factor that accounts for better performance. The reason is that the gap creation can be performed faster and with higher precision due to the communication between the right-lane leaders and followers.

Also in van Arem et al. [8], it is investigated what the impacts of CACC-equipped vehicles on traffic flow characteristics are in a highway merging scenario from 4 to 3 lanes (this is a lane drop and not an on-ramp though).

During the simulation, the equipped vehicles turn off the CACC when they change lanes and turn it back on afterwards. An addition is some cases, where a special lane is used only by CACC vehicles in order to evaluate whether the flow characteristics can be further improved. CACC drivers do not necessarily move towards the CACC lanes, however when they are there, they will not leave it. The simulation setup is better shown in the figure below (the CACC lanes are coloured in dark grey).

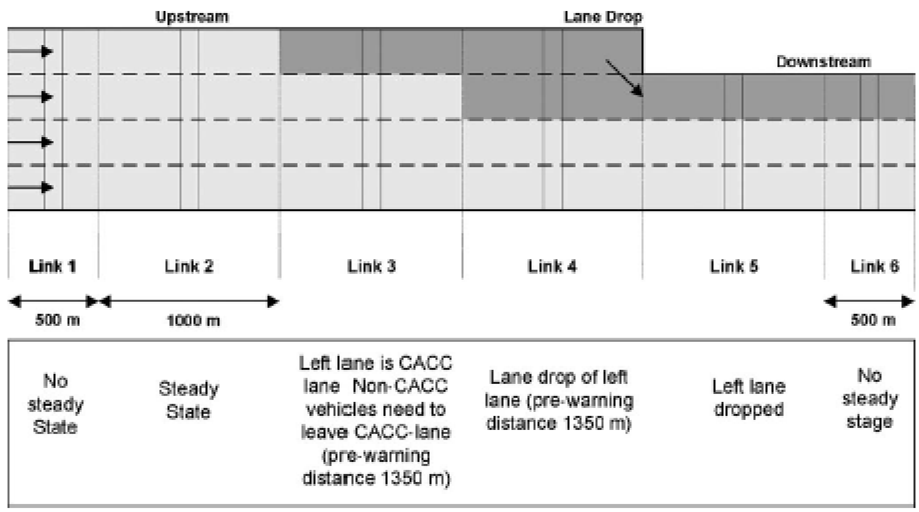


Figure 5 Simulation road setup with lane drop and CACC dedicated lane [8]

The CACC penetration rates were multiples of 20%. According to the observations, the number of shockwaves right before the lane drop (link 4) decreased dramatically as the CACC penetration rate increased. When CACC lanes were included the results had very small differences. Regarding speeds right before and after the lane drop (link 4 and link 5 respectively), the results differ; in link 4 the speeds increase as the CACC penetration rate increases (with only exception the 20% rate where speeds are lower than the reference case) and in the CACC lanes scenarios they are higher. On the contrary, in link 5 the speeds are almost equal in all penetration rates (0% and 100% are a little higher), however when a CACC lane exists the speeds are lower.

From this simulation experiment, it is concluded that in general CACC improves traffic flow performance, however this depends on the traffic flow conditions and the CACC penetration rate. More particularly, traffic flow improves more in high traffic volumes and in higher CACC penetration rates, resulting in more vehicles included in CACC platoons and, thus, higher string stability and reduced headways. The CACC dedicated lanes are beneficial but only for higher CACC penetration rates. Another positive finding is that highway capacity increases, which is very beneficial especially in higher volumes. Nevertheless, a negative finding is that CACC platoons, due to the small headways, do not allow other vehicles to merge, resulting in many of them being deleted during the simulation but, in real situations, making it unsafe to have platoons of CACC equipped vehicles in highways.

In Davis [9], the effect of ACC on traffic flow near an on-ramp is examined. The test site consists of an acceleration lane and a one-lane highway. The ACC penetration rates are 0%, 50% and 100% and regard vehicles at both the highway and acceleration lane.

In the beginning the two first penetration rates are examined. It is observed that for 50% ACC vehicles, the spatial extent of the congested region is less and the distance travelled for a defined time (10 minutes) is higher. Also the throughput is 7% higher.

In the paper, it is suggested that just implementing ACC-equipped vehicles does not benefit as much as an additional interaction between merging and highway vehicles. Cooperative merging is the adjustment of speed and position of a mainline vehicle in order to allow a merging vehicle to enter the highway without it having to extremely decelerate. For that scenario, it is assumed that all ACC vehicles are equipped for cooperative merging. This cooperation is possible only among ACC-equipped vehicles, assuming manual vehicles cannot cooperate. In the simulations being carried out, the highway demand was 1500 veh/h and the on-ramp demand 400 veh/h. With 50% ACC penetration rate, congestion almost disappears and the throughput increases 20%. With an on-ramp demand equal to 630 veh/h, the throughput is 15% increased and the total distance being travelled is 4% higher. In total, in this paper it is concluded that cooperative merging between ACC-equipped vehicles can only reduce the congestions created at on-ramps.

In Knoop et al. [10], it is mentioned how traffic is distributed per lane near merging zones, taking into account the Variable Speed Limits (VSL). In this paper, it is stated that right upstream of an on-ramp, the right lane is underused when in normal speed limit (120 km/h). Also it is mentioned that when the speeds are not equal in all lanes, not all capacity is used. However, if the lane distribution becomes more equal (which indeed happens when a VSL of 60 km/h is incorporated), the right lane will be more used and it is possible that fewer gaps will be available for merging vehicles. Then, there are two possible consequences; they will either merge at lower speeds, affecting the rest of mainline traffic and causing congestions or the stopped vehicles at the acceleration lane will wait for an acceptable gap to be created and will cause congestions at the entrance lane due to the reduced merging ratio.

The conclusion is that before considering the use of VSL, one should take these possible effects into account and consider the demand on both the main stream and the on-ramp.

After the literature is revised there are certain outcomes that can be deduced:

- In lane changing, the steps are lane change intention, preparation, execution and then relaxation (according to figure 3 and based on [4]). In merging, lane changes are mandatory. Therefore, intention is always present, however it is not always certain how early upstream of the merging point it appears and this is where this step can be included in the proposed solution. Where our research should mainly focus on is preparation and execution. Relaxation can be influenced, however, since it is a step that occurs anyway, it will probably be included at a small extent.
- Merging depends a lot on gap creation, searching and accepting. Thus, the research should focus on these aspects. The ability to create gaps will result in less gap rejecting and more gap accepting. As a result, emphasis should be given in the ways which will lead to higher gap creation in the short term and higher gap acceptance/lower gap rejection in the longer term.
- With regards to gap searching, the merging process would be much easier if merging drivers knew beforehand when and where they should merge, resulting in zero or little gap searching. This is the other aspect where the research should focus.

Regarding the aforementioned literature, there are certain aspects that need to be noted:

1) In [1] and [9], the highway segments are single-lane. In that way, there is no possibility of including cooperative lane changing (i.e. some right lane vehicles moving to the left to create more space for merging vehicles). Cooperative lane changing is a measure that can be implemented to assist gap creation.
2) Also in [1], the RSU messages are transmitted only to the CACC-equipped vehicles. Nowadays, that more and more manual vehicles use navigation system devices, the messages could be transmitted through them and not only to ACC- or CACC-equipped vehicles. The deduction here is that a vehicle does not necessarily need to include the very newest technologies in order to be part of a merging assistant system.

At this point, however, it should be mentioned that since these simulations are purely experimental, there are many assumptions being made (e.g. in [1] the driver cannot overrule ACC. This results in collisions, while normally those incidents could be possibly avoided).

3. Design framework

3.1 Examination site

The examination site is an on-ramp on the A20 highway. This on-ramp is the junction between A20 and avenue S112. A20 was chosen due to its position (north of Rotterdam) and, as a result, its high traffic volumes, especially in the morning and evening peaks. Moreover, this specific on-ramp was chosen for two reasons. First, according to the data (speeds and flows per lane per minute) gathered at specific ldetedtor locations and obtained by Rijkswaterstaat, congestion starts formulating approximately 300 metres after the end of the acceleration lane. Since the next off-ramp on the A20 is more than 1 kilometre away from our on-ramp, it is evident that this on-ramp is responsible for the congestions being created at this location. The second reason is that a weaving section is located upstream of our on-ramp, contributing to the already existing congestion and making its implications even worse. Therefore, if the congestion starting at the on-ramp is dealt with, its contribution will positively affect a larger part of the A20. The exact location of the on-ramp is shown in Figure 6, with a more detailed scheme following.

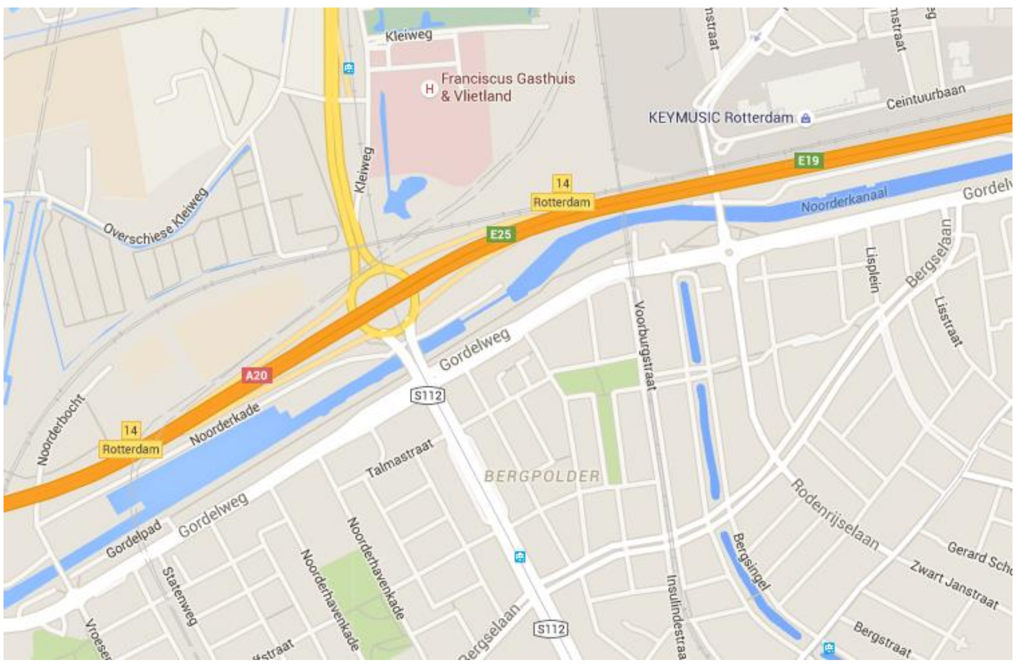
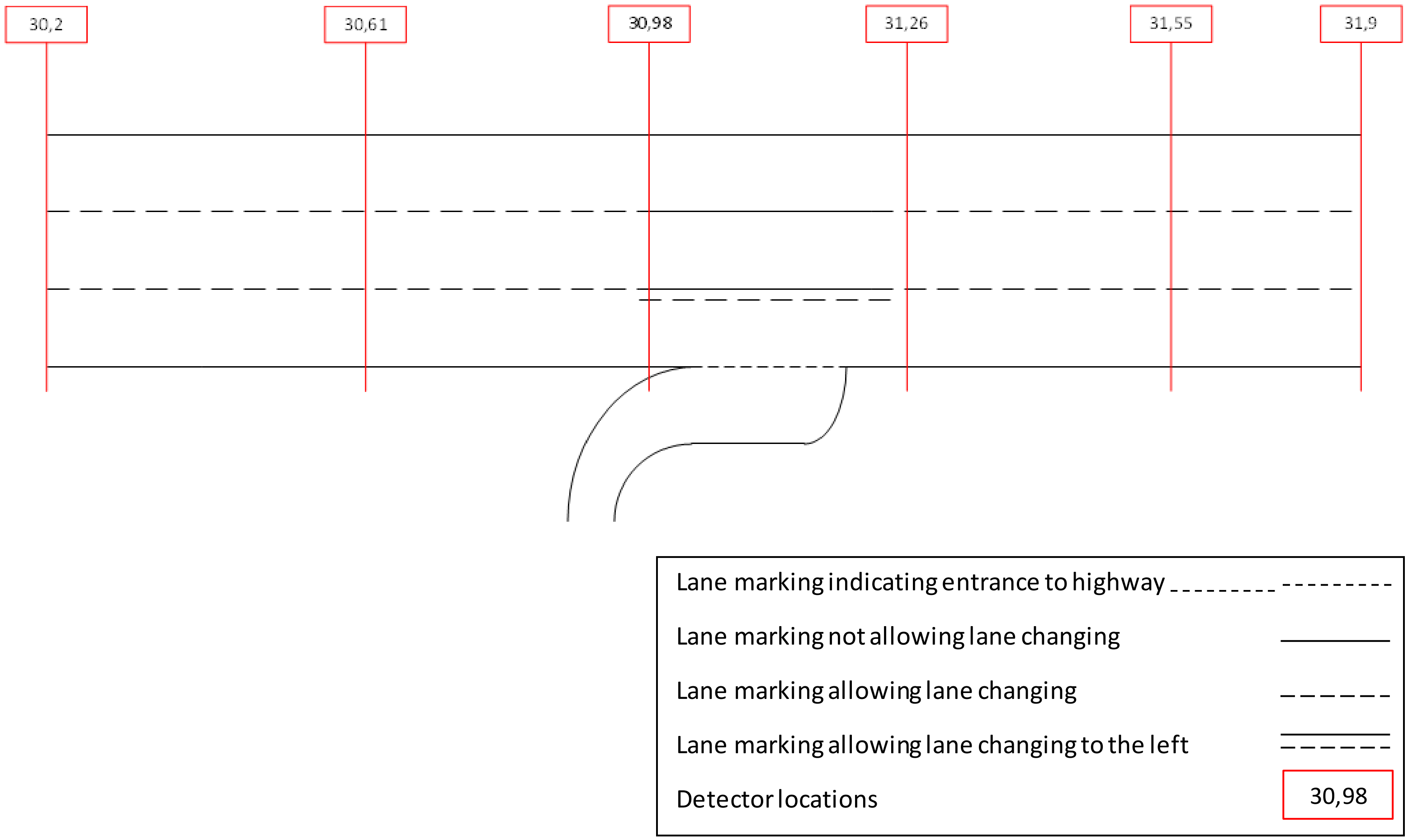


Figure 6 Merging location under examination



3.2 Simulation programme

The first step is to decide which simulation programme will be chosen. Simulation is the method that will be used to validate the measures being proposed. Since it is hard to implement them in reality, it is far easier to test them in a simulation environment. There is a number of simulation programmes being already used in similar analyses, such as AIMSUN or VISSIM [6]. In our case MOTUS, a microscopic traffic simulation package, will be the programme to be used.

MOTUS has several advantages compared to other microsimulation programmes. One of them is the fact that the user has full knowledge and understanding of their actions. In other words, there are no “black boxes”. Furthermore, the fact that MOTUS is developed in Java offers the opportunity for Java class expansions when it comes to new technologies’ implementation. Last but not least, it is easier to focus on specific parts of complex (e.g. multi-lane) networks during simulation.

Once the road segment is complete, the obtained data are incorporated and simulated in order for MOTUS to bring them as close to reality as possible. The outcomes of the programme are graphs, showing the real data and the simulated ones. To bring them closer, there is a number of parameters that can be calibrated in order to provide a better match.

3.3 Design of the examination site

The second step that has to be performed is the initial design of this road section. This was performed with use of a Matlab code combined with Google Earth. The road section was designed with the following steps:

1) Creation of set of segments
2) Each segment is divided from its previous when there is difference in numbers of lanes or in lane change prohibitions and/or allowances
3) For each segment there are properties defined. Those are the speed limit, upstream and downstream sections, the number of lanes and what lane changes are allowed, the origin and destination of its vehicles and the detectors it incorporates

Once the road section is constructed, its properties are loaded in the Matlab code. In that way, the segment can be visualised and, later, the detectors and the data gathered (speeds and flows) can be included in order for the simulation to begin. The section both in Google Earth and in MOTUS is shown in the figures below.

Figure 7 Examination site in Google Earth

Figure 8 Examination site in MOTUS

3.4 Parameter calibration

MOTUS is a microscopic traffic model and, as such, it has two components: the longitudinal model and the lateral one. The parameters used in our simulation are divided with respect to those two components, based on the Lane Change Model with Relaxation and Synchronisation (LMRS) [11]. The LMRS has lane change desire as its main component, but it also includes car following (described by the adapted version of the Intelligent Driver Model (IDM+)), as well as relaxation and synchronisation in order to make the best possible fit with traffic dynamics.

The IDM+ describes car following, however it is related to lane changing as well. The acceleration and headway formulas (which are shown and described in section 4.2.2) are used in MOTUS when a driver follows its leader or during synchronisation with the neighbours and, when necessary, gap creation.

According to LMRS, there are three kinds of desires for a vehicle to change lanes; keep right, gain speed and follow a route. These desires combined give the total lane change desire from lane i to lane j, which is equal to:

$$d^{ij} = d_r^{ij} + \theta_v^{ij} * (d_s^{ij} + d_b^{ij}) \text{, where}$$

d^{ij}_r= desire to follow a route

d^{ij}_s= desire to gain speed

d^{ij}_b= keep-right desire

θ^{ij}_v= level at which voluntary incentives are included

Also, according to LMRS there are three kinds of lane changes based on drivers' behaviour: free, synchronised and cooperative. Those three desires are compared with the following formula, according to which four desire ranges are created.

$$0 < d_{free} < d_{sync} < d_{coop} < 1$$

In the LMRS, d_{free} is set by default to 0.365, d_{sync} 0.577 and d_{coop} 0.788. These values are not changed in the model. On the contrary, the car-following parameters being calibrated are:

- α_{car} (car acceleration)
- α_{truck} (truck acceleration)
- b (deceleration)
- T_{max} (desired time headway between two vehicles)

The lane-change parameters are:

- T_{min} (minimum time headway between two vehicles)
- τ (relaxation time)
- x_0 (anticipation distance)
- t_0 (anticipation time)
- $v_{gain\ car}$ (speed gain for cars)
- $v_{gain\ truck}$ (speed gain for trucks)

- v_{crit} (speed at which flow is equally distributed at all lanes)

The initial LMRS parameter values needed to be calibrated to provide a better fit for our model. Initially, during the first simulation runs it was observed that trucks change lanes more than in reality (in certain cases they even drove in the left lane). It was also observed that vehicles rarely changed lanes, resulting in severe congestions in the right lane. Thus, the goal of the simulated model was to incorporate:

1) The fact that trucks should stay on the right lane
2) The fact that vehicles should change lanes more often
3) The fact that the speed limit on the test area is 80 km/h instead of 120 km/h

This was possible by testing several values for the parameters, taking into account the specifics of our case study. In the table below, the initial and calibrated values are shown. The calibrated parameters have the values that are at the same time as close to reality and as close to the initial values as possible.

Table 2 Calibrated LMRS parameters

	Initial values	Calibrated values
α_{car}	1.25 m/s²	1.2 m/s²
α_{truck}	0.4 m/s²	0.8 m/s²
b	2.09 m/s²	2.09 m/s²
T_{max}	1.2 s	0.9 s
T_{min}	0.56 s	0.5 s
τ	25 s	25 s
x_0	295 m	300 m
t_0	43 s	80 s
$v_{gain\ car}$	69.6 km/h	15 km/h
$v_{gain\ truck}$	69.6 km/h	100 km/h
v_{crit}	60 km/h	30 km/h

As it can be observed, some parameters stayed the same, others changed slightly and the rest were highly changed.

- Deceleration b and relaxation time τ remained exactly the same.
- Car acceleration α_{car} was slightly decreased. The initial value at 1.25 m/s^2 was almost equally attractive, however a small reduction provided better results. Thus, since the parameter's change was negligible, the slightly smaller value was selected.
- Anticipation distance x_0 was slightly increased. This is actually the initial value in the LMRS model, based on the last traffic signs indicating a lane drop however, exactly like before, this small change provided better results.
- Truck acceleration α_{truck} was doubled. This change was made due to the fact that trucks remain on the right lane and an acceleration as small as 0.4 m/s^2 makes simulated congestion worse than reality. Despite this high increase, the new value is still acceptable. To ensure that trucks stay on the right lane and do not change lanes, $v_{gain\ truck}$ was highly increased as well.
- T_{max} and T_{min} were decreased as well. The former provided better simulation results, since a smaller desired headway leads to higher flow in general and higher capacity during free flow conditions. The latter increased the highway capacity at such an extent that the simulation runs did not unexpectedly stop due to the occurring collisions. First it was attempted to make similar reductions because a small difference between T_{max} and T_{min} would result in negligible relaxation.

However, this reduction was the best that could be achieved, otherwise a smaller T_{min} lead to free flow conditions during the whole simulation period.

- The highest changes were made in t_0, $v_{gain\ car}$ and v_{crit}. In t_0, the value is almost doubled. This means that the desire to change lanes starts earlier, therefore more lane changes occur prior to the merging point in order to make place in the right lane for the merging vehicles. In $v_{gain\ car}$, the reduction is very high. This happens for the same reason as t_0; the lower value of $v_{gain\ car}$ indicate that vehicles change lanes more easily. In the LMRS, the speed limit is 120 km/h, while in our case study it is 80 km/h. This high difference indicates that vehicles have much more sensitivity in lane changing and will make lane changes far more often. Thus, when it becomes clear that the right lane is about to be blocked, more vehicles will move to the middle or even to the left lane. The two aforementioned parameters show the need to relieve the right lane from the congestion caused by the on-ramp and shift it more towards the left, as mentioned before. Last, in v_{crit}, the value is reduced in half. Because of the high speed limit difference, the speed in which the share of vehicles per lane is more equal, should decrease as well.

3.5 Current situation simulation runs

The provided data by Rijkswaterstaat were flows and speeds on A20 at minute intervals for October and November 2015. In order to decide which of them should be simulated, there were some criteria that needed to be met. The congestion should begin after the on-ramp, so congestions caused by shockwaves originating way downstream of the merging point were rejected. Furthermore, the congestion should not move more upstream than the beginning of the simulated road segment. When vehicles originate at the simulation run, in the beginning they should move in uncongested flows. For those reasons, and after sorting out the provided data, two days were chosen: Tuesday, 27/10/2015 and Friday, 27/11/2015 during their morning peaks (07:00-10:00).

Figures 9-12 show the flows and speeds per detector per lane (the right lane is represented with blue colour, the middle with green and the left with red) at a minute basis for both days as they occurred after the model calibration (the last detector at 31.9 is excluded since it is located 600 metres after the end of the acceleration lane and its outcomes are not representative due to a simulation artefact in which vehicles are deleted at the end of the road segment). The dashed lines are the real data, while the solid lines are the simulated data.

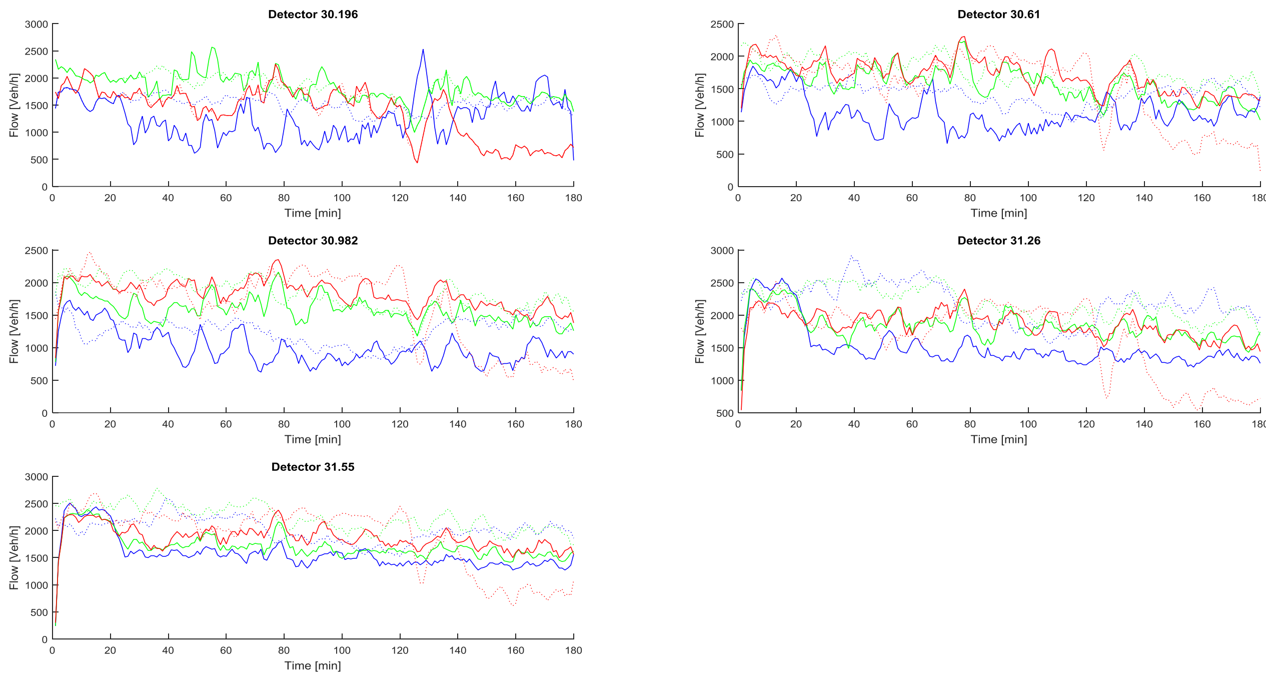


Figure 9 Real and simulated flows on 27/10/2015

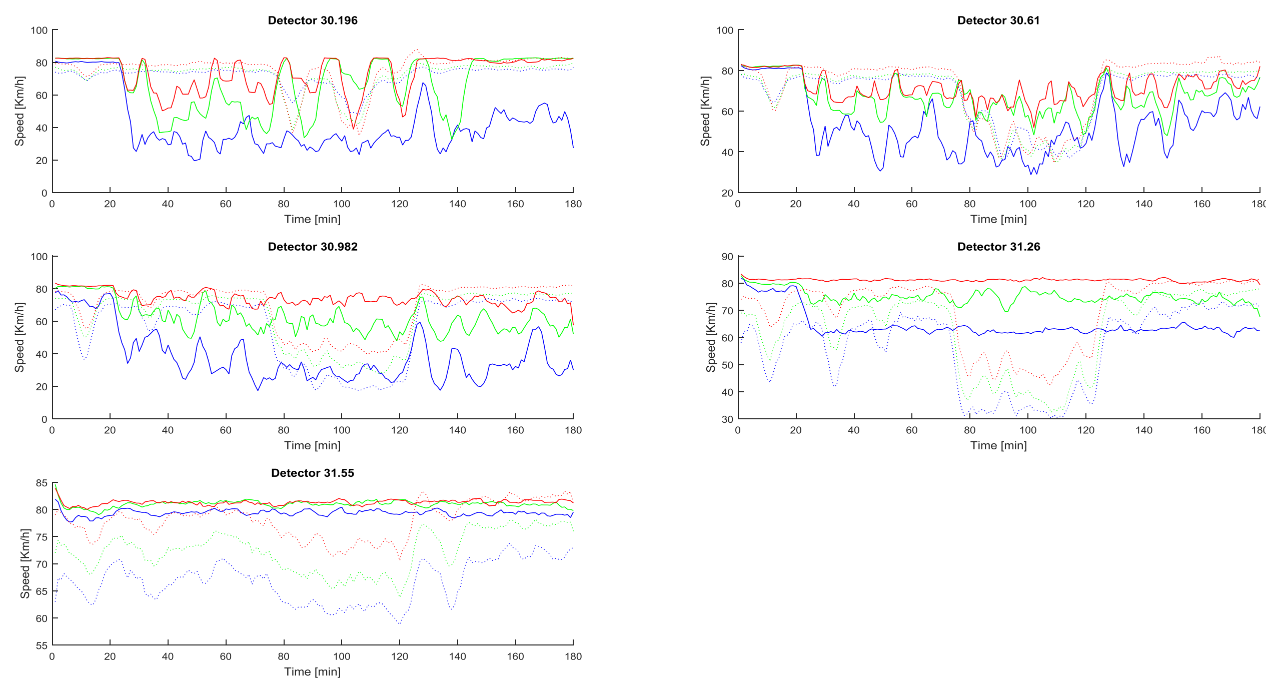


Figure 10 Real and simulated speeds on 27/10/2015

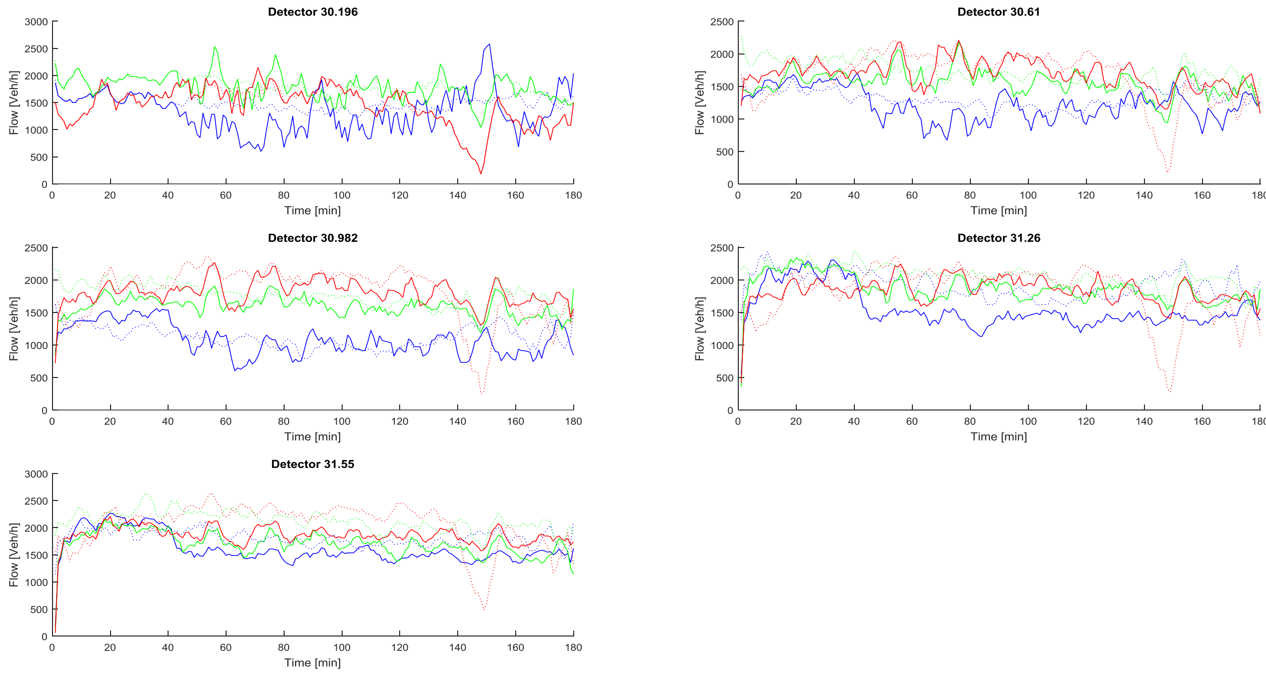


Figure 11 Real and simulated flows on 27/11/2015

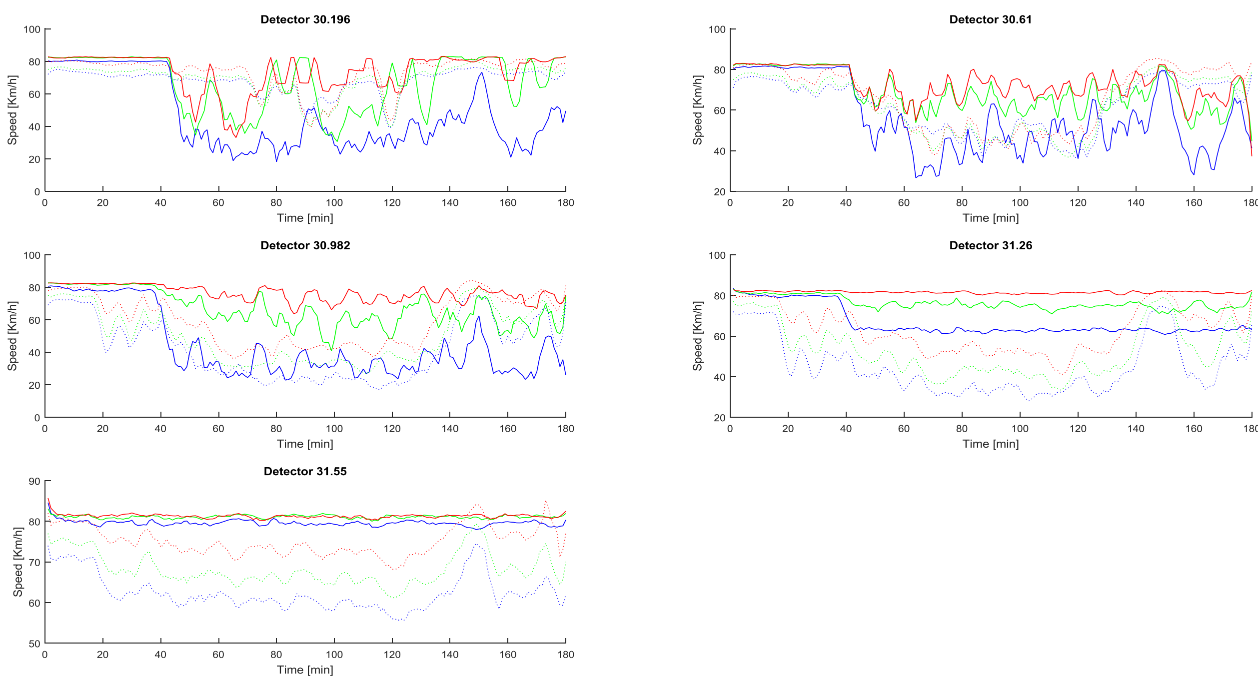


Figure 12 Real and simulated speeds on 27/11/2015

From the four aforementioned graphs, more emphasis is given on detectors 30.61, 30.98 and 31.26. The most important is the second as it is located right upstream of the merging point, therefore the main congestion effects appear there.

On detector 30.98 the flow on the right lane is far lower than the other two, the difference starting to increase 40 minutes after the simulation beginning. The same holds for detectors 30.61 and 31.26 but with some differences. In the former, flows tend to equalise 120 minutes after the simulation beginning while in the latter the difference is present till the end of simulation, being nevertheless very smaller.

Regarding speeds, vehicles move almost always faster in the left and middle lane, while their difference with the right lane is high. Especially in detector 30.98 after a certain period (20 minutes on 27/10/2015 and 40 minutes on 27/11/2015) the differences increase a lot and remain similar until the end of simulation. On detector 30.61 the speed differences begin at the same time but 120 minutes after the beginning they tend to equalise, exactly like flows. On detector 31.26 differences exist too, but remain the same until the end.

To better understand the flow behaviour with respect to the road layout, x-t diagrams with speed colour indication per lane for both days in real and simulated data will be shown below.

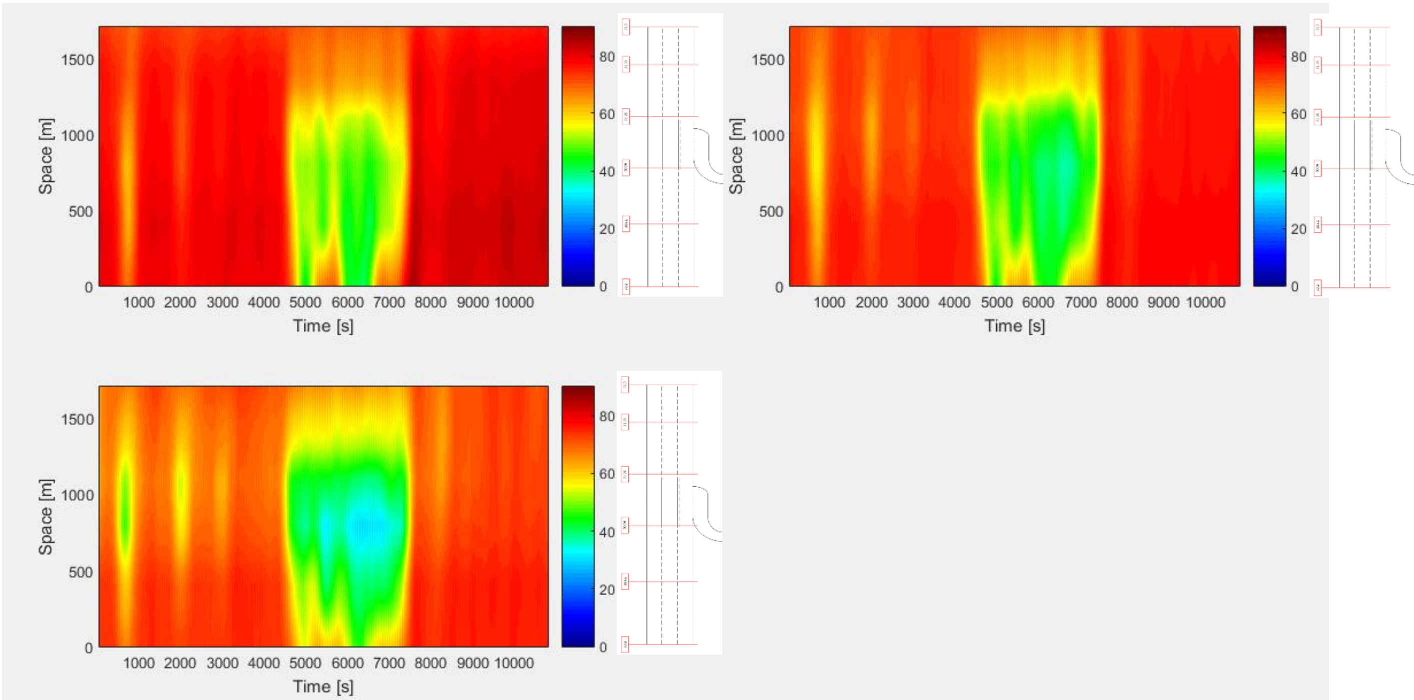


Figure 13 Congestion at left, middle and right lane respectively (real data 27/10/2015)

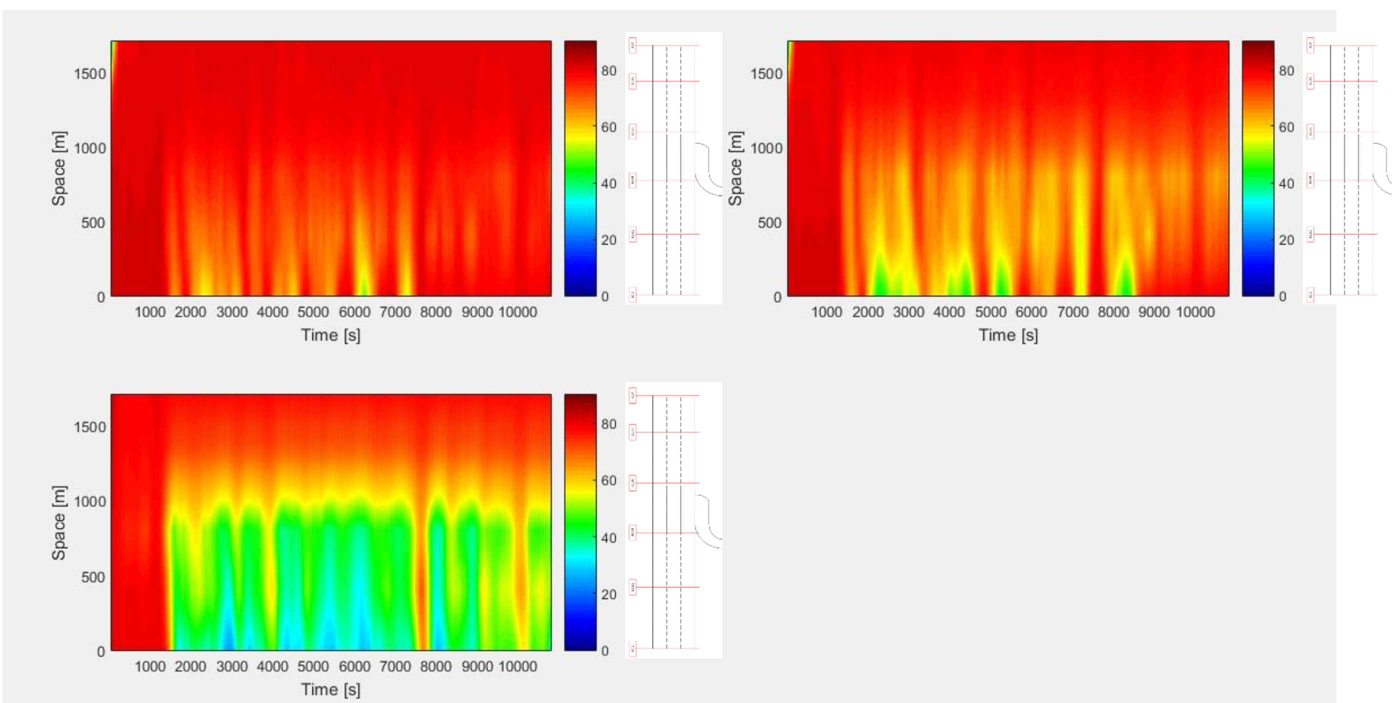


Figure 14 Congestion at left, middle and right lane respectively (simulated data 27/10/2015)

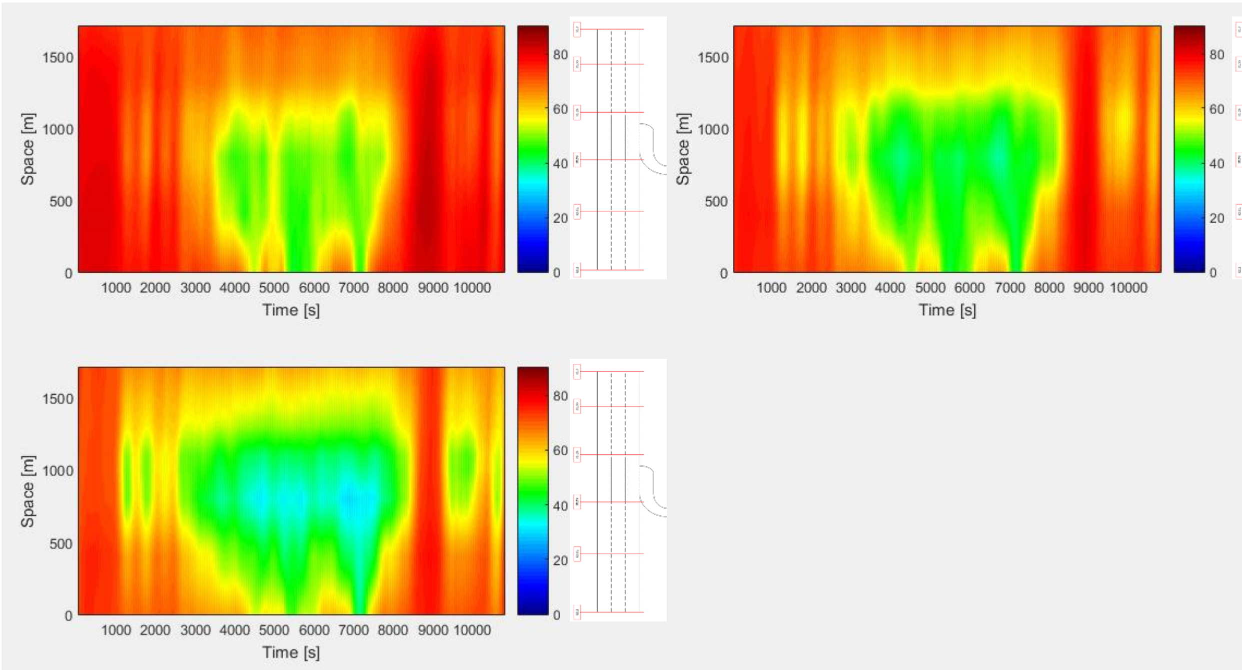


Figure 15 Congestion at left, middle and right lane respectively (real data 27/11/2015)

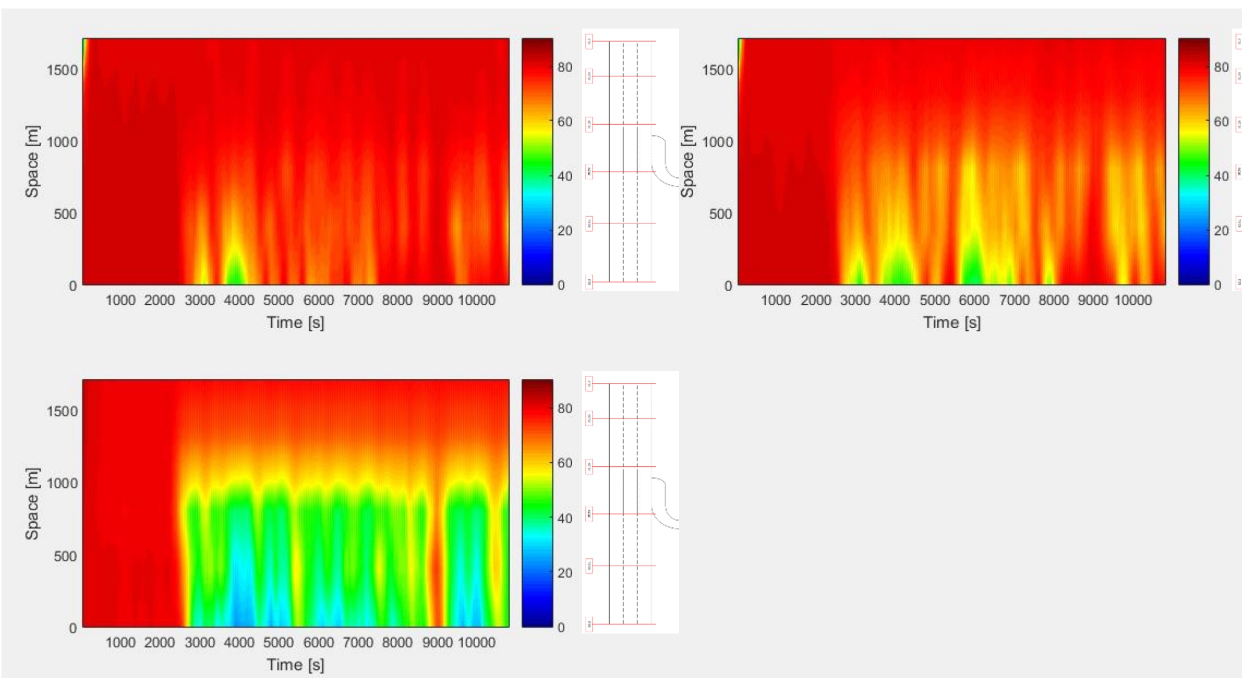


Figure 16 Congestion at left, middle and right lane respectively (simulated data 27/11/2015)

From all the above graphs there are several deductions that can be made:

- The fit between real and calibrated data is not perfect. It is better in flows than in speeds (figures 9-12) but there are still differences. However, the main features such as capacity drop or onset of congestion are captured at a satisfactory way.
- In simulation, congestion is almost zero in the middle and left lanes, while in the right it is more intense than reality and with a higher duration. Also, in all three lanes the congestion's head is at the end of the acceleration lane while in reality it begins about 200 m more downstream. In both real and simulated graphs, nevertheless, it is captured that congestion is worse in the right lane, better in the middle and with the fewest consequences in the left lane.
- The presence of such differences among the three lanes enhances the perception that vehicles could be better distributed along the highway. When congestion starts forming in the right lane, it could be suggested that more vehicles move to the two other lanes so that the speeds at each lane are equally distributed and the traffic conditions are similar.

4. ITS description and simulation

4.1 Applied measures

The purpose of this research is the improvement of the merging procedure. As mentioned in chapter 2, for the merging procedure to be more efficient, the stages of gap creation as well as gap acceptance should be optimised. In order for a vehicle to merge more easily and more effectively, the gap within which it will merge should be created upstream of the merging point. In order for a gap, thus space, to be created the right-lane drivers should either change their speeds by accelerating/decelerating or leave their lane so that the merging vehicle can "replace" them. This process can be , therefore, made with one of the two following manoeuvres by right-lane vehicles:

3) courtesy yielding by reducing speed
4) lane changing towards the left

In case they change to the middle lane, then the middle lane drivers have to perform the two aforementioned measures to make space too. Finally, when a middle lane vehicle needs to move towards the left lane, the left lane drivers can only create a gap by accelerating or decelerating since no further lane changes are possible. This whole procedure is shown in the flow chart below.

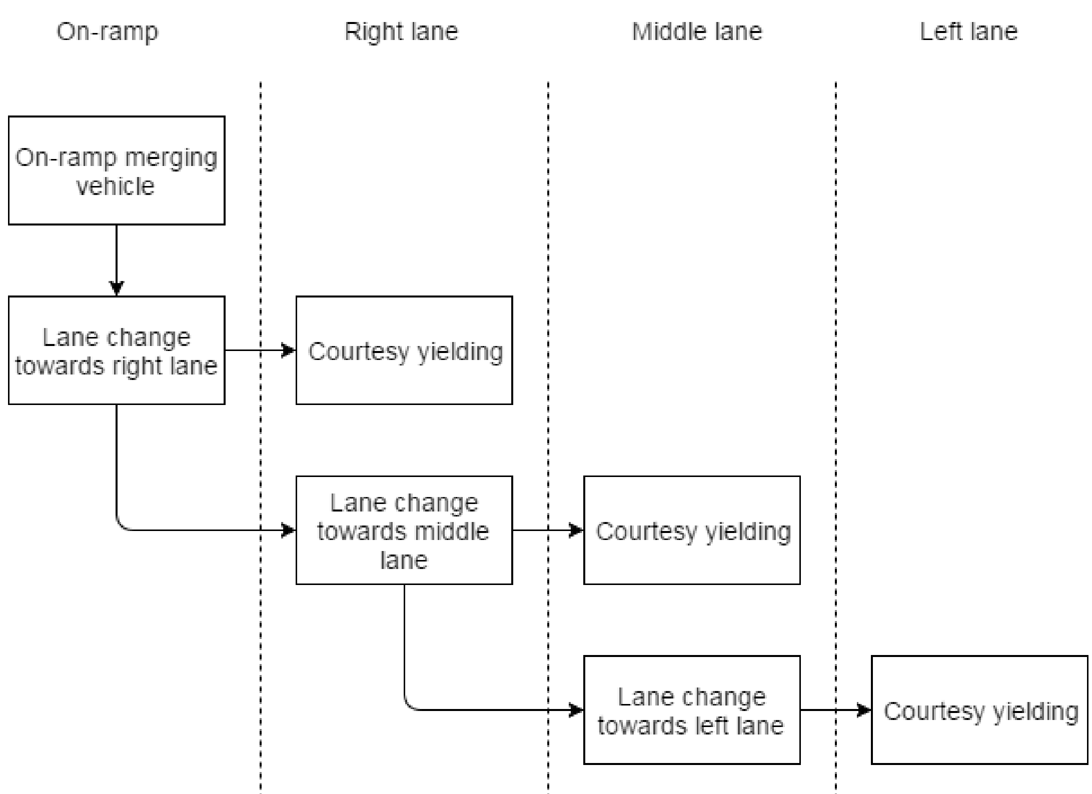


Figure 17 Merging procedure per lane

The components of the flow chart are visualised in order to become more understandable. Prior to that, however, the time variables (defining when the aforementioned measures will be taken) are explained and then implemented in the figures.

- t_{init}: the gap creation for all lane changes should be made upstream of the merging point. This process takes some time, thus the moment it begins should be defined. t_{init} is defined as the moment the two aforementioned gap creating manoeuvres start being executed. Furthermore, the time needed for an on-ramp vehicle to reach the merging point if it keeps moving with steady speed is equal to t_{init} as well. From t_{init} till t_{arr} (the moment when the on-ramp vehicle arrives at the merging point) all the necessary gap creations should be complete.
- t_{begin}: at t_{init} the right-lane vehicles start either decelerating or changing lanes. In the latter case, vehicles from the middle lane will need to create a gap. t_{begin} has the same meaning as t_{init}; the difference is that, compared to the previous variable, here the on-ramp vehicle is replaced with the right-lane one and the right-lane vehicle is replaced with the middle-lane one. t_{begin} is also used when it comes to middle-left lane changes.
- t_{th}: first the putative leader and follower have to be defined. The time they will reach the merging point is t_L and t_F respectively. In case $t_F - t_{init} \leq t_{th}$ or/and $t_{init} - t_L \leq t_{th}$, then one/both of the follower and leader will be requested to change lanes (cooperative lane changing). Otherwise the follower will be required to decelerate (courtesy yielding) and the leader to accelerate if possible. This holds for all lane changes except for the ones from the middle to the left lane, where only courtesy yielding is feasible.
- t_{ign}: there is a threshold above which no orders are transmitted and the lane change can be made without any measures being taken. If $t_F - t_{init} > t_{ign}$ and $t_{init} - t_L > t_{ign}$, then the lane change can be freely made.

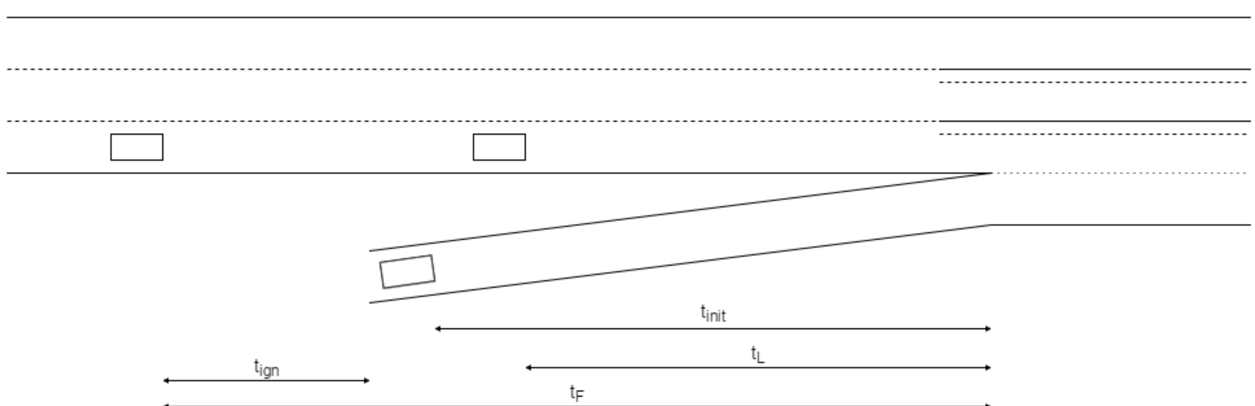


Figure 18 Scenario where the follower is ignored ($t_F - t_{init} > t_{ign}$)

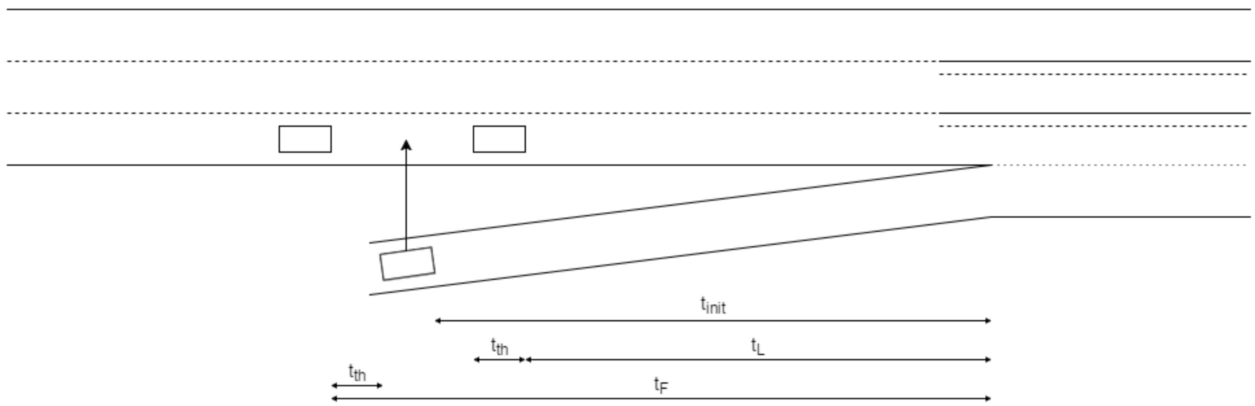


Figure 19 Scenario where right lane vehicles decelerate and accelerate ($t_{th} < t_F - t_{init} \leq t_{ign}$)

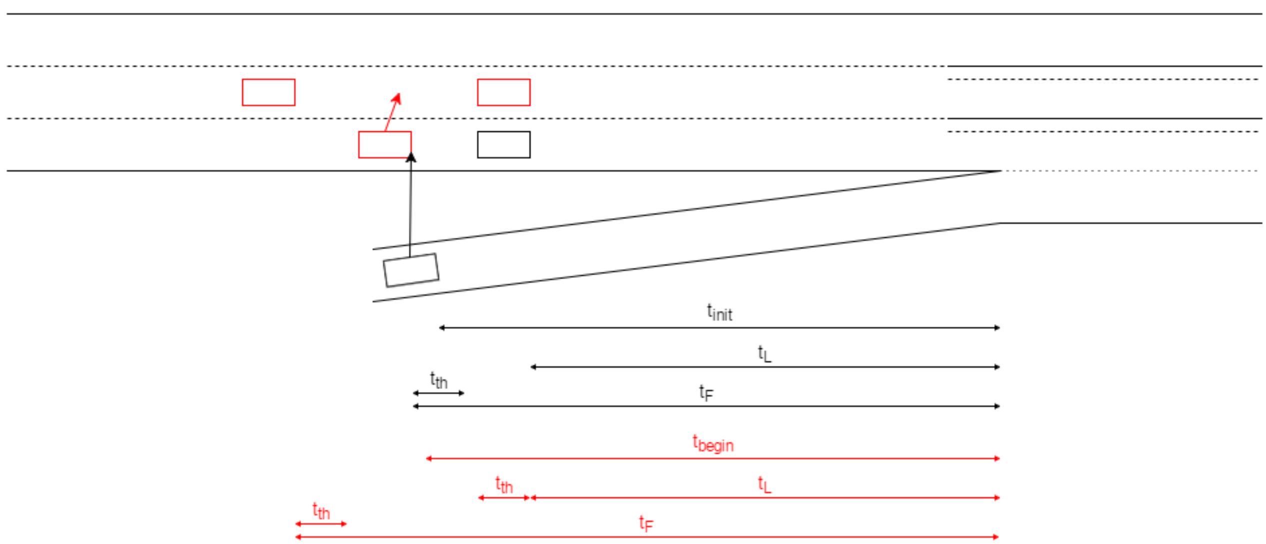


Figure 20 Scenario where right lane vehicle changes lane ($t_F - t_{init} \leq t_{th}$) and middle lane vehicles decelerate and accelerate ($t_{th} < t_F - t_{begin} \leq t_{ign}$)

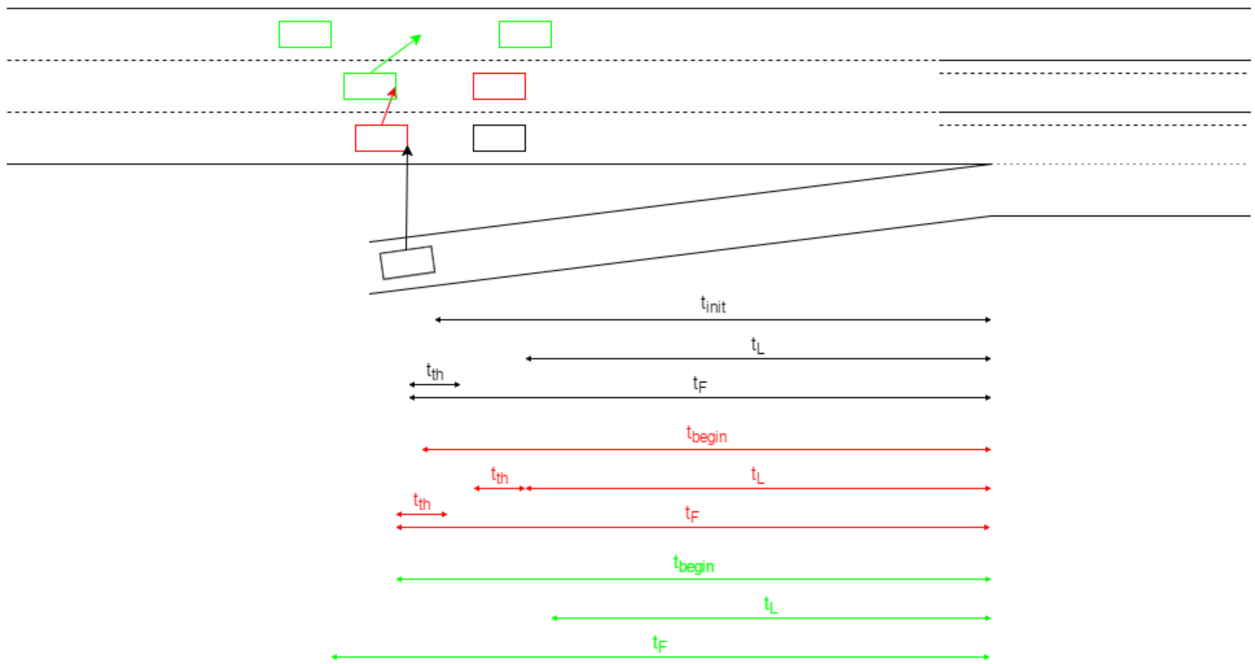


Figure 21 Scenario where right (t_F - $t_{initv} \leq t_{th}$) and middle lane (t_F - $t_{begin} \leq t_{th}$) vehicles change lanes and left lane vehicles decelerate and accelerate

4.2 Merging assistant

The merging assistant is the system which is designed in order to improve the merging procedure and reduce its resulting congestion. In chapter 2 it was mentioned that CACC was a measure that enhances traffic flow stability, something resulting from the fact that vehicles have proper longitudinal communication and synchronisation. Moreover, the communication and synchronisation at a lateral level were achieved with the use of an RSU. Our system consists of a number of technologies that will allow drivers both at the highway and the on-ramp to know how and when the former should create a gap by decelerating or changing lanes and the latter when and where to merge. Those components are:

3) One RSU located right upstream of the merging point (at detector 30.98), being able to detect the traffic characteristics at all 4 lanes (3 highway lanes and the on-ramp), process them and then transmit advice to the drivers of all vehicles.
4) ACC. A defined percentage of vehicles is ACC-equipped. The ACC's characteristics will have certain additional functions compared to current ACC. Also the instructions transmitted to ACC-equipped vehicles will differ from the ones transmitted to manual vehicles, taking into account the way the headway can be applied by both vehicle categories.

Before the system description, its variables will be explained:

- q_{th}: above this flow threshold the measures will start being implemented. It is preferable that q_{th} is located around the top of the fundamental diagram's congested branch or even higher (Figure 22).

- T_{adv}: the advised headway provided to ACC-equipped vehicles.
- λ_{sp}: speed factor > 1. The leaders' current speed is multiplied with this factor and the product is the advised speed provided to leaders when they are asked to accelerate, using the speed limit as a boundary.
- N_{enable}, $N_{disable}$: if the flow is close to q_{th}, it could be the case that it may be alternately above or below it. Therefore, in order to avoid switching the detector on and off minute after minute, once $q > q_{th}$, the assistant becomes active after N_{enable} consecutive minutes that this condition is true. The same holds when, after the assistant is active for some time, $q < q_{th}$. This condition should be true for $N_{disable}$ minutes before the controller becomes inactive.
- pACC: penetration level of ACC, i.e. percentage of ACC-equipped vehicles.
- comp, lccomp: in order to account for driving behaviour, a compliance rate should be taken into account. It is possible that not all drivers will comply with the provided advice, therefore a compliance rate can be set from the beginning of the analysis. This rate is divided in two parts; longitudinal (comp) and lateral (lccomp) compliance rate. Compliance rate is divided because a driver may be unwilling to change lanes (e.g. due to a downstream off-ramp that he/she wants to follow), but eager to decelerate in order to make space for lane changing vehicles. Furthermore, for ACC-equipped vehicles, comp is set to 1, since the driver is not involved in the longitudinal compliance. However, lccomp is related only to the driver and thus the vehicle behaves exactly like the manual ones in lccomp.

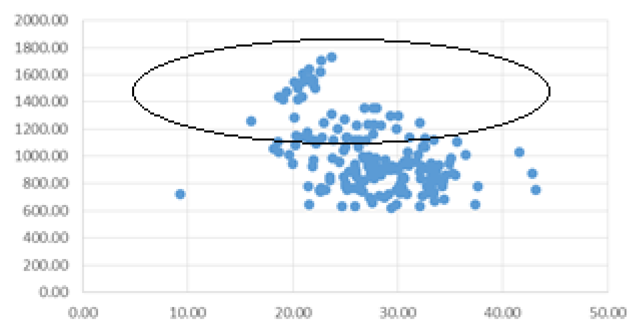


Figure 22 Flows above q_{th} where the merging assistant is activated

Since the variables are defined, the way the system works is explained below in steps:

1) q is constantly checked on the right lane on detector 30.98. If $q \geq q_{th}$ for at least N_{enable} consecutive minutes, the assistant becomes active.
2) The RSU detects the on-ramp vehicles with their positions and speeds. Based on those, when the time needed to reach the merging point becomes equal to t_{init} the gap creation preparation begins. The RSU then defines the leader and follower from the right lane as mentioned above. If a right (or middle) lane vehicle needs to change lanes, the same process is performed agai n between right-middle (or middle-left) lane vehicles.

All the combinations of the measures taken are shown in the table below (t is either t_F or t_L):

Table 3 Actions performed by the leader and follower according to the different time variables

	Leader	Follower
$\lvert t - t_{begin} \rvert \leq t_{th}$	Lane change	Lane change
$t_{th} < \lvert t - t_{begin} \rvert \leq t_{ign}$	Accelerate if possible	Decelerate
$\lvert t - t_{begin} \rvert > t_{ign}$	Ignored	Ignored

These cases hold for all three lane changes; however, as mentioned before, everything is triggered from the on-ramp-right lane change. For that reason, t_{init} is replaced with t_{begin}. However, in this table t_{begin} has the same meaning as t_{init}.

3) Once $q < q_{th}$ for at least $N_{disable}$ consecutive minutes, the assistant becomes inactive.

4.2.1 Restrictions

Trucks rarely overtake. Furthermore, the lane change of a truck will demand either larger gap preparation times or stronger decelerations. In both cases it is possible that congestion will begin a lot earlier. Therefore, if for a truck it holds that $t_F - t_{init} \leq t_{th}$, it will simply decelerate and the driver will not be asked to change lanes. If it is a leader and $t_{init} - t_L \leq t_{th}$, it is supposed that the lane changer will wait until its headway is large enough and then it will merge.

It is also possible that a vehicle could be included in more than one lane changes or is a multiple leader and/or follower. However, this can cause certain problems. For example, a multiple follower may start applying a certain deceleration for the first lane changer and then be requested to decelerate even more for the other lane changer. The second deceleration advice, however, will be provided later and the vehicle will not have enough time to apply it. This holds both for lane changes within the highway and for merging manoeuvres. Therefore, it is suggested that once a vehicle is given a certain task, it will be immediately excluded from other tasks and the system will not provide it with any other advice. The only exception is when a vehicle is first ignored by the system, as shown in Table 3.

The restriction will be expressed with two formulas. Assuming two consecutive lane changes i and i+1, it can be deducted that:

$$t_{L_{i+1}} \neq t_{F_i}$$

for all lane changes. This formula accounts for the impossibility of multiple tasks, meaning that the time needed for a leader to reach the merging point cannot be exactly the same time needed for a follower to reach it. Also,

$$t_{L_{i+1}} \neq t_{L_i} \text{ and } t_{F_{i+1}} \neq t_{F_i}$$

for all lane changes. This means that a vehicle cannot be leader or follower of two consecutive lane changes.

4.2.2 Car-following model

When the measure of courtesy yielding is implemented a car following model has to be applied. In order to define the applied acceleration for leaders and deceleration for followers, the aforementioned IDM+, will be used. The acceleration/deceleration will be calculated by the following formula:

$$\frac{dv}{dt} = a * \min\{1 - \left(\frac{v}{v_{des}}\right)^4, 1 - \left(\frac{s^*}{s}\right)^2\}, \text{ where}$$

$$s^* = s_{min} + v * T_{des} + \frac{v * \Delta v}{2\sqrt{ab}}$$

α = maximum acceleration
v = current speed
v_{des} = desired speed
s* = desired space headway
s = current space headway
s_{min} = minimum headway in congestion
T_{des} = desired time headway
Δv = speed difference between vehicle and its predecessor
b = maximum deceleration

When there is interaction between a manual and an ACC-equipped vehicle or between two ACC-equipped vehicles, the aforementioned formulas remain the same. Also, for ACC-equipped vehicles all the parameters have the same values as for the manual ones, since these values are sensible for the former too. This, together with the fact that the model is simpler, lead to the decision to keep the same formulas and parameter values.

4.2.3 Lane changing model

The lane changing model is based on LMRS, as shown in the formula in section 3.4. Since advice for lane changes is transmitted to highway drivers, the aforementioned formula is assumed to have a new component d_a, which implies the lane change desire based on the respective system advice. The formula will now be:

$$d^{ij} = d_r^{ij} + \theta_v^{ij} * (d_s^{ij} + d_b^{ij} + d_a^{ij})$$

The total desire will differ per lane. For on-ramp vehicles, d^{ij}_{α} will be equal to 0 because their drivers are not advised to change lanes, they just have to do it. Furthermore, for all lane changes within the highway d^{r}_{ij} equals to 0 since vehicles do not have to perform any manoeuvres in order to follow their desired route (e.g. no lane drops or on- and off-ramps). On the contrary, all lane changes include voluntary desire. Therefore, for all lane change advice to highway vehicles the voluntary desire is always fully included.

Since the proposed lane changes are related to the vehicle position with respect to the merging point, it is assumed that the value of d^{i}_{α} is similar to the one of d^{i}_{r}. The same formula as d^{i}_{r} is used, including however the lane change compliance rate in order to interpret human behaviour. Thus:

$$d_\alpha^i = \max\left\{1 - \frac{x_i^a}{x_0}, 1 - \frac{t_i^a}{t_0}, 0\right\} * c, \text{ where}$$

$$c = lccomp * d_{coop}$$

Based on the drivers' desire combined with the system advice, d^i_α will have different values. Here, it is taken for granted that the system advises for lane changes only towards the left. The different values of d^i_α are the following:

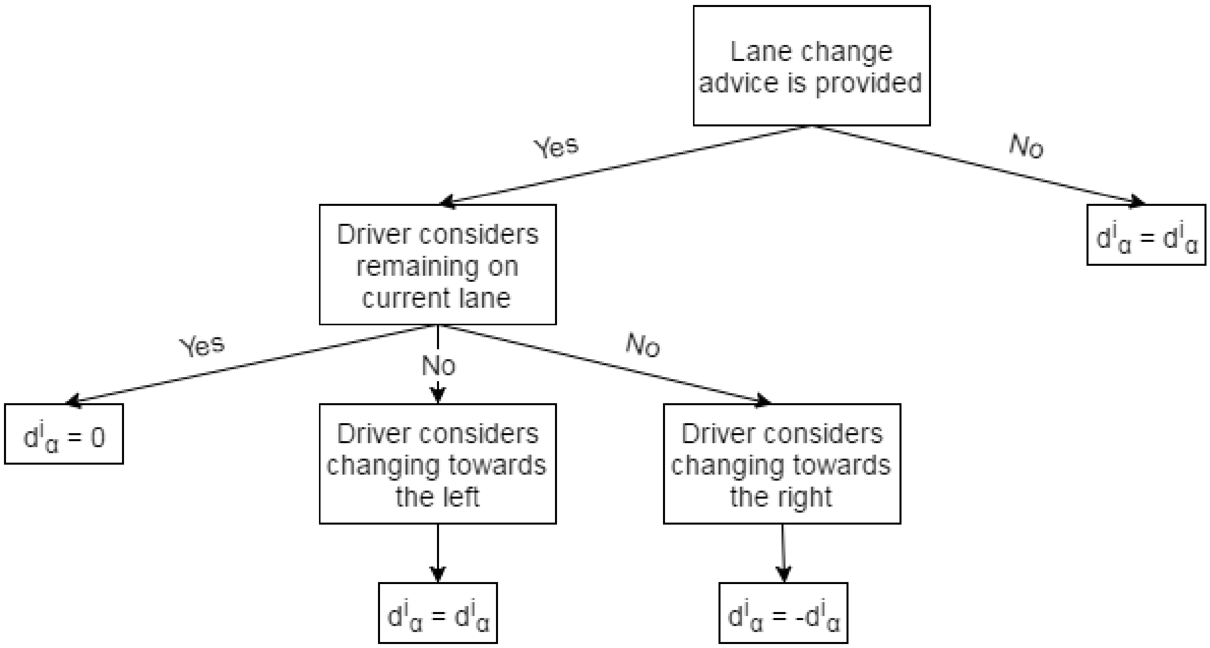


Figure 23 Different values of d^i_α

4.2.4 Relaxation

After a lane change is performed, the follower has to decelerate because of the previous headway's violation. The relaxation time is equal to τ. After τ seconds, the headway will return to a predefined value.

The situation becomes more complex when it comes to ACC-equipped vehicles. If a headway is applied before the lane change and then is suddenly violated, normally the vehicle will have a very intense deceleration in order to maintain its previous headway. This can lead to severe traffic disruptions moving upstream and resulting in serious congestions, perhaps even accidents. Therefore, in the system it is suggested that the ACC design will be such that during the relaxation phase the ACC-equipped vehicles will behave the same way as the manual ones.

The way the relaxation will be applied depends on T_{adv} (if it exists), on T(t) and on the longitudinal compliance rate (comp). By default:

$$T_{tar} = T_{max}$$

If there is T_{adv}, the target headway will be:

$$T_{tar} = T_{adv} * comp + T_{max} * (1 - comp)$$

When no headway is proposed (T_{adv} = 0) and T(t) > T_{max}, then the driver will return to the regular headway. Thus:

$$T(t) = T_{max}$$

otherwise, if T_{adv} = 0 and T(t) < T_{max}

$$T(t + \Delta t) = T(t) + (T_{tar} - T(t)) * \frac{\Delta t}{\tau}$$

4.3 Simulation scenarios

After the variables, phases (lane changing, courtesy yielding and relaxation) and formulas are defined and implemented in MOTUS, the simulation can begin. In order to define the effectiveness of the proposed measures a number of simulation runs needs to be performed. Each simulation run incorporates a different scenario, being tested for both days. Each scenario consists of different values in certain variables.

The variables that will vary per scenario are three: ACC penetration level, drivers' compliance percentage (both longitudinal and lateral) and flow threshold. These (and λ_{sp}) are the only variables not related with time. The time variables are assumed to have only one value that does not change throughout the scenarios under examination. The reason is that the on-ramp has very small length (230 metres) and, as a result, the time needed for accelerations, deceleration and lane changes (t_{init}) is very limited. The possible range of the rest time variables is very strict as well and, therefore, it is decided that their values remain the same throughout the simulations. Moreover, λ_{sp} is not as crucial as the rest non-time variables (since acceleration is not always possible to be implemented), thus only one value is given there too.

In sum, the non-varying variables will have the following values:

- t_{init} = 10 seconds
- t_{th} = 2 seconds
- t_{ign} = 5 seconds
- T_{adv} = 3 seconds
- N_{enable} = 1 minute
- $N_{disable}$ = 3 minutes
- λ_{sp} = 1.05

Regarding the three aforementioned variables, each one will initially will be tested on those values:

- ACC penetration level : 0, 0.5, 1
- compliance : 80%, 100%
- flow threshold : 800 veh/h, 1000 veh/h

Although the compliance rate is divided in two sub-components, here it is taken as one variable, thus it is regarded that longitudinal and lateral compliance rates are the same. Furthermore, for each scenario to be more robust, a number of seeds should be performed. The more the seeds the more the results will converge to one value. For our case, 30 seeds will be performed per scenario.

4.3.1 Measures of effectiveness

The effectiveness of the proposed system will be measured with a number of indicators. These indicators will be average travel time, average delays and vehicle-kilometres travelled. Those vehicle-kilometres refer only to the vehicles that cross the whole A20 section, thus the on-ramp vehicles that enter the highway are not taken into account. The reason is the fact that the research performed refers to the on-ramp as a bottleneck, therefore the vehicles upstream of it, as well as the traffic situation should be mainly concerned. The more effective the ITS, the more the vehicle-kilometres and the lower the total travel time and delays. Moreover, it is important that delays occupy a smaller percentage of total travel time.

In total, the combinations of the different variable values will be 12 and are shown together with the outcomes in table 4.

4.4 Analysis on 27/10/2015

The first day that was analysed was 27/10/2015. The outcomes of the base case and each scenario are shown in the following table. First, the results of the base case are presented and then each scenario separately, including the differences with the base case in percentages.

Table 4 Base case and simulation scenarios with travel times, delays and vehicle-kilometres

Scenario	Compliance (%)	Flow threshold (veh/h)	ACC penetration rate (%)	Avg. TT (s)	Avg. TT change (%)	Delay (s)	Delay change (%)	Vehicle-kilometres	Vehicle-kilometres change (%)
Base case				115.8	-	40.9	-	22583	-
1	80	800	0	112.6	-2.8	37.7	-7.8	22751	+0.7
2	80	800	50	106.4	-8.2	31.4	-23.2	23431	+3.8
3	80	800	100	109.9	-5.1	34.8	-14.8	22882	+1.3
4	80	1000	0	113.6	-1.9	38.7	-5.3	22722	+0.6
5	80	1000	50	105.4	-9	30.4	-25.6	23526	+4.2
6	80	1000	100	109.5	-5.5	34.4	-15.9	22928	+1.5
7	100	800	0	120.9	+4.4	45.9	+12.2	22214	-1.6
8	100	800	50	112.3	-3	37.3	-8.7	23059	+2.1
9	100	800	100	114	-1.6	38.9	-3.9	22692	+0.5
10	100	1000	0	119.3	+3	44.3	+8.5	22340	-1.1
11	100	1000	50	110.4	-4.7	35.4	-13.3	23146	+2.5
12	100	1000	100	113.7	-1.8	38.6	-5.6	22726	+0.6

From table 4, it is observed that scenarios 2, 3, 5, 6 and 11 give the most positive outcomes compared to the base case. Apart from 2 scenarios (7 and 10), all the others resulted in more vehicle-kilometres and lower travel times and delays. In more detail, it is noteworthy that when the results of the 3 variables are compared, the following outcomes arise:

1) 80% compliance rate provides better results than 100% compliance
2) 50% ACC compliance rate is more preferable than 100% and, of course, even more than 0%
3) when it comes to q_{th} there is something interesting appearing: with 0% ACC penetration rate the results are better when q_{th} = 800 veh/h, however this occurs only in 80% compliance rate (scenarios 1 and 4). In 100% compliance rate (scenarios 7 and 10), but also in scenarios with 50% and 100% ACC rate, larger q_{th} results in lower times and more vehicles.

However, table 4 shows mostly the combination of the controller and ACC (apart from the cases where the ACC penetration rate is 0%). In the next three subsections it will be shown how each one of the proposed measures separately affects the traffic situation in the on-ramp bottleneck, as well as what the performance of the combination of the best outcomes per measure is. This is better explained in the following flow chart.

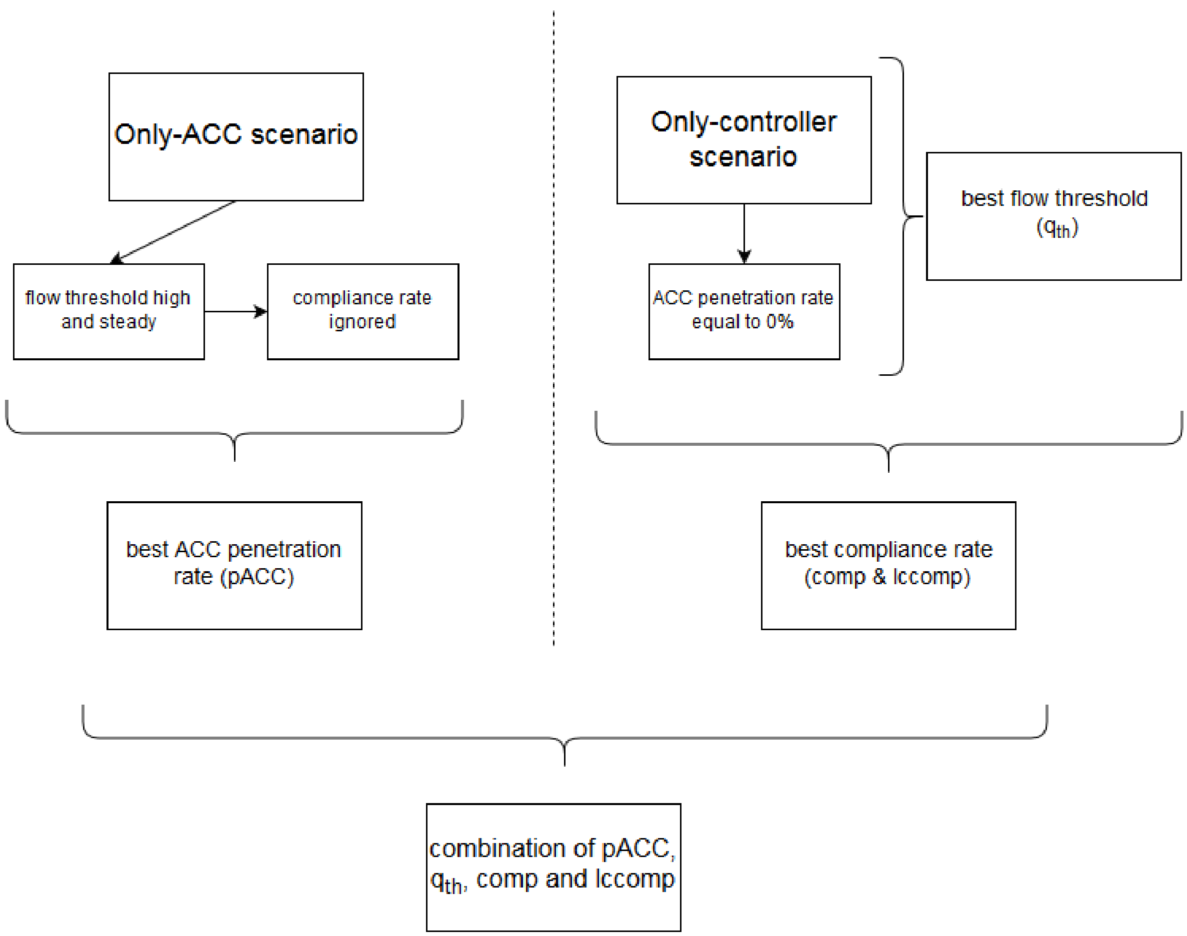


Figure 24 Scenarios under examination and definition of best pACC, q_{th}, and (lc)comp

4.4.1 Only-ACC case

During this case the flow threshold will be high enough so that the controller is not active at all during the simulation period. For 27/10 this threshold is found to be equal to 2000 veh/h. The variables that will change are ACC penetration rate and compliance rate. However, since the controller is not active during the whole simulation period the compliance rate value makes no difference. Thus, now the sub-scenarios of the “only-ACC” case differ only in the ACC penetration rate. In the following table those different scenarios, together with the initial base case are shown.

Table 5 “Only-ACC” case scenarios (best pACC definition)

pACC (%)	Travel time (s)	Travel time change (%)	Delay (s)	Delay change (%)	Vehicle-kilometres	Vehicle-kilometres change (%)
Base case	115.8	-	40.9	-	22583	-
100	104.1	-10.1	29.1	-28.8	23399	+3.6
90	102.7	-11.3	27.7	-32.3	23630	+4.6
80	102.3	-11.7	27.4	-33	23754	+5.2
70	101.5	-12.3	26.6	-35	23863	+5.7
60	101.8	-12.1	26.8	-34.5	23863	+5.7
50	102.3	-11.7	27.4	-33	23785	+5.3
40	103.5	-10.6	28.6	-30.5	23661	+4.8
30	104.9	-9.4	30	-26.7	23516	+4.1
0	115.8	0	40.9	0	22556	-0.1

The table shows what the situation would be only with the presence of ACC. However, the fact that in the last simulation run the ACC penetration rate is 0% should theoretically mean that there would be no changes in travel times, delays and vehicle-kilometres. The changes, which are still very small, are possibly created due to the fact that, compared to the initial base case scenario, there are now two more vehicle classes: ACC- equipped cars and trucks. As a result, just their presence affects the final outcomes. Another explanation of this small variance is only a simple stochastic outcome variation.

From table 5 it is observed that a penetration rate of 70% will give the lowest travel times and delays and the most vehicle-kilometres (the latter are the same as 60% but the times are slightly lower). When the penetration rate becomes 80% the outcomes are worse again and almost equal to the ones of 50% penetration rate. Therefore, for the data of 27/10/2015, 70% ACC penetration rate will be regarded as the ideal one.

From the previous paragraph, it can be deducted that the performance reaches its peak during a certain pACC range and then deteriorates again. This can be possibly explained as an optimal manual-ACC-equipped vehicle ratio that enhances the total traffic performance.

4.4.2 Only-controller case

In the next case, the flow threshold is tested at lower values. In this way, the controller will be active for longer times, thus its contribution to congestion reduction can be evaluated. In order to make this evaluation more robust, the ACC penetration rate will be 0%. First, the ideal flow threshold will be found and afterwards different compliance rates will be tested.

With regards to q_{th} some further explanation should be made. Most flow values (e.g. 800 veh/h) can be either in the free flow branch of the fundamental diagram or in the congested one. The lower the flow value above which the controller becomes active, the sooner in the free flow branch decelerations and lane changes have to be performed and, as a result, it is very possible that congestion will start forming sooner. Also, the controller will give deceleration and lane change orders within congestion, making it even more intense. Therefore, it is suggested that if the controller becomes active higher in the fundamental diagram it will provide better results. A possible solution would be a flow within the capacity drop range (i.e. higher than the top of the congested branch and lower than the top of the free flow branch). This can be defined during the "only-controller" case scenario.

Since from table 4 it was observed that the outcomes were better with 80% compliance rate, first this rate will be used in order to define what the ideal flow threshold will be. After q_{th} is determined, different compliance rates will be tested. In the next table, the results with different flow thresholds will be shown. By default the compliance rate is 80% and the ACC penetration rate 0%.

Table 6 "Only-controller" case scenarios (best q_{th} definition)

q_{th} (veh/h)	Travel time (s)	Travel time change (%)	Delay (s)	Delay change (%)	Vehicle-kilometres	Vehicle-kilometres change (%)
Base case	115.8	-	40.9	-	22583	-
2000	115.8	0	40.9	0	22556	-0.1
1400	113.1	-2.3	38.3	-6.4	22714	+0.6
1300	113.1	-2.3	38.2	-6.6	22697	+0.5
1200	112.7	-2.7	37.8	-7.6	22766	+0.8
1100	113.2	-2.2	38.3	-6.4	22698	+0.5
1000	113.6	-1.9	38.7	-5.4	22722	+0.6
900	113.7	-1.8	38.8	-5.1	22705	+0.5
800	112.6	-2.8	37.7	-7.8	22751	+0.7
700	113.2	-2.2	38.4	-6.1	22704	+0.5
600	113.6	-1.9	38.7	-5.4	22702	+0.5

From table 6 the outcomes show that the controller performs better when the flow threshold is either equal to 800 veh/h or 1200 veh/h. Taking these as default values, in the next two tables different compliance rates will be examined for each flow threshold.

Table 7 "Only-controller" case scenario with q_{th}=800 veh/h (best (lc)comp)

(lc)comp (%)	Travel time (s)	Travel time change (%)	Delay (s)	Delay change (%)	Vehicle-kilometres	Vehicle-kilometres change (%)
Base case	115.8	-	40.9	-	22583	-
100	120.9	+4.4	45.9	+12.2	22214	-1.6
90	114	-1.6	39.1	-4.4	22668	+0.4
80	112.6	-2.8	37.7	-7.8	22751	+0.7
70	113	-2.4	38.1	-6.8	22732	+0.7
60	113.1	-2.3	38.3	-6.4	22731	+0.7
50	112.9	-2.5	38.1	-6.8	22746	+0.7
40	113.5	-2	38.6	-5.6	22678	+0.4

Table 8 "Only-controller" case scenario with q_{th}=1200 veh/h (best (lc)comp)

(lc)comp (%)	Travel time (s)	Travel time change (%)	Delay (s)	Delay change (%)	Vehicle-kilometres	Vehicle-kilometres change (%)
Base case	115.8	-	40.9	-	22583	-
100	118	+1.9	43	+5.1	22430	-0.7
90	113.4	-2.1	38.5	-5.9	22705	+0.5
80	112.7	-2.7	37.8	-7.6	22766	+0.8
70	112.4	-2.9	37.5	-8.3	22777	+0.9
60	113	-2.4	38.2	-6.6	22739	+0.7
50	112	-3.3	37.2	-9	22756	+0.8
40	113.5	-2	38.6	-5.6	22697	+0.5

From tables 7 and 8, there are two outcomes resulting from the two flow thresholds. When q_{th} = 800 veh/h the ideal compliance rate is 80%, while when q_{th} = 1200 veh/h the best performance occurs when the compliance rate is only 50%. This can be easily explained; for a lower q_{th} the assistant will be active for a longer time, therefore it is important to have a high compliance rate. On the other hand, if the controller is active for a low time, the compliance rate is not as important as before.

4.4.3 Best variable combination

From subsections 4.4.1 and 4.4.2, the resulting ideal variable values in total, were:

- pACC = 70%
- q_{th} & (lc)comp: 800 veh/h & 80% respectively
- q_{th} & (lc)comp: 1200 veh/h & 50% respectively

The last simulation runs for 27/10/2015 were the combinations of the best variable values, thus they included these values as input. The case when q_{th} and (lc)comp are 800 veh/h and 80% respectively will be scenario A, while the other case will be scenario B. The resulting travel times, delays and vehicle-kilometres are the following for all the aforementioned scenarios.

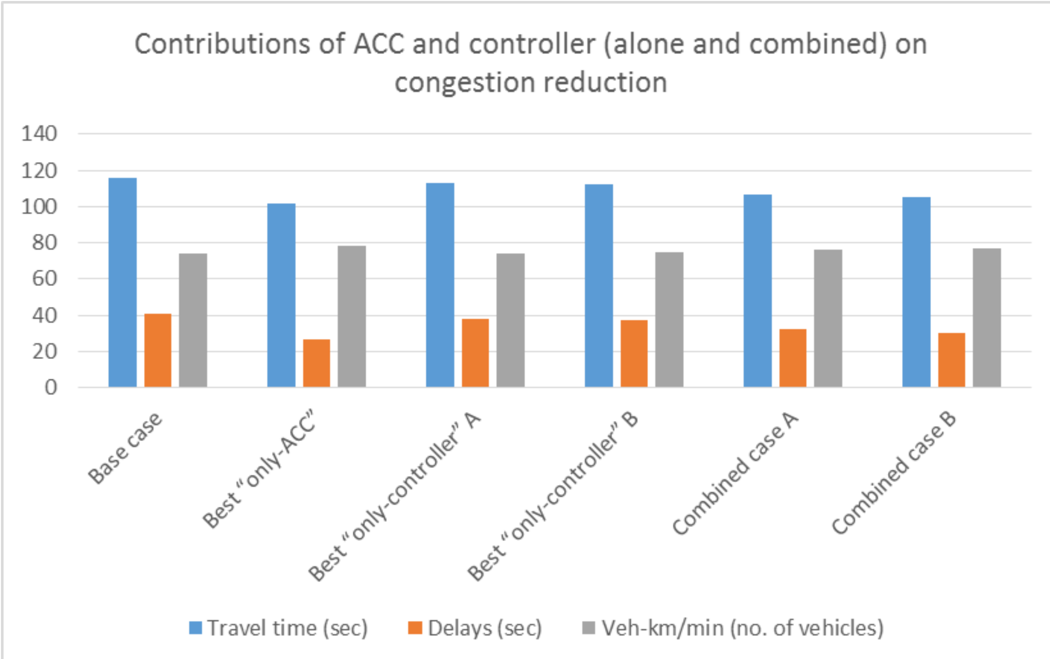


Figure 25 Scenarios on 27/10/2015 and their outcomes

From the analysis of tables 5-8 and figure 25, the next outcomes can be deduced.

1) The best results among all the tested ones were the ones where the controller was not active and the ACC penetration rate was 70%.
2) The "only-ACC" scenario resulted in far better results than the "only-controller" one. The vehicle-kilometres were more than the base case and the travel times and delays were a lot lower (the latter were up to 35% lower than the base case scenario).
3) The best pACC from "only-ACC" scenario and the best (lc)comp and q_{th} from the "only-controller" (for both cases) resulted in positive outcomes each one. Their combination gave better results than the "only-controller" scenario and worse than "only-ACC".
4) From the aforementioned points, it can be deduced that ACC has a greater impact on congestion reduction than the controller. However, a more robust result can be obtained after the check of 27/11/2015.

4.5 Analysis on 27/11/2015

For the second day the same process as before will be followed. First the "only-ACC" case will be tested, then the "only controller" and then their combination. The outcomes will be compared to the ones of 27/10/2015.

4.5.1 Only-ACC case

The flow above which the controller is inactive is 1900 veh/h. As in 4.4.1, the compliance rate does not influence the outcomes, thus only the ACC penetration rate is modified and the most effective value is found. The results are shown in the table below.

Table 9 "Only-ACC" case scenarios (best pACC definition)

pACC (%)	Travel time (s)	Travel time change (%)	Delay (s)	Delay change (%)	Vehicle-kilometres	Vehicle-kilometres change (%)
Base case	100.1	-	25.7	-	23071	-
100	102	+1.9	27	+4.8	23424	+1.5
90	100.7	+0.6	25.7	0	23623	+2.4
80	99.7	-0.4	24.8	-3.5	23705	+2.7
70	98.4	-1.7	23.6	-8.2	23749	+2.9
60	97.1	-3	22.3	-13.2	23752	+3
50	97.2	-2.9	22.6	-12.1	23712	+2.8
40	95.5	-4.5	21	-18.3	23696	+2.7
30	98.7	-1.4	24.1	-6.2	23560	+2.1

In table 9 it is observed that the performance is the best when pACC is 40 %.

4.5.2 Only-controller case

In this scenario, like before, it is regarded that no ACC is used and the controller's contribution alone is examined. First, (and with compliance rate equal to 80% by default), different flow threshold values are examined.

Table 10 "Only-controller" case scenarios (best q_{th} definition)

q_{th} (veh/h)	Travel time (s)	Travel time change (%)	Delay (s)	Delay change (%)	Vehicle-kilometres	Vehicle-kilometres change (%)
Base case	100.1	-	25.7	-	23071	-
1900	101.5	+1.5	27.2	+5.5	23045	-0.1
1300	85.8	-14.2	12.1	-53	23469	+1.7
1200	80.6	-19.5	7	-72.6	23598	+2.3
1100	81.4	-18.6	7.9	-69.3	23577	+2.2
1000	81.4	-18.6	7.9	-69.3	23588	+2.2
900	81.7	-18.4	8.1	-68.4	23571	+2.2
800	82.2	-17.9	8.7	--66.4	23538	+2
700	82	-18.1	8.4	-67.3	23545	+2.1
600	82.2	-17.9	8.6	-66.5	23521	+1.9

The outcome is clear and shows that the system performs more effectively when the flow threshold is equal to 1200 veh/h, exactly like in 27/10/2015. In the next step q_{th} is set equal to this value and the best compliance rate is examined.

Table 11 "Only-controller" case scenario (best (lc)comp definition)

comp, lccomp (%)	Travel time (s)	Travel time change (%)	Delay (s)	Delay change (%)	Vehicle-kilometres	Vehicle-kilometres change (%)
Base case	100.1	-	25.7	-	23071	-
100	93.1	-7	19.1	-25.8	23169	+0.4
90	85.2	-14.8	11.5	-55.3	23467	+1.7
80	80.6	-19.5	7	-72.6	23598	+2.3
70	86.3	-13.8	12.6	-51.2	23433	+1.6
60	88.8	-11.2	15	-41.7	23356	+1.2
50	97.5	-2.6	23.3	-9.6	23127	+0.2

The outcomes from this table are clear as well and show that the best results are obtained when the compliance rate is equal to 80%.

4.5.3 Best variable combination

From the two previous subchapters the best performing variable values are:

- pACC = 40%
- q_{th} = 1200 veh/h
- (lc)comp = 80%

Those values are put together in the last simulation run, forming the combined case scenario. In the next chart, this scenario, as well as the best "only-ACC" and "only-controller" are presented.

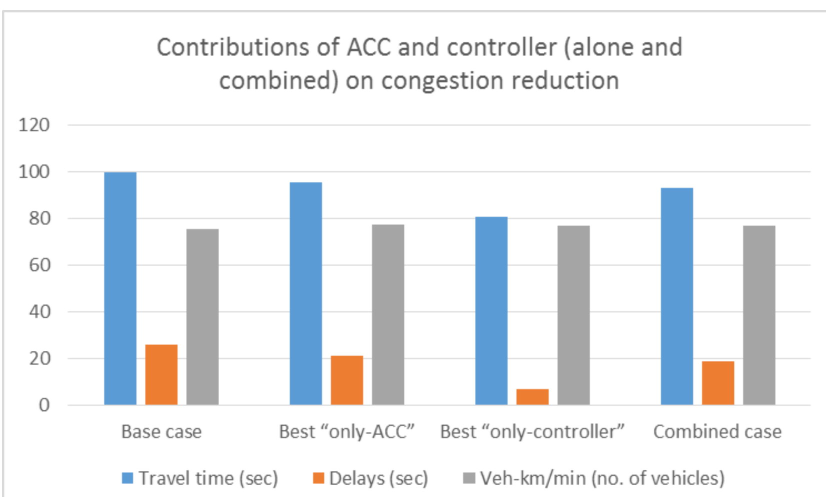


Figure 26 Scenarios on 27/11/2015 and their outcomes

Since both days were examined and the outcomes are more robust, there are certain deductions that can be made.

1) Each measure (ACC and controller) separately affects the travel times and delays at a positive extent.
2) On 27/10/2015 the initial travel times and delays are higher and the vehicle-kilometres fewer than on 27/11/2015. When the “only-ACC” and “only-controller” scenarios of both days are observed, it is remarkable that the ACC is more efficient on 27/10 and the controller more efficient on 27/11. Therefore, depending on the initial delays, the effectiveness per measure can vary.
3) The outcomes of the combined scenarios were between the ones of “only-ACC” and “only-controller” scenarios. However, a more careful look (especially in 27/11/2015) shows that the outcomes of the combined scenarios are closer to the ones of “only-ACC” scenarios. Hence, if both measures are implemented simultaneously, they will perform better when the congestion is more severe and the travel times and delays higher.

5. Conclusions and recommendations

5.1 Conclusions

On-ramps are among the most usual bottleneck locations. The merging process results in drivers attempting to align with each other, leading to accelerations, decelerations and lane changes that trigger congestion themselves.

One of the on-ramp bottlenecks is located on the A20 highway. After the acceleration lane, congestion begins and it propagates upstream, affecting vehicles in the highway and resulting in higher travel times and delays. A measure to tackle these problems is the improvement of the communication between highway and merging vehicles. This communication consists of information on neighbouring vehicles, more precisely their speeds and positions. The right-lane-highway drivers know when the next merging vehicle will enter the highway and are asked to adjust their speeds or locations in order to make space. The former is achieved with courtesy yielding and the latter with lane changing towards the left. If a right-lane vehicle should move to the middle lane, a middle lane driver has to adjust their speed and location as well.

The aforementioned communication can be achieved through a controller being located at the merging point and detecting vehicles and their characteristics at both streams. Then it calculates when the on-ramp and right-lane vehicles will reach the merging point and transmits the proper instruction to the right-lane vehicle. With regards to courtesy yielding, the second smart technology being applied (only on highway vehicles) is ACC; ACC-equipped vehicles can adjust their speed faster, more easily and with higher precision.

The ITS under investigation are modelled with a microsimulation programme, called MOTUS. The input is data from two different days, more precisely flows and mean speeds per minute during the morning peak at detectors located on the highway. The output is vehicle-kilometres that are travelled at the studied section during the peak, as well as their mean travel times and delays.

During the analyses, different scenarios were investigated, at which certain input variables (ACC penetration rate, flow above which the controller is active and drivers' compliance rate) were given different values in order to determine when the best performance was achieved. First, the traffic performance only with the controller implementation was examined. Then the controller was excluded and the performance only with ACC-equipped vehicles was tested. From those two cases the best-performing variable values were obtained and combined to determine if their combination gives better results.

The outcomes were very interesting. First of all, it was observed that when the initial congestion is more severe, the ACC implementation had a more effective contribution to its relief than the controller. On the other hand, the controller was more effective the second day under simulation, when the congestion was not as heavy.

The reason for this difference can be easily explained. The controller imposes changes in traffic state (accelerations and decelerations), as well as lane changes. The former result at some extent from the use of ACC too. However, lane changes are one of the reasons of congestion formation, since they can be considered as disturbances on traffic stability. In that sense, the lane change advice provided by the controller is regarded as a necessary evil that reduces its effectiveness. Prior to gap creation, a lane change within the highway results in decelerations by upstream vehicles and traffic disturbances. If the initial delays are lower, the need for lane changes can be diminished, therefore the merging assistant gives mainly deceleration and acceleration advice. This is possibly the reason why the controller has a more significant performance at days with smaller initial delays.

On the second day, with lower initial delays, the controller performed outstandingly. Since the traffic flow was initially smoother, the lane change advice of the controller almost made delays disappear. Therefore, although lane changes can cause congestions themselves, the way they are imposed by the controller annihilates their negative effects. The controller can, thus, be a really effective measure in days when delays are a smaller percentage (around 20%-25% or less) of total travel time.

When the measures of ACC and controller are combined they result in positive outcomes, however their performance lies between the ones of ACC and the controller separately (in some cases around the mean performance of the two) and not as a sum of them. The factors that mostly affect the outcomes are the ACC penetration rate and the drivers' compliance rate. The flow threshold of the controller does not affect the outcomes as much.

5.2 Recommendations

The findings of the research gave results that could be proven useful when ITS implementation at on-ramps is examined. There are, however, certain recommendations that can be made for further improvements.

- During this research there were certain assumptions being made, which are not compatible with reality. The most important of them is that vehicles drive with steady speed from the moment they are detected until they reach the merging point. Also, it is assumed that trucks have a standard percentage among the whole traffic, stay only on the right lane and never overtake. All these simplifications should be taken into account before any further research.
- In order to get more robust outcomes two days were examined. However, still this sample is very small compared to the fact that these congestions occur almost at a daily basis. Further research should include a higher sample in order to obtain more solid outcomes.
- One of the most important components of this research is human behaviour. During the simulation it was assumed that there are standardised compliance rates, i.e. percentage of drivers that will comply with the provided system feedback and either follow the advised speed or drive with their desired speed. However, human behaviour goes beyond that and is far more complex. For example, drivers may be unwilling to change lanes or do it very close to the merging point. Also, it is possible that a driver may get instructions that are regarded as difficult or impossible to follow. For that reason, these systems should be possibly tested in real conditions, not only with field tests, but also with experiments in real traffic without every driver being necessarily aware of the experiment taking place.

In total, the merging assistance cannot be effective if the applied measures start at or after the merging point. Drivers need time to adapt to the merging environment and the provided advice. These obstacles can be avoided if the driving procedure becomes fully automated but this is not something that can occur in the near future. Moreover, difficulties can be present in case the speeds at the two streams (highway and on-ramp) have high differences, since the adaptation of the on-ramp vehicles to the highway speed cannot be accomplished at once.

The main conclusion is that the merging assistance, irrespective of which measure is applied, should begin prior to the merging point, at a time high enough so that all the involved vehicles can be fully prepared. In case the provided assistance is in the form of a controller, thus no direct communication is present, the controller should have constant observation of the traffic state of each vehicle, thus detect any changes in speeds and make the provided advice more dynamic. Nevertheless, the advice should be altered at such an extent that the drivers will not require high time to adjust to those modifications.

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