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Evaluation and modelling of the traffic flow effects of truck platooning

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ABSTRACT

With automated and cooperative driving making its breakthrough, and related systems in fast development, their future influence and impact on roads and traffic may be extensive. Truck platooning is such an application that relies on the development of Cooperative Adaptive Cruise Control (CACC) and is said to be practice ready. While the main advantages of truck platooning lie in emission and energy reduction, claims are also being made for the influence on traffic flow. In this paper, we pose hypotheses based on some of the main claims. We also attempt to substantiate and give quantitative proof of the potential effects of truck platooning on traffic flow performance. The simulation model LMRS-IDM + is extended to encompass the main influencing dynamics related to potential effects of truck platooning, based on empirical findings. The effects of truck platooning were tested for the influence of traffic states, truck gap settings, platoon sizes, and the share of equipped trucks. This resulted in outcomes regarding the total traffic performance, the performance of traffic at ramps, and the ability of a platoon to remain platooning as part of a case experiment performed on a part of the Trans-European ITS Corridor. The results showed that truck platooning may have a small negative effect on the total non-saturated traffic flow, however with a much larger negative effect on saturated traffic flow. However, drivers may be reluctant to platoon in saturated traffic in any case. The ability of inflowing traffic to merge at on-ramps was found to be affected by truck platoons, with platoon disengagements occurring under various conditions. The applied gap settings for platooning trucks did not significantly affect the merge time, while a higher gap did lead to a higher number of disengagements. The ability of trucks to platoon was positively affected by a greater percentage of equipped trucks and by larger platoon sizes. Shorter gap times also slightly improved the ability of trucks to remain in platooning formation. Finally, recommendations are given to improve platoon strategies and for policymakers to only allow truck platooning outside of busy (near-) saturated traffic, even though drivers may be reluctant to use the system in these conditions. Also, recommendations are made to investigate potential differences in the effects between the European and American contexts for truck-platooning.

1. Introduction

Automated driving has been explored and researched for many decades, with many tracing the first steps as far back as the 1930s. Since then, much research has been performed, with ATA (2015) and Tsugawa et al. (2016) giving a good overview of milestones throughout the years. Recent developments that have seen the first driver assistance systems and partially automated vehicles

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Nomenclature

d	lane change desire
d_{free}	desire threshold for free lane changes
d_{sync}	desire threshold for synchronized lane changes
d_{coop}	desire threshold for cooperative lane changes
T_{max}	maximum/normal desired gap [m]
T_{min}	minimum desired gap (lane changes) [m]
T_{plat}	the desired gap when platooning [m]
T_{cur}	current actual gap [m]
a	maximum acceleration [m/s^2]
b	maximum deceleration [m/s^2]
d_r	desire to follow a route
d_s	desire to gain or maintain speed
d_b	bias for right-keeping behaviour
d_c	desire for courtesy lane changes
d_t	desire for trucks not overtaking on the 3rd lane
v_0	desired speed [m/s]
v_{sync}	speed threshold for synchronisation [m/s]
τ	headway relaxation time [s]
s	distance gap [m]
s_0	stopping distance [m]
s^*	dynamic desired headway [m]
T	current desired gap [m]
c_{lc}	level of courtesy for courtesy lane changes
k	CACC leader acceleration sensitivity
TTS	the total time spent [hours]
TND	the total network delay [hours]
n	maximum platoon size
TT_i	total travel time of vehicle i [s]
TT_{ff}	free flow travel time [s]
PT	platooning time (PT) ratio

introduced on our roads. Different definitions of automated vehicles exist (NHTSA, 2016; Gasser et al., 2012; SAE, 2018), with Gasser et al. (2012) defining four levels of automation from driver assistance systems, to partial automation, high automation and finally full automation. We will address the levels of automation based on the SAE levels. Adaptive Cruise Control (ACC) is an example of SAE level 1 vehicle automation, that allows a vehicle to control the longitudinal driving task in free driving or car-following, while a human driver controls the lateral movement. Level 2 automation represents partial automation, in which the lateral control of a vehicle in a lane is also controlled by the vehicles automated systems. In the higher levels of automation, a vehicle may have complete control over the vehicle, under certain conditions on certain roads and for SAE level 3 with a driver still required to retake control when requested. During this time, vehicle cooperation has also been researched and developed, which allows vehicles to communicate through short-range wireless communication (Ploeg et al., 2011). This allowed Cooperative-ACC (CACC) to be developed as a way to greatly increase vehicle control and capabilities (Ploeg et al., 2011). These developments did not go unnoticed by the long-distance hauling community, who envisaged great benefits from the automated and cooperative technology (Harker, 2001). This eventually led to the development of what is now generally considered truck platooning. The term ‘vehicle platooning’, or ‘truck platooning’, when referring to trucks, in its broadest sense, uses radar, video and vehicle-vehicle communications to form and maintain a close-headway formation between at least two in-lane vehicles, controlling the vehicles longitudinally and sometimes laterally at highway speeds (ATA, 2015). This means that truck platooning can be defined as either level 1 or level 2 and even higher levels of automation, depending on the level of control by the human driver. Most current field operational tests and developments focus on level 1 or level 2 trucks with a driver actively involved.

There have been many claims in regard to the main benefits of truck platooning as a business case is constructed to back their development and deployment. The main benefits cited are a reduction of fuel consumption (Browand et al., 2004; Dávila et al., 2010; Lu et al., 2014; Tsugawa et al., 2016; McAuliffe et al., 2018), reduction in emissions (Browand et al., 2004; Dávila et al., 2010; Lu et al., 2014) lower labour costs (Janssen et al., 2015), improved safety (Aki et al., 2012; Dávila et al., 2010) and traffic flow improvements (Kunze et al., 2009; Motamedidehkordi et al., 2016; Van Arem et al., 2006). The first two potential benefits are often seen as the most important and have been proven in various laboratory, simulation and field operational tests. There is growing consensus that fuel saving gains can be achieved of about 5% for the leading truck and in the range of 10–15% for following trucks (Browand et al., 2004; Lu et al., 2014; Nieuwenhuijze et al., 2012; Tsugawa et al., 2016) and in some cases as high as 20–25% under ideal conditions (Al Alam et al., 2010; Browand et al., 2004; Dávila et al., 2010; Lu et al., 2011; Tsugawa et al., 2016).

It is often argued that a reduction in labour costs is required to construct a positive business case and can be made possible due to longer rest periods for drivers in automated trucks and operations efficiency. The safety argument is often mentioned (Association, 2016; Dávila and Nombela, 2010; EU2016, 2016), but has yet to be proven from research. Finally, the effect of truck platooning on traffic flow performance is also often mentioned. However, in-depth research into actual overall and generic quantitative benefits on traffic flow lacks, despite increasing traffic flow evidence for specific contexts. There are a number of issues that need to be considered, such as the effects of shorter headways on capacity or improved traffic flow stability, but also potential negative effects such as blocking at ramps. The majority of these positive and detrimental effects will mainly be present on busier inter-urban road networks, with mixed level of service and higher number of ramps. The first main contribution of this paper lies in giving a broad evaluation of the traffic effects of truck platooning as far as is possible with the current development of modelling and feasibility of real-life testing. Experimental testing on all considered aspects is currently infeasible; however using empirical data from fundamental tests and furthering modelling techniques allows credible predictions to be made. The second main contribution of the paper lies in the extension and calibration of current state-of-the-art models to be able to extensively evaluate truck platooning. In the paper, we aim to give an overview and discussion of the potential traffic flow effects of truck platooning and give a quantitative estimation of some of the main effects of truck platooning on traffic flow performance through a simulation experiment.

The potential effects of these aspects are reviewed in the following section. In Section 3, we give a description of the applied model and the basis for the model. Section 4 presents the simulation case and sensitivity analyses, and the results of the case are given in Section 5, followed by a discussion of the results and the main research questions in Section 6.

2. Influence on traffic flow

The effects of truck platooning on traffic flow can be split into different categories, depending on their source and type of influence. To analyse the potential influencing variables, we define two main categories: the longitudinal traffic effects and vehicle interaction effects. The longitudinal effects encompass all the effects that directly affect longitudinal traffic flow, such as traffic stability, aggregated vehicle headways, etc. Vehicle interaction effects look at the influence of interaction between vehicles, which for truck platooning mostly involves the influence near ramps and weaving-sections.

2.1. Longitudinal traffic flow effects

The three main effects on traffic flow from longitudinal driving that potentially have the greatest effect are discussed. These are the *time-headways* or gaps between vehicles, *traffic homogeneity* and *traffic stability*. Various authors have previously mentioned that these aspects may have a significant effect and are cited per aspect.

2.1.1. Capacity and time-headways

The longitudinal effects on traffic flow are important when considering the capacity and potential throughput of a road. The capacity of a road is defined by the number of vehicles that can pass in a set time period and is directly related to the following distance of vehicles (Highway Capacity Manual, 2010). Therefore the time gap between vehicles has a direct effect on capacity and traffic flow. Note that we use the term *time gap* here that is defined as the time between two vehicles from the back of the predecessor to the front to the follower. *Time-headway* refers to time between the front of two vehicles, and is correlated to the time gap. For the operational capacity, we are interested in the aggregated time-headway. Literature indicates that values in the future may be achieved as low as 0.3 s (Van Arem et al., 2006) or 0.6 s for cars (Nowakowski et al., 2010; Milanés and Shladover, 2014). If these gaps are maintained over a long enough time, they will also influence the aggregated time-headway and could potentially lead to higher capacities (Janssen et al., 2015; Nieuwenhuijze et al., 2012; Schermers et al., 2004; Van Arem et al., 2006). The use of dedicated truck platooning lanes with long platoons of up to 10 trucks could yield more than a doubling of capacity (Tsugawa et al., 2016). Tsugawa et al. (2016) investigated multiple different combinations of truck platoon size, following distance and speed. They found that even with two or three vehicle truck platoons, capacity gains could be achieved of up to 25% on a dedicated lane. However, they are quick to point out that erratic behaviour of normal passenger car drivers and motorcyclists do not need to be considered, therefore the truck platoon control systems did not need to be designed to respond safely to all of those erratic behaviours. For this reason, Tsugawa et al. (2016)'s results must be considered as a theoretical optimum for capacity increase. On roads with mixed traffic, defined as a combination of (partially) cooperative and automated and non-automated vehicles, such capacity gains will never be reached, due to a substantially lower penetration rate of platooning and the complex interactions. Due to these aspects, researchers often restrain from quantifying potential capacity gains and often just state that it is 'theoretically possible' based on a calculation of a single platoon.

2.1.2. Traffic homogeneity and stability

Truck platoons have also been found to potentially improve traffic flow through increasing overall traffic homogeneity (Motamedidehkordi et al., 2016; Nieuwenhuijze et al., 2012; Ramezani et al., 2018). Improvement of traffic throughput with increasing homogeneity has previously been concluded for CACC systems in passenger cars with sufficiently high penetration rates (Milanés et al., 2014; Calvert et al., 2012; Van Arem et al., 2006). Improvements in flow were found of nearly 10% for penetration rates of 30% of the vehicle population, and increased quadratically with the penetration rate (Shladover et al., 2012). Ramezani et al. (2018) recently performed a simulation driven analysis of the effects of truck-platooning using empirically derived data from various experiments. Their approach on a freeway corridor with significant congestion suggested that CACC trucks could improve traffic operations in terms of vehicle miles travelled, average speed and flow rate. The study also claimed that general traffic conditions were not affected. A simple transition in thought towards truck platooning is therefore not surprising. The premise is that platooning trucks maintain a much more constant speed and trajectory resulting in a positive effect on homogeneity of surrounding vehicles.

In regard to traffic stability, Ploeg et al (2011) states the short time gaps and inter vehicle spaces may actually increase disturbances in traffic flows. Any potential speed variations of the leading vehicle may be amplified by following vehicles, resulting in negative side effects on traffic flow (Nieuwenhuijze et al., 2012; Ploeg et al., 2011). And speed changes may be unavoidable in mixed traffic due to the behaviour of other unconnected vehicles (Tsugawa et al., 2016). The opposite is however also given as a possibility in research that states that traffic stability will probably increase with the presence of cooperative truck platoons (Bakermans, 2016; Bergenhem et al., 2012; Janssen et al., 2015). This will be dependent on highly reliable and accurate cooperative communication (Ploeg et al., 2015), and with increasingly improved controllers for inter-vehicle cooperation has already shown to be able to improve traffic flow in various cases (Milanés et al., 2014; Ploeg, 2014).

A main prerequisite of a theoretical capacity gain from truck platooning comes with the condition that the gaps during platooning must be maintained over a significant distance and time (ATA, 2015; Milanés et al., 2014), which complies with the definition of road capacity. This also applies for all potential gains from the longitudinal aspects. In mixed traffic, it is unclear to what extent this can be presumed to be realistic. If this is not possible, then it may be the case that truck platooning could have a negative overall effect on traffic flow, as suggested by Ploeg et al. (2011) and Tsugawa et al. (2016), however for this the evidence also lacks.

2.2. Lateral movement and vehicle interactions

Under ideal traffic circumstances, one may expect that certain improvements may be found in traffic flow, as described in the previous sub-section. Truck platooning in a closed system with exclusively equipped vehicles offers the greatest advantages. However, in mixed traffic with manual non-connected and non-cooperative vehicles, interactions occur that affect the local driving dynamics of a platoon of trucks and the local traffic conditions. We consider two main interactions that can affect traffic flow. The first is cut-ins and cut-throughs, and the second is altered overtaking strategies.

2.2.1. Cut-ins

One of the main difficulties often mentioned in literature for truck platooning is the so-called blocking-effect. The blocking-effect refers to an increased difficulty for other non-platooning vehicles to laterally pass through or around a platoon of trucks. This often occurs when a vehicle needs to exit at an off-ramp, enter at an on-ramp, or perform a weaving action (Nowakowski et al., 2015). Thus, when another vehicle is required to make a mandatory lane change in the vicinity of a platoon, this results in two common tactics, which are related to the two difficulties mentioned here. These are cutting through a platoon or manoeuvring around it.

Often when a vehicle has limited time to perform a lane change manoeuvre, there is an increased probability that it will cut-in in between two trucks to reach its desired lane. Although it is generally thought to be undesirable to drive between trucks, especially when the trucks are in close proximity, it remains very possible to do so. Yang et al. (2018) have found that even trucks driving at gaps of 0.6 s at 65 mph (approx. 100 km/h), which equates to a gap of 17.5 m, vehicles would still be willing to use the gap to change lanes by cutting through a truck platoon. Other research has found similar behaviour from other drivers, willing to accept very small gaps to perform required lane change manoeuvres, especially in the vicinity of ramps, and that such behaviour is just about unavoidable (Kunze et al., 2009; Nowakowski et al., 2015). Cut-ins and cut-throughs will almost certainly affect the CACC system used for truck platooning and in turn affect the platooning formation. Cut-ins have three main effects on the platoon, and mainly on the first follower behind the cut-in vehicles (Milanés et al., 2016):

- Firstly, the inter-vehicle distance is suddenly decreased, potentially causing the following vehicle to brake to return to a desired following distance.
- Secondly, the cut-in vehicle will serve as the leading vehicle for the following truck, depending on the CACC settings.
- Thirdly, the ability to maintain CACC driving diminishes and retracts to ACC, presuming the cut-in vehicle is non-cooperative with the trucks.

In the case of a cut-through, the same disturbances apply, only with a cut-through, the platoon has the opportunity to reconnect after the vehicle has left the lane on which the platoon is present. With a cut-in, the platoon will disperse, at least for a while. Some current trucks already make use of ACC, however there is little evidence to its use in busier traffic, mainly due to sudden responses and trust issues due to cut-ins (Rajaonah et al., 2006; Zhang et al., 2004). In case a cut-in vehicle has a higher speed than the truck, the ACC doesn't have to respond, but the actual response would depend on the actual controller used. Increasingly, controller design is improving, and subsequently responses to cut-ins should also improve. If a cut-in vehicle would brake in front of a truck would lead to more serious consequences, also for the ACC vehicle.

Cut-ins and cut-throughs have the ability to negatively affect the main goals of truck platooning, such as reduced energy consumption and emissions, due to braking manoeuvres of the following truck during a cut-in (Aki et al., 2012; Nowakowski et al., 2015). However, recent evidence has shown that the effects of cut-ins on energy consumptions using the latest controllers may now only have a minor effect (McAuliffe et al., 2018). Furthermore, traffic homogeneity and stability is also affected during a cut-in. A sudden braking action causes a disturbance in traffic flow that has the potential, especially in moderate to busy traffic, to exacerbate into a shockwave and create upstream congestion. Tabibi (2004) found that the discontinuation of platoons near ramps, has the potential to increase local operational capacity up to 7–15%. Such actions may be deliberate design choices for CACC operations to maintain the goals of truck platooning, to prevent unsafe cut-throughs (ATA, 2015) and to prevent deterioration of traffic flow performance.

2.2.2. Overtaking strategies

The second consequence of the blocking effect is altered passing strategies by other vehicles to pass or sit behind a platoon. It is not known what portion of vehicles will choose this option compared to cutting-through and under which conditions. Nevertheless, it is known that this will happen and that it may also have an effect on traffic flow. A vehicle requiring to take an off-ramp or perform a weaving manoeuvre would be required to make a choice to reduce speed and change lane behind the platoon, or to substantially increase their speed and overtake the entire platoon. In both cases, there is the potential to create both unsafe circumstances and disturbances in traffic flow (Tabibi, 2004). For braking followed by an abrupt lane change, it is easy to understand how this may cause a disturbance and negatively affect traffic, as well as lowering the aggregated speed of traffic. Also, attempting to overtake an entire platoon within a limited time period and in busy traffic may lead to unsafe lane change manoeuvres that in turn not only affect traffic safety, but also may cause disturbances to traffic flow. Another potential negative effect of blocking comes from on-ramps. On on-ramps both speeding up and braking to get around a platoon are feasible tactics. However, as on-ramps are generally limited in length, there is also a real probability that a vehicle may almost come to a standstill in a bid to manoeuvre behind a passing truck platoon. This would either mean entering a motorway at a dangerously low speed or not being able to enter the motorway at the ramp and therefore remaining stationary on the on-ramp and in turn affect other vehicles on the ramp. The number of platooning trucks obviously also affects this issue and is one reason why truck platoons of two or three trucks are currently mostly considered. At present, there is no empirical quantification and very little experimental evidence to allow the quantification of these affects. Nevertheless, they are effects that have been found from FOT's and are realistic to presume.

3. Model setup and goals

This chapter describes the model that is used to simulate both regular human driver behaviour, as well as truck platooning CACC vehicles. As truck platooning affects vehicle interactions, both in terms of longitudinal following as well as interactions between lanes, microscopic simulation is an obvious choice. By investigating these interactions, simulation will give us quantifiable insights into the effects of truck platooning on traffic flow performance. This section discusses the selected base model, including changes to this model to explicitly consider these interaction mechanisms for truck platoons. The section starts with us posing four hypotheses, which are considered in the course of the paper to give direction to the research.

3.1. Goal and hypotheses

The main goal of the case is to gain quantitative insight into the effects of truck platooning on the wider traffic flows. From Section 2, we derived that there are potential effects relating to longitudinal traffic flow due to changes in gaps and the potential that traffic stability will be altered. Furthermore, the interaction between vehicles is expected to be influenced by truck platoons, which includes different lane change strategies and tactics by other road users and the probability that platoons will be disturbed in operation due to cut-ins and cut-throughs. To this end, the case in Section 4 reviews the extent to which traffic is affected by truck platoons of different lengths, frequencies and gaps, and will consider traffic situations in which interactions with truck platoons take place at ramps and a weaving section, as well as considering the relevance of different traffic states. The scope for the investigation focusses on busier 'inter-urban' networks in which lower levels of service below free-flow exist often also with higher numbers of ramps, such as in Europe or many coastal areas of the US. On completely quiet free-flowing routes, many of the described issues should not arise.

To aid the discussion, we pose four hypotheses that will be evaluated and the results from the case will be discussed in Section 5. These hypotheses are:

1. Truck platooning has a marginal positive effect on traffic flow performance, if any.
2. The main positive effects on traffic flow performance are from truck platooning close proximity driving and improved traffic stability, while the greatest negative effects are from blocking at ramps.
3. Longer platoons have a greater positive traffic flow performance effect, as do shorter gap-times while platooning and a greater penetration rate of truck platooning capability.
4. Platooning in dense traffic is substantially less effective for traffic flow than in quieter traffic.

The hypotheses are posed as non-statistical hypotheses to be used to aid and structure the answer to the overall questions posed in this research, rather than giving the answer themselves. They are not intended to be statistically evaluated and be the main focus of the paper.

3.2. Base model

The selected base model is the Lane change Model with Relaxation and Synchronisation (LMRS) (Schakel et al., 2012) in combination with the IDM+ car-following model (Schakel et al., 2010). The incorporation of relaxation and synchronisation, which many models lack, is important for realistic interactions with truck platoons at merge locations. In particular, both relaxation and synchronisation allow cut-ins, rather than rejected gaps or unreasonable acceptance thresholds. Also, the LMRS is modular, and can easily be extended with incentives for lane changes. Some extensions are made to the model that pertains to truck platooning. Note that these additions to the base model are necessary, but not the main focus of this paper. They are discussed in the following subsections, but first a short overview of the LMRS is given to explain the relevant main principles. For additional information, the reader is referred to Schakel et al. (2012).

The LMRS is based on lane change desire d that comes from a number of lane change incentives. Desire has a typical range between -1 and 1, where only positive values may trigger a lane change. The positive range is divided in 4 area's by $0 < d_{free} < d_{sync} < d_{coop} < 1$. Various behaviours occur in these ranges:

- $d < d_{free}$ (No LC); the lane change desire is too small to perform a lane change.
- $d_{free} \leq d < d_{sync}$ (FLC); a lane change is performed, but only if it happens to be possible.
- $d_{sync} \leq d < d_{coop}$ (SLC); if the adjacent gap is not suitable, the subject vehicle will adjust speed and position to the target lane.
- $d_{coop} \leq d$ (CLC); the follower in the target lane notices the potential lane changer, and yields to provide a suitable gap, i.e. gap-creation or courtesy yielding.

For each of the lane change incentives, a level of desire is calculated. The incentives are aggregated as shown in Eq. (1). In this paper, we introduce an additional incentive, namely the desire d_c for courtesy lane changes, described in Section 3.2.1.

$$d = d_r + \theta_v \cdot (d_s + d_b + d_c + d_t) \tag{1}$$

where

- d_r is desired for following the route and infrastructure
- d_s is desire to gain or maintain speed
- d_b is a bias for right-keeping behaviour
- d_c is desire for courtesy lane changes
- d_t is desire for trucks not overtaking on the 3rd lane
- $\theta_v$is a factor by which voluntary incentives are considered

The LMRS is used in combination with the IDM+ (Schakel et al., 2010). The IDM+ depends on a drivers own speed v, speed difference with the leader Δv and the space gap to the leader s as given in Eqs. (2) and (3).

$$v' = a \cdot \min\left(1 - \left(\frac{v}{v_0}\right)^4, 1 - \left(\frac{s^*}{s}\right)^2\right) \tag{2}$$

$$s^* = s_0 + v \cdot T + \frac{v \cdot \Delta v}{2\sqrt{a \cdot b}} \tag{3}$$

where

- a is the maximum acceleration
- v_0 is the desired speed
- s_0 is the stopping distance
- T is the current desired gap
- b is the maximum comfortable deceleration
- s^* is a *dynamic* desired headway

Other LMRS parameters, required to understand the remainder of this paper, are: the regular car-following headway T_{max}, the minimum acceptable headway when changing lane T_{min}, the relaxation time τ by which the headway T relaxes exponentially to T_{max} after a lane change, and the extent of spatial and temporal anticipation in following a route x_0 and t_0.

3.2.1. *Courtesy lane changes*

Although the LMRS provides cooperation through gap-creation (or courtesy yielding), it has no explicit form of courtesy lane changes, i.e. lane changes that are performed to provide space for the lane change of another vehicle (sometimes also referred to as cooperative lane changes, but for the LMRS this entails lane changes with longitudinal gap-creation). Courtesy lane changes are widely reported in literature (Wang, 2005; Marczak et al., 2013), and more importantly may facilitate lane changes by merging vehicles in critical situations. Truck platoons may lead to such critical merging situations, thus a realistic modelling of the effects of truck platoons on merging requires a model with courtesy lane changes.

We include courtesy lane changes by adding a voluntary lane change incentive with desire d_c. All vehicles i on an adjacent lane within an anticipated sight distance of x_0 are considered, but only one vehicle providing the strongest courtesy incentive, determines the desire. This is shown in Eq. (4). The desire is reduced linearly over space for adjacent leaders that are further away, reaching a desire of 0 for adjacent leaders at a distancex_0. In our simulation, we assume c_{lc}= 1, meaning a mainline driver can experience up to an equal amount of desire to change lane as the merging driver. Note however that the actual courtesy lane change only occurs if the gap is also acceptable, and other incentives do not counteract the desire. In other words, drivers perform a courtesy lane change simply "when possible", which means c_{lc}= 1 does not represent unreasonably strong sensitivity. Furthermore, (Daamen et al., 2010) found empirically that no merging vehicle was overtaken by multiple mainline vehicles, indicating a high degree of cooperation from mainline vehicles. A sensitivity analysis on c_{lc} is presented in Section 4.4.

$$d_c = c_{lc} \cdot \max\left(d_i \cdot \left(1 - \left(\frac{s_i}{x_0}\right)\right)\right) \tag{4}$$

where

- c_{lc} is a parameter in the range [0 … 1] that reflects the level of courtesy
- s_i is the distance gap to adjacent leader i, always smaller than x_0
- d_i is the desire of adjacent leader i to change to the lane of the vehicle

3.2.2. *Synchronisation and cooperation*

The LMRS is extended for synchronisation to improve overall validity. In the LMRS, a driver that has $d_{sync} \leq d < d_{coop}$ is itself synchronising, but not receiving cooperation from the target lane. This is fine in free flow traffic, or even in congested traffic when traffic in the target lane has equal or lower speeds. These situations smoothly progress into a lane change, either with or without consecutive cooperation. However, if speeds are low and the target lane has a higher speed, the synchronising vehicle will remain in a near-stationary state, blocking all following traffic, while vehicles in the target lane keep overtaking. This results in overly severe congestion, which mostly affects the merging vehicles. To overcome this, we disable synchronisation altogether if $d_{sync} \leq d < d_{coop}$ and $v < v_{sync}$, where v_{sync} is a relatively low speed below which drivers care less about synchronising. We choose a value equal to $x_0/t_0 \approx 24.7$ km/h, the same speed below which space is dominant over remaining time for the route incentive. One can think of this speed as the speed by which drivers continue moving alongside traffic in the target lane without sufficient gaps, until remaining space is critical and stopping is required. Note that synchronisation is always active for $d \geq d_{coop}$. A sensitivity analysis on v_{sync} is presented in Section 4.4.

3.3. Platooning model

The model is further extended to simulate platooning CACC trucks. This involves behavioural adaptation, the CACC car-following rules, and the platooning strategy.

3.3.1. Adaptations to lane change behaviour

We assume the platooning system is always used when possible for equipped trucks. Indirect modification of user behaviour is applied by reducing voluntary lane changes in case a truck is platooning. In particular, we use $d_s = d_c = 0$. This means lane changes are not performed in regard to speed or courtesy for other lane changing vehicles, as a platooning truck will remain in a platoon. All other incentives are retained, as these pertain to traffic rules or the route. Note that the first vehicle of a platoon does not have this behavioural adaptation, as our system applies no incentive to the driver to remain a platoon leader. Furthermore we assume that platooning trucks do not engage in cooperation (gap-creation, courtesy yielding) for lane changes of other vehicles. Note that the platoon leader is not considered to be platooning, and may slow down for cooperation.

3.3.2. Longitudinal CACC model

We simulate the CACC model by applying three different modes to CACC trucks:

- *Human mode*; this is the same as the model for human drivers, and is used for the evaluation of gap-acceptance.
- *ACC mode*; if an equipped truck does not have another equipped truck as its leader, the system is in ACC mode.
- *CACC mode*; with an equipped leader, an equipped truck goes into close following CACC mode.

Both automated modes are given in Eqs. (5)–(8), where a_{int} is the interaction term with the leader which is defined differently than in the IDM+. Note that the ACC model is equal to the model for human drivers, except for the parameter values for acceleration and gap, which allow us to capture the main differences between human drivers and ACC. Parameter a_{CACC} is the maximum acceleration of the CACC system (also in ACC mode), which reflects a different sensitivity to the leader. Parameter k $(0 \leq k \leq 1)$ is the extent to which the acceleration from the ACC part of the system changes towards the received acceleration of the leader a_l in CACC mode. The considered CACC model is thus assumed to communicate the acceleration to the following vehicle. By incorporating the leader's acceleration in the acceleration of the follower, any disruption of one truck should quickly affect acceleration of the following trucks. As this occurs rapidly, the absolute level of deceleration can be lower, i.e. we obtain a more stable car-following.

$$v' = a_{CACC} \cdot \min\left(1 - \left(\frac{v}{v_0}\right)^4, a_{int}\right) \tag{5}$$

$$a_{int} = \begin{cases} a_{int}^{ACC}, & notplatooning/ACCmode \\ (1-k) \cdot a_{int}^{ACC} + k \cdot \frac{a_l}{a_{CACC}}, & platooning/CACCmode \end{cases} \tag{6}$$

$$a_{int}^{ACC} = 1 - \left(\frac{s_{CACC}^*}{s}\right)^2 \tag{7}$$

$$s_{CACC}^* = s_0 + v \cdot T_{CACC} + \frac{v \cdot \Delta v}{2\sqrt{a_{CACC} \cdot b}} \tag{8}$$

The value of T_{CACC} is pivotal in both the ACC and CACC mode and depends on the mode, but is also affected by relaxation in a similar manner as humans. In particular, we assume the system is able to recognise a lane changing vehicle (i.e. by lane markings or angle), and momentarily accept smaller gaps. This means that the system balances between the momentary higher risk of a shorter gap, and the risk of causing head-tail collisions due to strong deceleration. In case of a lane changing vehicle, the current gap is $T_{cur} = (s - s_0)/v$. The CACC gap is then instantaneously set to this value, with a minimum of T_{plat}, the platooning gap of the system. Any lower value is considered too dangerous, even for a short while and even if large decelerations are required. Also, if the current relaxed value ofT_{CACC} $(T'(t))$ is smaller, this value is retained. This is captured in Eq. (9).

$$T_{CACC}(t) = \min(T'(t), \max(T_{cur}(t), T_{plat})) \tag{9}$$

For every time step that the gap is relaxed, it returns to the default values. This occurs as given in Eq. (10), where τ_{CACC} is the relaxation time of the system, and $T_{tar}(t)$ is the current target gap based on the mode. In particular we have $T_{tar} = T_{plat}$ if the truck is allowed to join with the leader, and $T_{tar} = T_{ACC}$ otherwise. Note that in this way, a change from CACC to ACC mode is also smooth, as T_{CACC} never changes instantaneously to a larger value, while T_{tar} does.

$$T'(t) = T_{CACC}(t - \Delta t) + \frac{T_{tar}(t) - T_{CACC}(t - \Delta t)}{\tau_{CACC}} \tag{10}$$

3.3.3. Platooning strategy

CACC platoons can be formed in many ways, including active strategies where trucks will accelerate or decelerate to find each other (Liang et al., 2015). In our case we rely on natural platoon formation, in combination with a long stretch of freeway being modelled upstream of our area of interest. To facilitate merging, platoons have a maximum size of n vehicles. The value of T_{tar} is set to T_{plat} only if the leader is an equipped truck, and the total platoon size (leading platoon plus the own vehicle) will not exceed n. This holds for all vehicles with the CACC gap in Fig. 1. Any following platoon vehicles are not considered. Instead, a follower will become a new platoon leader, while the own vehicle joins the downstream platoon (i.e. if B would join with A, C would detach). In all other cases T_{tar} is set to T_{ACC}. Thus, the ACC mode is used if there is no equipped leader, or a large gap needs to be maintained to not exceed the maximum platoon size.

The size of the platoon is *not* determined solely by the number of vehicles that have $T_{tar} = T_{plat}$, as this may already be the case for a truck approaching a platoon from a large distance (i.e. truck B), not allowing trucks behind the vehicle to platoon over a possibly long time period. To actually be counted as part of a platoon, two criteria need to be met: $T_{tar} = T_{plat}$ and $T_{cur} < T_{ACC}$. Thus, the vehicle is considered to be platooning if a small gap is being used as there is an equipped leader, and the vehicle has approached its leader to within T_{ACC}. This means that truck B operates the ACC mode, but with T_{plat}. If B comes within T_{ACC} of A, it would switch to the CACC mode.

The platooning strategy is shown in Fig. 1. There, truck A uses the ACC gap and mode as it would become the 4th truck in the platoon. Truck B is using the CACC gap as it could become the second truck in a platoon with A. But it is still far away from A (beyond the ACC gap) and is therefore not considered to be platooning. Truck C can consequently remain the 3rd truck in the second platoon. Truck D is lowering the gap temporarily for a lane changing vehicle. The speed of the platoon is determined by the leader truck, with the following platooning trucks adopting the leaders speed according to the dynamics and characteristics of the car-following model.

4. Case study

With limited opportunities for expansive field operational testing, we aim to give insights into traffic flow performance effects of truck platooning through simulation, using state-of-the-art models and the latest insights into the main influencing aspects of truck platooning on traffic flow and driving behaviour. A simulation case is performed for a real road corridor in which we consider the main factors derived from literature as described in Section 2.

4.1. Network

The case is carried out for a 56.6 km motorway corridor, derived from the Dutch motorway A67 near the city of Eindhoven. This is an interesting corridor that is well known as a freight-corridor from Germany to Belgium and through the Netherlands and will daily yield truck shares of 20% up to nearly 50% at times. At the same time, the A67 also overlaps with a busy commuter route (A2) that increases the interaction between truck and passenger car flows. The A67 is currently also in use as part of the Cooperative ITS Corridor Joint deployment (2014) from Austria through Germany to The Netherlands, and has been considered as an ideal corridor for truck platooning in the region. An overview of the experimental corridor is given in Fig. 2. In the figure, the accentuated areas are areas of interest for specific performance indicators pertaining to merging. There are 5 onramps and 3 off-ramps and a major weaving section present on the considered section of the corridor. Furthermore, a 30.1 km warm-up section is included at the start of the corridor in which trucks have the opportunity to naturalistically form platoons. No performance indicators are derived for this section. In real-life, there are also ramps on the warm-up section, however these have been removed as data was not available on this section. Instead, demand entering the section at Someren is shifted in time (20 min) and space (30.1 km). Also on the overlapping A2 motorway, a section of 1.1 km is included to allow traffic to form realistic distributions over the road. All on- and off-ramps also include some additional length. The main bottleneck is formed by a combination of onramp Geldrop, and off-ramp N2, where up to 50% may leave the freeway in the morning rush-hour.

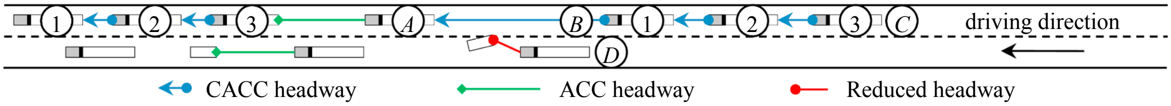

Fig. 1. Platooning strategy for a maximum platoon size of n = 3.

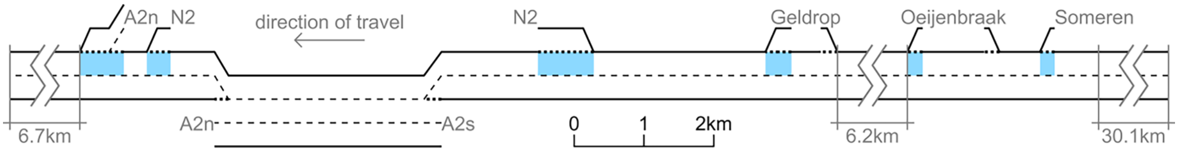

Fig. 2. Considered truck platooning corridor.

4.2. Calibration and vehicle settings

Three types of vehicles are defined for the case. These are: passenger cars, non-CACC equipped trucks, and CACC-equipped trucks. The variables of the **passenger cars** and **non-CACC equipped trucks** are based on calibrating the model to resemble overall traffic patterns on the A67. In particular we aim for a similar overall level of congestion, triggered by the correct bottleneck. For this it was sufficient to use the following parameter values:

- Most values are equal to the default values, as calibrated in Schakel et al. (2012). Important values are:
  - o Desired speed v_0 of cars is 123.7 km/h, with a standard deviation of 12 km/h.
  - o Desired speed v_0 of trucks is 85 km/h, with a standard deviation 2.5 km/h.
  - o Maximum comfortable deceleration b of 2.09 s.
  - o Headway relaxation time τ= 25 s.
- In Schakel et al. (2015), the model was calibrated to the same bottleneck on the A67 from empirical data. From this we use a_{car}= 1.56 m/s^2, and a_{truck}= 0.8 m/s^2.
- The gap T_{max} is distributed as in (Calvert et al., 2017), which was derived from empirical research. We only exclude the lowest bin of 0.2 s, as this is too small for our simulation time step. This results in a mean of 0.81 s, which is not far from the 0.89 s calibrated in Schakel et al. (2015). Note that the mean applied desired gap setting will not necessarily be the gap that vehicles will always drive at, but rather the gap when car-following in stable traffic. In practice (both on the road and in simulation), the mean gap distribution is higher, as vehicle are not always following or traffic heterogeneity doesn't allow it.
- We use T_{min}= 0.25 s to allow cut-ins in case of critical lane changes (i.e. very desired), even in a platoon if platoon gaps allow. The value is close to the 0.23 s in Schakel et al. (2015).

The resulting congestion patterns are shown in Fig. 3, and show that the bottleneck between onramp Geldrop and off-ramp N2

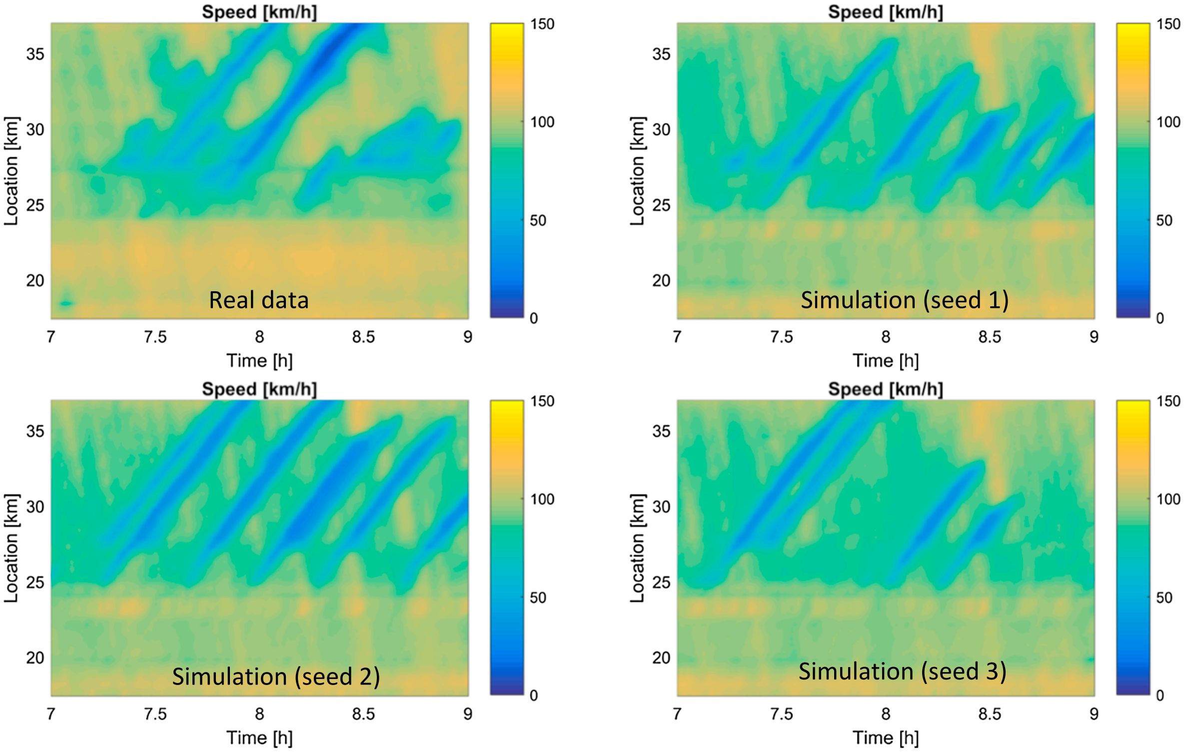

Fig. 3. Congestion pattern from real data, and 3 calibrated runs from simulation.

(28 km through 24 km) triggers congestion in the form of moving jams, some of which reach the upstream end of the considered section (excluding warm-up section).

Equipped-CACC-trucks are trucks that are able to platoon using CACC technology as in the described algorithm given in Section 3. These trucks share many parameters with non-CACC equipped trucks, including the parameters of car-following that determine the human-evaluated gap-acceptance for lane changing. The equipped trucks will be allowed to form platoons on the fly, when another equipped-truck is in the vicinity. Depending on the settings in the scenario, platoons of trucks will be limited to a maximum n of two or three trucks per platoon, while the platooning gap T_{plat} will be 0.3 s, 0.5 s or 0.7 s. Other CACC parameters are derived from empirical research (Milanés, and Shladover, 2014), and are:

- When an equipped-CACC truck cannot join with the leading vehicle, the ACC mode is applied with T_{ACC}= 1.2 s.
- We have a_{CACC}= 0.6 m/s^2 which reflects less aggressive car-following in line with goals of reducing fuel consumption.
- Headway relaxation time is set to τ_{CACC}= 10 s, which is shorter than for humans for safety reasons of the CACC system, i.e. the increased risk of the short gap opposed to strong deceleration should not pertain.

A balance between the ACC term and obtaining the leader acceleration is given by k= 0.5. We conducted a sensitivity analysis on single platoons to test where the first vehicle experienced a perturbation, and found a value of 0.5 to be a good balance between robustness and perturbation, without resulting in quickly changing uncomfortable accelerations. Fig. 4 shows a comparison of the CACC model for different values of k, as well as with the model for non-CACC equipped trucks for a theoretical platoon of 21 trucks. It can be seen that CACC equipped trucks decelerate strongly for lower values quicker than non-CACC equipped trucks, and even more so for higher values of k. However, for k> 0.5 the acceleration starts to become erratic and changes rapidly, which is uncomfortable and unrealistic. These results show no significant stability differences between non-CACC and CACC trucks, however, the CACC trucks are able to show this for lower acceleration (0.6 m/s^2 instead of 0.8 m/s^2) and a lower following headway (0.5 s instead of 0.81 s).

Scenarios

The effects of truck platooning are investigated using four main variables in the scenarios, namely the *traffic state*, as the basis for the scenario, *maximum platoon sizes, penetration of equipped-CACC-trucks*, and the *platoon strategy* given by the gap times while platooning. The traffic states are derived from the time of day in which a scenario takes place and also defines the base scenario's in which no equipped-CACC-trucks are present. A flow intensity-capacity ratio (I/C) is applied to indicate the ratio of the traffic demand compared to the normal capacity. Under normal circumstances, congestion will occur for an I/C value near or above 1.0. The base scenarios are:

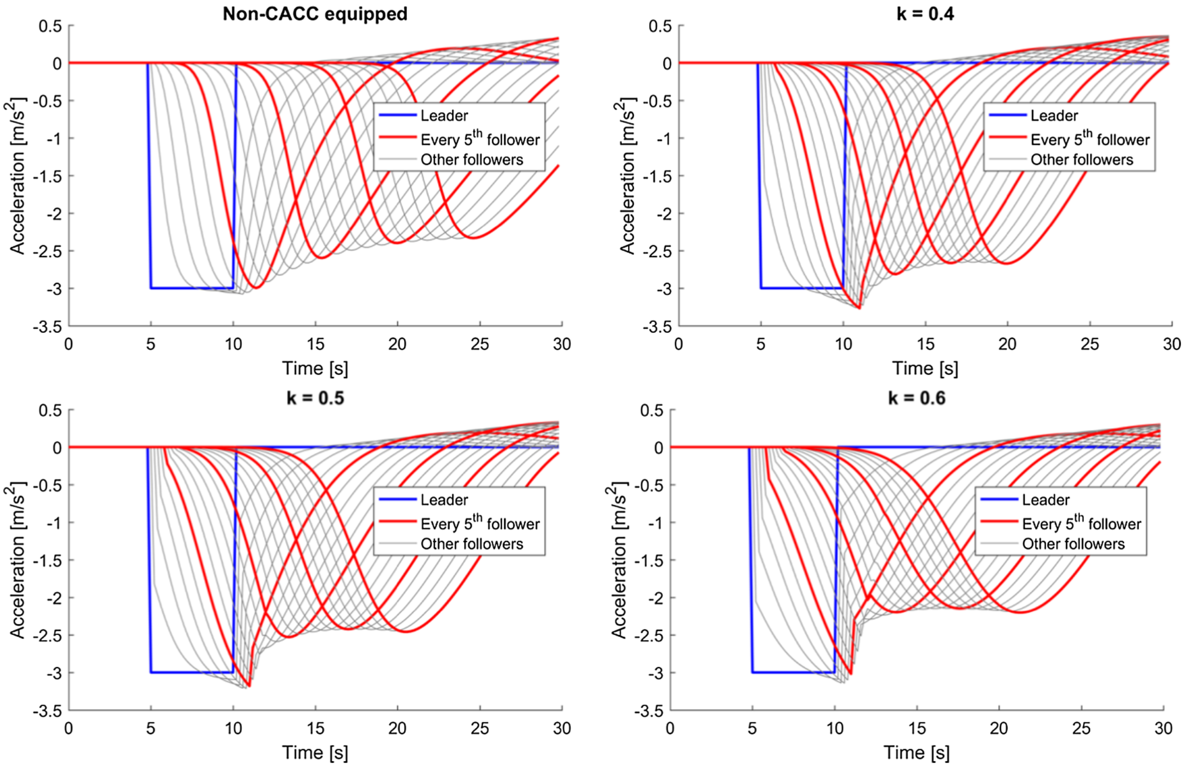

Fig. 4. Comparison of non-CACC equipped model and CACC model for different values of k.

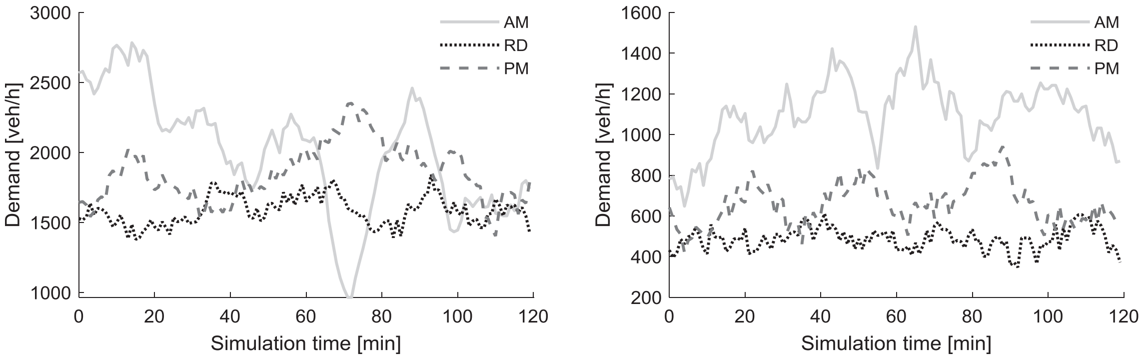

Fig. 5. Traffic demand profiles for the A67 (left) and Geldrop on-ramp (right).

- Morning (AM), 07:00–09:00, saturated traffic with an I/C ratio $>$ 100% and 30% trucks.
- Off Peak (OP), 12:00–14:00, quiet traffic with an I/C ratio of $\sim$60% and 40% trucks.
- Afternoon (PM), 16:00–18:00, busy non-congested traffic, I/C ratio of $\sim$80% and 25% trucks.

The traffic demand profiles (without warm-up time), that are a derived 10-minute moving average and calibrated from data, are shown in Fig. 5 for the main A67 road and for the busiest ramp location (Geldrop) to give an indication of traffic demand for the three different periods that are considered.

Each scenario considers a 120 min period, with a prior 45 min warm-up period allowing trucks to fully pass the 56.6 km corridor. Traffic flows are derived from real traffic counts from a representative day (13th September 2016). Within each scenario, the inflow of traffic is identical, as well as the composition of vehicle types, and follows the patterns obtained from data. Furthermore, maximum platoon sizes of two and three trucks are considered. Penetration rates of 20%, 50% and 80% of equipped-CACC-trucks are considered (note: equipped does not necessarily mean platooning), as well as time-gaps (T_{plat}) in platoons of 0.3, 0.5 and 0.7 s. Finally, for AM and PM, we consider an extreme scenario with a penetration rate of 100%, a time-gap setting of 0.3 s and an infinite maximum platoon size. These values for the extreme scenarios may not be considered completely realistic, but are performed to show the boundary values for the indicators from the impact of truck platooning in the case. 30 simulation runs are performed per scenario, which is more than sufficient to ensure validity. All combinations are shown in Table 1, giving 44 scenarios and 1320 model runs.

4.3. Performance indicators

As the main objective is to evaluate the effect on traffic flow performance, the main performance indicators are chosen with this in mind. The main quantitative KPI's are the *total time spent* and the *total network delay*. The total time spent (TTS) is defined as the total time that all vehicles spend on the analysed section of the corridor and is an indication of the total traffic fluency:

$$TTS = \sum_{i=0}^{n} (t_B^i - t_A^i) \tag{11}$$

where

- t_B^i is the time vehicle i passes location B
- n is the total number of vehicles in the entire simulation

Locations A and B are the start and end point of individual trips, excluding the 30.1 km warm-up section. The total network delay

Table 1
Overview of all applied scenarios (* indicates the 'extreme' cases).

Time period	% equipped trucks [%]					Max platoon length [n]			Intra-platoon time gap [s]			Number of scenarios
	0	20	50	80	100	Two	Three	∞	0.3	0.5	0.7	
REF AM	X											1
REF OP	X											1
REF PM	X											1
AM		X	X	X		X	X		X	X	X	18
AM*					X			X	X			1
OP			X				X		X	X	X	3
PM		X	X	X		X	X		X	X	X	18
PM*					X			X	X			1

(TND) is defined as the total time that vehicles are delayed compared to free-flow conditions and indicates the severity of congestion:

$$TND = \sum_{i=0}^{n} (TT_i - TT_{ff}) \tag{12}$$

where

- TT_{ff} is the free flow travel time along the corridor, corresponding to uncongested and unconstrained traffic conditions, that is, the desired speed
- TT_i is the total travel time of vehicle i

Furthermore, the number and the influence of the maximum platoon size are evaluated, as well as their platooning distance and average number of cut-ins and disengagements. The distribution of *platooning time* (PT) ratio considers the total fraction of time that all equipped trucks are actually in a platoon:

$$PT \; \frac{\sum (t_{end}^{j} - t_{start}^{j})}{(t_{B}^{j} - t_{A}^{j})} \tag{13}$$

where

- t_A^j is the time ‘truck platooning enabled’ vehicle j passes location A
- t_{start}^j is the time ‘truck platooning enabled’ vehicle j starts platooning
- t_{end}^j is the time ‘truck platooning enabled’ vehicle j finishes platooning

The effect of blocking and cut-ins at ramps is investigated using the indicators *time to merge* (TTM) and *the number of disengagements at ramps* (NumD). TTM gives the average time that all inflowing vehicles require to merge from the point they enter the onramp to the point they leave the onramp. The NumD is the total number of platoon disengagements next to a ramp.

4.4. Additional sensitivity analysis

In this section, we show the sensitivity of relevant performance indicators on parameters c_{lc}, the level of courtesy for courtesy lane changes, and v_{sync}, the speed threshold for synchronisation, as described in Section 3.2. The sensitivity analysis is performed for all reference scenarios. The level of courtesy for courtesy lane changes parameter c_{lc} contributes to the model by providing space for lane changing vehicles, and merging vehicles in particular. Therefore, we focus on its influence on the TTM. For c_{lc}, values of 0, 0.25, 0.5, 0.75 and 1.0 have been tested. The speed threshold for synchronisation parameter v_{sync} prevents unreasonable blocking by synchronising vehicles that, at low speeds, do not have a gap in the target lane, nor are involved in cooperation in the default situation as their desire is still below the desire threshold for cooperative lane changes d_{coop}. This blocking can cause delays for the following vehicles, and the influence of v_{sync} is hence tested with TND indicator. For v_{sync} the default value is $x_0/t_0 \approx$ 24.6 km/h, and factors of 0, 0.5, 2 and 3 have been applied here.

Fig. 6a shows the sensitivity of Time To Merge (TTM) with respect to the courtesy lane changes parameter c_{lc} for the reference OP scenario. As expected, a negative correlation between c_{lc} and TTM is found. The more sensitive drivers are to lane change desire of drivers in adjacent lanes, the shorter the TTM becomes for merging vehicles. The parameter has the desired effect of creating space for merging vehicles. For free flowing traffic conditions, the improved behaviour is able to remove most of the unrealistic additional TTM caused by merging vehicles not having a sufficient gap on the mainline. Similarly, the outcomes of the PM and AM scenarios also

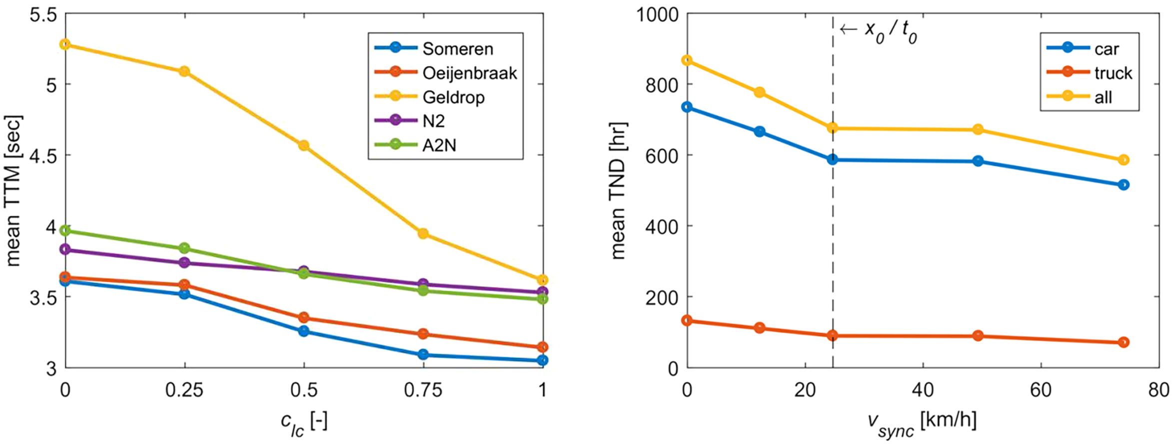

Fig. 6. A–b. a: Influence of c_{lc} on TTM (REF OP) / b: Influence of v_{sync} on TND (REF AM).

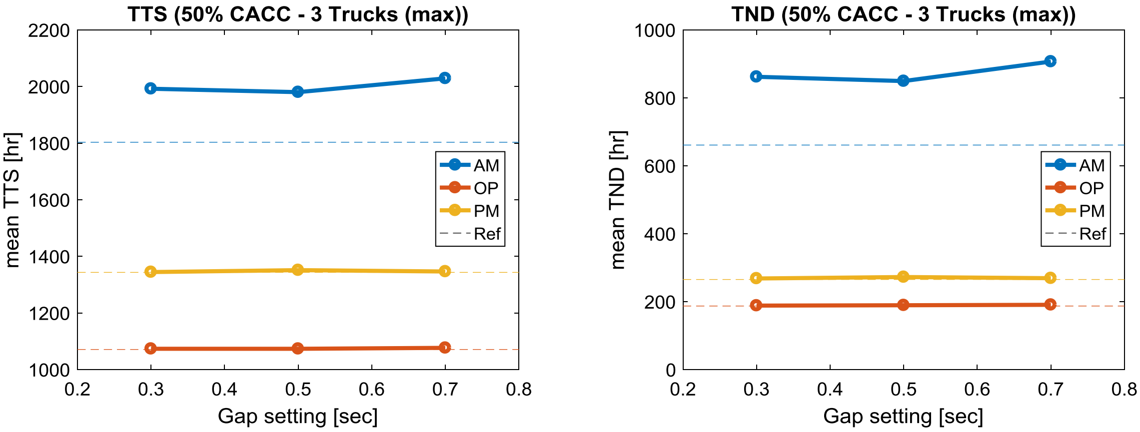

Fig. 7. A–b. TTS and TND for three-truck platoons (dashed lines show reference scenario without platooning).

show a negative correlation, although the absolute TTM values are higher as there is more traffic and congestion.

The influence of the speed threshold for synchronisation v_{sync} on the Total Network Delay (TND) is shown in Fig. 6b for the reference AM scenario. The assumed value throughout the rest of this paper is indicated with x_0/t_0. There is a clear negative correlation between v_{sync} and TND, with a distinct reduction for values below x_0/t_0, and only a mild additional reduction for larger values. Although no strong claim can be made on a correct value for v_{sync}, we do show that the applied value is reasonable as it removes most of the undesired additional delay by synchronising vehicles that block their followers. Larger values would have little effect, while smaller values would create unreasonable blocking. The reference OP and PM scenarios showed no influence to changes in the speed threshold for synchronisation v_{sync} as these scenarios have no significant congestion.

5. Results

The simulation case is carried out to show the effects of truck platooning on the aforementioned performance indicators and to aid

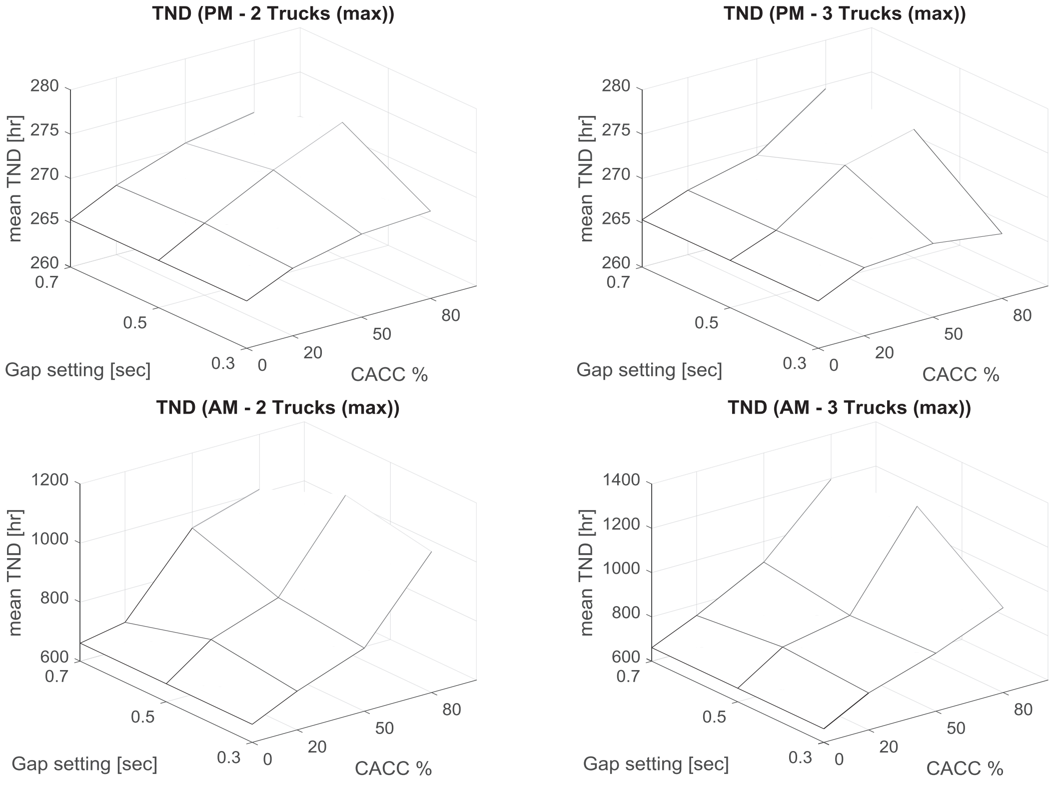

Fig. 8. A–d. TND for two- & three-truck platoons in the busy (PM) & congested (AM) scenarios.

Table 2
Percentage change in the network delay (TND) for busy traffic (PM).

		PM – 2 trucks (max)			PM – 3 trucks (max)				OP – 3 trucks (max)
Gap [s]		20%	50%	80%	20%	50%	80%	100%	50%
	0.3	0.9	1.5	1.7	0.9	1.1	0.7	−2.9	0.7
	0.5	1.1	2.5	3.8	0.8	2.7	3.5		1.2
	0.7	0.9	1.9	2.5	0.7	1.4	3.5		1.9

discussion in regard to the hypotheses that are posed in Section 3.1. The results of the performance indicators are presented and discussed in this sub section in three categories, starting with the effect on the general traffic performance and followed by the merging performance under various conditions and completed with the performance related to truck platooning. In this, the base scenarios for quiet (OP), busy (PM) and congested (AM) are considered with the other main scenario variables of the gap settings, maximum truck platoon size, and percentage of equipped trucks.

5.1. *Traffic flow performance*

The results for the Total Time Spent (TTS) and Total Network Delay (TND) are given in Figs. 7 and 8, and the TND is further detailed in Tables 2 and 3. As the results of the TTS and TND show close similarities, they are presented together here.

Fig. 8a–d shows the absolute values of the TND and shows a trend in the deterioration of traffic flow with increasing penetration of equipped trucks (CACC %), but an inconsistent trend for an increase in the gap settings of the platooning trucks. The increase in TND in the scenarios with congestion (AM) is much greater than for the busy scenarios (PM). Tables 2 and 3 give the relative percentage change compared to the reference for the busy and congested scenario. The increase in delay caused by truck platooning is small for PM, but still ranges up to 4% in this time period. Interestingly, the increased delay trend is broken for the 80% and 0.3 s scenario. The extreme scenario with 100% of trucks equipped at 0.3 s is the only scenario that shows an improvement in the overall delay. And this result is only seen in busy PM traffic and not in the congested AM traffic. The TND increases in AM scenarios range from 10 to 90%, in which the extreme scenario has the largest increase in delay contrary to the PM scenarios. The results do not show any clear indication for the difference between a maximum of two-truck platoons or three truck platoons. Furthermore, the quiet (OP) scenarios do not appear to differ greatly from the busy (PM) scenarios.

5.2. *Merging performance*

The ability of vehicles to merge onto the main corridor at ramps is analysed using the Time-To-Merge (TTM). On the corridor, three regular on-ramps are present at locations 1 (Someren), 2 (Oeijenbraak) and 3 (Geldrop). Location 4 (N2) and 5 (A2N) are motorway junctions between merging motorway flows. Table 4 gives the percentage change for the TTM for three (overlapping) subsets of all scenarios. Each subset indicates the influence of a particular combination of variables (system settings and demand). The TTM shows a minor increase in nearly all cases. For on-ramps in AM and for a high percentage of equipped trucks, the increase is larger. Although increasing truck platooning increases TTM in nearly all cases, other variables have no influence on this. Fig. 9a–e shows the results for the busy traffic (PM) scenarios for three-truck platoons.

Fig. 9a–c show that in comparison to Fig. 9d–e the TTM is relevant and influenced for on-ramps, while for motorway merges, the TTM is hardly affected at all. The flat shape of the graphs in Fig. 9d–e demonstrate this. The results show that the gap settings of the platooning trucks have very little effect on the TTM of vehicles entering from a ramp for all scenarios up to a penetration rate of at least 50%. We do note that for the higher share of equipped trucks of 80%, we do see small increases in TTM (see Fig. 9a–c). A higher percentage of equipped trucks in the busy scenario results in higher TTM values. The busier traffic state (AM) clearly shows a much higher TTM value for all onramps compared to the busy (PM) and quiet (OP) traffic states, therefore demonstrating that the presence of congestion is significant, while busy traffic compared to quiet traffic is less significant for merging ability. Finally, the influence of different platoon sizes may indicate that longer platoons have a negative effect on the ability of vehicles to effectively merge, however the difference between two or three truck platoons from the experiment is small: Table 2 shows a general increase for two-truck platoons of 1–3% in TTM and 2–5% for three-truck(max) platoons. However, these results remain inconclusive and require more extensive research to draw strong conclusions.

Table 3
Percentage change in the network delay (TND) for congested traffic (AM).

		AM – 2 trucks (max)			AM – 3 trucks (max)			
Gap [s]		20%	50%	80%	20%	50%	80%	100%
	0.3	10.6	23.1	62.9	16.0	30.4	48.7	91.3
	0.5	16.3	28.2	71.1	19.6	28.5	90.3	
	0.7	4.3	43.1	53.3	13.5	37.2	81.1	

Table 4
Overview of TTM for all variables (system settings and demand) in [s] and [% change]

		Reference			Gap-size and traffic state [all: 50% equipped & max 3 truck-pltn]									% equipped trucks [all: 0.5 s & 3 truck-pl]					Size of platoon [all: 50% equip. & busy(PM)]						
		OP	PM	AM	Quiet(OP)			Busy(PM)			Cong(AM)			OP	Busy(PM)			AM	Two			Three			inf
					0.3	0.5	0.7	0.3	0.5	0.7	0.3	0.5	0.7	50	20	50	80	50	0.3	0.5	0.7	0.3	0.5	0.7	0.3
Location TTM in [sec/%]	1	3.0	3.1	5.3	3.2	3.3	3.2	3.2	3.2	3.2	8.3	7.3	8.8	3.3	3.1	3.2	3.6	7.3	3.1	3.2	3.2	3.2	3.2	3.2	3.9
					3.7	7.5	6.4	4.0	4.8	4.0	56.1	37.2	65.0	7.5	1.2	4.8	17.0	37.2	1.8	3.9	2.9	4.0	4.8	4.0	26.5
	2	3.1	3.2	5.1	3.3	3.4	3.3	3.3	3.3	3.3	7.7	7.5	9.0	3.4	3.2	3.3	3.5	7.5	3.3	3.3	3.2	3.3	3.3	3.3	4.0
					5.0	7.5	5.1	2.6	2.4	3.8	51.5	47.8	78.3	7.5	0.1	2.4	8.8	47.8	1.5	1.7	0.9	2.6	2.4	3.8	23.5
	3	3.6	3.9	13.5	3.8	3.8	3.8	4.0	4.2	4.1	18.7	18.4	20.3	3.8	4.0	4.2	4.4	18.4	4.0	4.0	4.0	4.0	4.2	4.1	4.8
					3.9	5.4	5.7	2.8	7.8	3.8	38.4	35.8	50.4	5.4	1.6	7.8	11.6	35.8	1.2	2.9	2.4	2.8	7.8	3.8	22.2
	4	3.5	3.4	3.5	3.6	3.5	3.6	3.3	3.4	3.4	3.4	3.5	3.4	3.5	3.3	3.4	3.4	3.5	3.3	3.4	3.4	3.3	3.4	3.4	3.4
					1.3	0.3	0.6	−0.3	0.0	−0.1	−0.1	0.2	−0.1	0.3	−0.2	0.0	0.4	0.2	−0.1	0.1	0.0	−0.3	0.0	−0.1	0.8
	5	3.5	3.7	3.5	3.5	3.5	3.5	3.8	3.8	3.8	3.5	3.5	3.5	3.5	3.8	3.8	3.8	3.5	3.8	3.8	3.8	3.8	3.8	3.8	3.8
					0.8	0.6	0.5	0.7	0.8	0.5	0.3	0.9	0.6	0.6	0.6	0.8	1.3	0.9	0.5	0.7	0.5	0.7	0.8	0.5	1.6

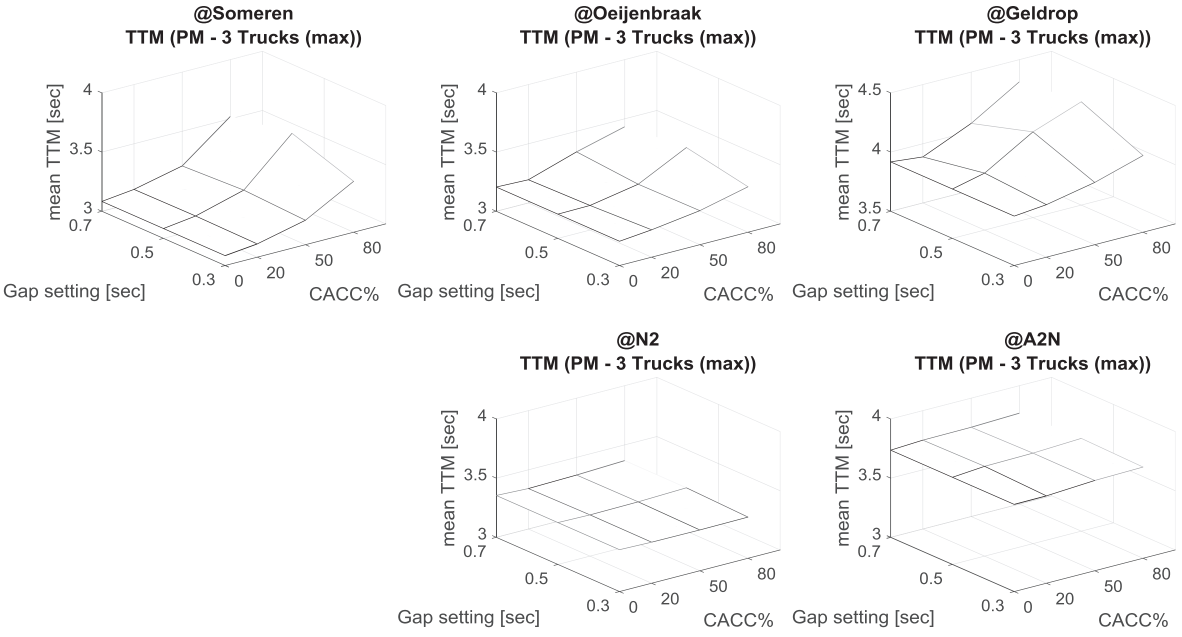

Fig. 9. A–e. TTM per weaving section for max three-truck platoons in the busy (PM) scenario.

5.3. *Platooning performance: cut-ins & disengagements*

The ability of trucks to platoon for a substantial time is measured with the Platoon-Time (PT) ratio. The results are relative for the considered corridor and not comparable with other networks, as they may have longer uninterrupted segments and other characteristics. The results of PT are shown in Figs. 10a–b and 11a. There is a clear trend that shows that for higher percentages of equipped trucks, the PT-ratio increases. These results are found for both two and three-truck platoon scenarios. When trucks are permitted to form platoons of up to three trucks, the PT-ratio is higher than for a maximum platoon size of two trucks. A trend also appears to be present for a higher PT-ratio with lower gap-settings. Although, the 20%-0.3 s scenario is a single exception to this trend. Finally, there is a slightly higher PT-ratio for the quiet and busy scenario compared to a slightly lower PT-value for the congested scenarios, which is evident from Fig. 11a.

The number of disengagements (NumD) is shown in Figs. 11b and 12a–f, and acts as an indicator for the number of cut-ins. In Fig. 12, sub figures a–c refer to on-ramps, while sub-figure d is a motorway split and e–f are motorway merges. Fig. 11b shows that the number of platoon disengagements is higher for scenarios that allow a higher number of trucks per platoon. Just as with the TTM, on-ramps are affected, while motorway merges are not. We found that the number of platoon disengagements increased for lower gaps between the trucks and with a higher percentage of equipped trucks. For the difference between traffic states in the different time periods no clear trend was found.

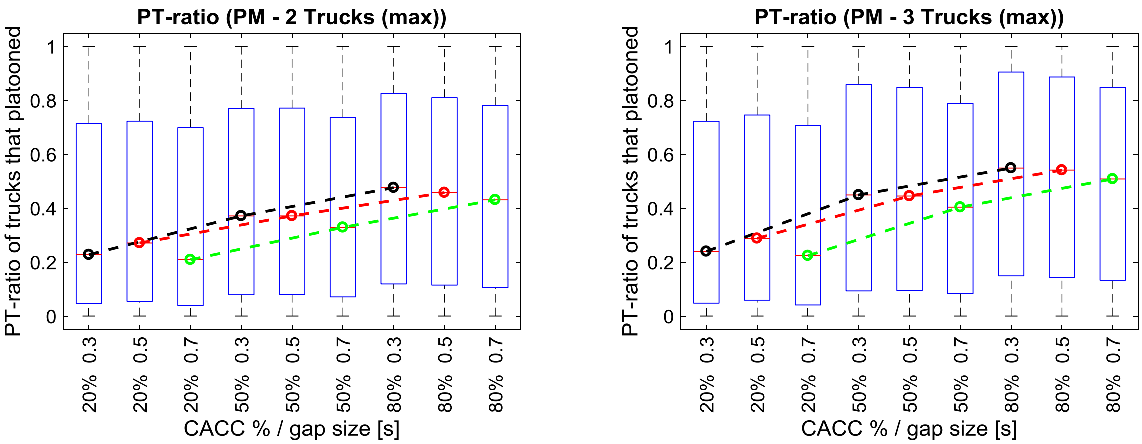

Fig. 10. A–b. Platooning Time (PT) ratio results for the busy (PM) scenario (aggregated per scenario over all runs).

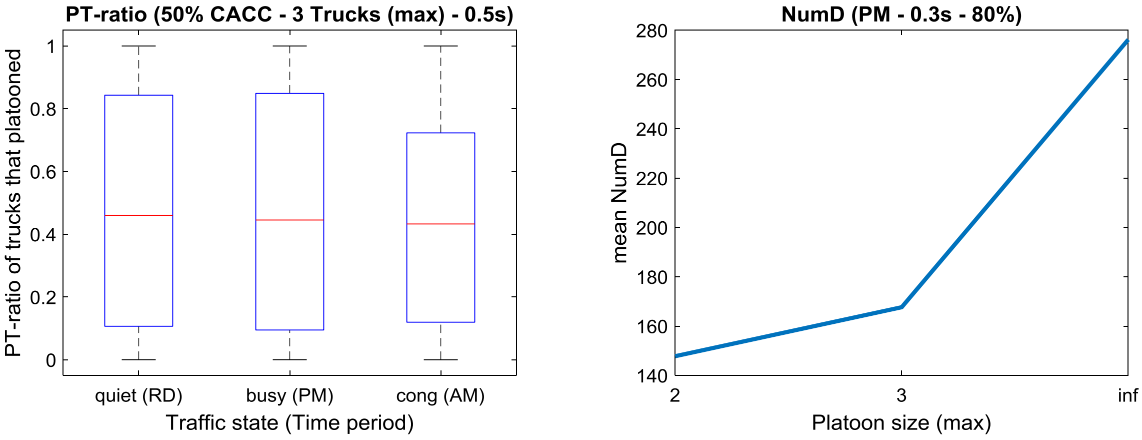

Fig. 11. a: PT-ratio per traffic state / b: Total NumD per platoon size for busy (PM).

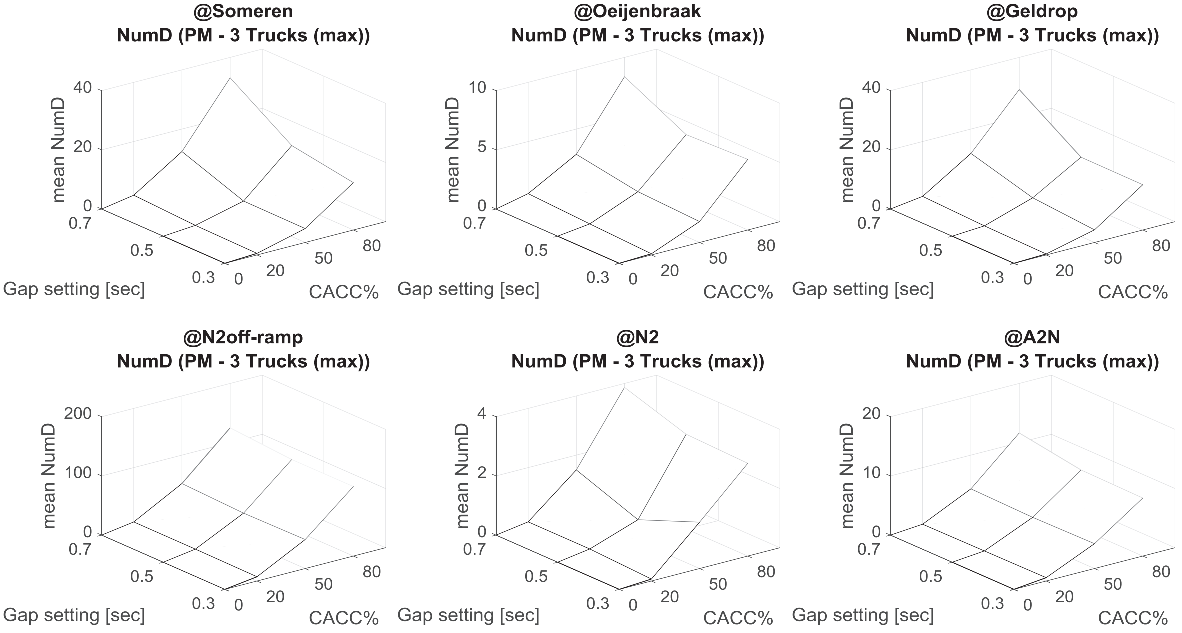

Fig. 12. A–f. NumD per weaving section for max three-truck platoons in the busy (PM) scenario.

6. Discussion & recommendations

The goal of this research is to give insight into the potential effects of truck platooning on traffic performance by advancing the development of models to include greater realism to do so. We have performed the experimental case with this goal in mind, using realistic values for the considered variables that are technically possible now and are expected to be in place once truck platoons become widespread reality. Similarly, the case considered a corridor that is already under consideration for truck platooning and is part of a large scale demonstration corridor for new intelligent transport system technologies. The results from the previous section are further discussed here with the main findings highlighted in Section 6.1 along with the conclusions for the hypotheses. Thereafter,

Table 5
Summary of the Influence of various truck platooning aspects. (brackets) indicate that the result is unclear.

Influence of a greater…… on the …	Gap setting	% equipped trucks	Max platoon size	Traffic volume (cong vs non-cong)
Traffic performance (TTS & TND)	o	–	(o)	– –
Merging ability at on-ramps (TTM^{-1})	o	–	–	– –
Platooning ability (PT-ratio)	–	+	+	–
Cut-ins (NumD^{-1})	–	–	–	(o)

we look at the limitations of this research and give recommendations for further research and for practice.

6.1. Discussion of results

We will look at the results for their effects on *traffic performance, merging ability*, and the *platooning ability* of equipped trucks, and per considered variable. The overall results are summarised in Table 5. Note that the evaluation in the table gives the system performance as positive, therefore a higher TTM or NumD is considered to be negative.

6.1.1. Traffic flow performance

The performance of traffic was measured by TTS and TND, to indicate delays for all vehicles. This showed that truck platooning under the considered scenarios had a small negative effect on traffic flow performance. The reduction in the TTS and TND when more trucks were equipped is unsurprising as there is more platooning in operation. There didn't appear to be any significant effect from higher or lower gap settings for platooning trucks. TTM also shows no difference in the blocking effect for different headway settings, indicating that the blocking effect could primarily be caused by a lack of cooperation for the small gap settings that were tested. The difference between a maximum platoon size of two or three trucks was too small to show any significant difference. In the 'extreme' scenario that considered all trucks able to platoon, with no maximum platoon sizes and gap settings of 0.3 s between trucks, a small improvement was found in traffic performance. This improvement of 2.9% reduction in TND for the busy (PM) scenario may be the result of a higher vehicle density for trucks as vastly longer platoons can be formed with very short following times, therefore taking up less space on the road. This would be in line with other literature that also suggested this as a possible improvement. The extreme scenario in congested traffic was much less positive; relatively high numbers of trucks driving at close proximity led to significantly higher delay times, which could be due to a greater disruption in the ability of other vehicles to manoeuvre between lanes. However, the extreme scenarios should be considered in their context as 'extreme', as having all trucks equipped with CACC and especially at a gap of 0.3 s is highly unlikely for the foreseeable future. We found that busier traffic had a negative effect on traffic performance, although the difference between the quiet and busy scenario was small. When traffic with congestion is considered, then truck platooning in the considered case has a large detrimental effect on traffic flow. The underlying mechanism and reason for this was found to be vehicles that struggled to perform lane changes near to platoons, and had to either slow to be able to change lane behind a platoon or force a sub-optimal lane change, forcing following vehicles to brake harder.

Hypothesis 1. '*Truck platooning has a marginal positive effect on traffic flow, if any*.'

In the experiment, we found that truck platooning had a negative effect on traffic flow, leading us to put the hypothesis in doubt. Marginal positive effects on traffic flow from shorter gaps were too small compared to the negative traffic flow effects for interactions with other traffic except for currently unrealistic settings for platoons.

6.1.2. Merging performance

We consider the ability of other vehicles to drive uninterrupted. This is considered by their ability to merge on weaving sections using the Time-To-Merge (TTM) indicator, and to a certain extent also the number of cut-ins reflected in platoon disengagements (NumD). For all motorway merges and splits, no significant effect was found on any of the variables or indicators, leading to the conclusion that truck platooning has no substantial effect in the considered case. This was not the case for on-ramps. TTM was not found to be influenced by the gap settings, however the number of disengagements was higher for higher gap settings. Fewer disengagements for the smallest gap setting may have also been caused by the ability of trucks to remain platooning during acceleration, where gaps increase naturally (capacity drop, delayed response). When a gap becomes large ($> T_{ACC}$), a truck is (momentarily) considered to not be platooning. The percentage of platooning trucks did have a negative effect of the ability to merge with higher TTM values found for higher equipped percentages. Also, longer platoons have a negative effect as well as busier traffic. These results are not surprising, as more platooning trucks, in longer platoons would logically increase the blocking effect. And in busy or even congested traffic, the availability of gaps to merge into could be much smaller, therefore leading to higher TTM values.

Hypothesis 2. '*The main positive effects on traffic are from truck platooning close proximity driving, while the greatest negative effects are from blocking at ramps*.'

The extreme scenario showed that a high number of trucks with very small gap times (0.3 s) can give positive effects on traffic flow. The blocking effect is also confirmed in the experiment, with other vehicles experiencing greater time to merge and requiring a greater number of cut-ins on platoons. These cut-ins will also disrupt traffic flow and the positive effects of platooning. Therefore, this hypothesis is accepted for the considered case.

Hypothesis 3. '*Longer platoons have a greater positive traffic flow effect, as do shorter gap-times while platooning and a greater penetration rate of truck platooning capability*.'

This hypothesis may be accepted from a theoretical point of view, which was demonstrated by the extreme scenario. Although for 100% equipped trucks at 0.3 s, a lower delay was found, for all other realistic levels, no improvement was found. Therefore, based on the experiment, the hypothesis only holds for the high end of the spectrum and not for levels of truck platooning that may initially be expected in the coming decades.

6.1.3. Platooning performance

While this paper focusses on traffic performance, the performance of platooning is also affected by traffic flow and is therefore also relevant. The case logically showed that a higher percentage of equipped trucks and a higher maximum platoon size had a positive effect on the time that trucks could platoon on average (PT-ratio). Furthermore, a lower gap time setting also resulted in a greater PT-ratio, which may be explained through a lower number of platoon disengagements for lower gaps. The ability of trucks to platoon in congested traffic in the AM scenario was shown to be lower, however there was very limited difference in platooning time between the busy and quiet scenarios. Therefore, truck platooning ability was shown to be best for low gap-settings, a higher number of equipped trucks, larger platoons sizes and in non-congested traffic.

Hypothesis 4. '*Platooning in dense traffic is substantially less effective than in quieter traffic*.'

We found that in the scenarios with congested traffic that platooning was affected the greatest, while the busy scenarios (PM) were not overly affected when compared to the quiet scenario. Therefore, this hypothesis is only partially accepted, as the density of traffic only starts to play a significant role close to congested levels of traffic flow. Further research is required to further pin-point the transition point.

6.2. Model limitations and recommendations

The applied model utilises state of the art aspects of traffic flow simulation and insights in the application of truck platooning. However, it is not without its limitations, as all models are. These limitations are discussed here and recommendations are given how future research may improve modelling of truck platoons, as well as interactions with other traffic.

- As the development of platooning systems progresses, more knowledge can be obtained on what strategies trucks apply to form platoons, and what characteristics define the longitudinal truck following (gap, sensitivity of response, etc.). We have assumed the ACC gap to be larger, and the CACC gap to be shorter than the average gap for human drivers. The validity of this assumption can be evaluated using empirical findings of the system. In this work we've implemented spontaneous platooning with a 30.1 km warm-up section. If platoons disengage within the rest of the network, active platoon formation might provide higher shares of platooning trucks. The system is exposed to disengagement solely due to acceleration, which relates to the sensitivity to the leading truck. In a way this is simply a categorization, a real issue only arises if other vehicles then enter the gap.
- Much uncertainty exists on how truck drivers with a platooning system will respond to surrounding vehicles. We have assumed that the drivers do not pro-actively cooperate with merging traffic (i.e., neither speed adjustments nor courtesy lane changes). Only when a merging vehicle forces itself in front of a CACC truck, is the system assumed to respond by deactivation. It might be that for example cooperation and courtesy do not deviate significantly, in which case traffic flow performance will increase relative to our results, while platooning performance decreases.
- The behaviour of other road users to truck platoons is equally uncertain. In particular within the scope of this paper, this is about merging behaviour. We have extended the LMRS with a rule to stop before the end of on-ramps, but only if critical. While this will let the merging vehicle fall back relative to the mainline traffic, it might not fully capture more advanced anticipation of merging drivers. It is also conceivable that truck platooning might result in more use of the emergency lane downstream of on-ramps.

While short-term effects may be investigated by testing such systems in driving simulators, longer term effects need to be derived from empirical data that will only become available as truck platooning system come into use. Potential effects of different levels of cooperation and courtesy lane changes could be obtained by varying these levels in simulation. Cooperation can be implemented in the model by changing the cooperation threshold from d_{coop} to $d_{coop} + (1 - c\_coop)\cdot(1 - d_{coop})$, where c_{coop} is the level of cooperation. Similarly, a varying level of courtesy lane changes of platooning trucks can be included by setting $0 < c_{lc} < 1$ when platooning.

6.3. Case limitations and context

The considered experimental case in this paper is performed for a valid and relevant road corridor using real data for flows and calibration and for vehicles settings. However, as with any experiment, the experiment has its limitations in regard to generic validity. These limitations logically come from geographical, societal, infrastructural, legal, and other factors. These are not necessarily shortcomings, but rather contextual issues in regard to the experiment and its results.

The geographical context of the experiment is The Netherlands, Europe. This entails Northern European traffic, which has been previously shown to be capable of achieving high lane capacity values, with vehicles driving at close proximity in dense traffic and high speeds (Hansen et al., 2003; Minderhoud et al., 2003), higher than what is commonly seen in the US. This is valid for car vehicles, but also for trucks in practice (even though guidelines for truck-drivers state differently). In Europe, vehicles are also required to drive on the outside lane when not performing overtaking maneuverers, contrary to common practice in the US and other places. And although not a great deal is known about this, the way drivers perform lane changes may also differ in the European context.

Ramezani et al. (2018) also performed an empirically based simulation study on truck platooning, but found more favourable traffic flow results. Therefore, we make a comparison with that work, which may help highlight some of the differences found in both approaches. Denser traffic (e.g. closer time gaps) and more traffic on the outer lanes could play an important part in the ability of truck platooning to improve traffic flow. If traffic is already efficient, then the potential to improve traffic flow through even shorter gap times is very limited. Merging onto a highway also becomes more difficult in denser traffic conditions. Often, drivers in Europe will facilitate lane changes by making gaps, by braking or changing lanes, however this would not be something that platooning trucks would do. Therefore, it may very well be expected that the blocking effect at merges, where truck platoons are present, could be substantially higher in the European context.

A final comparison relates to the local infrastructure and traffic characteristics. In this paper, we have aimed to include different types of merges and traffic flow demands, by considering different on-ramp locations and times of day. This allows one to compare these differences and gain insight into the potential effect of truck-platooning. In Ramezani et al. (2018), the focus was mainly on congested traffic, with much of their gains in traffic flow potentially being down to the reduction or delay of congestion at one specific bottleneck. They showed effectively that platooning could aid traffic in such a way, whereas the analysis in this paper focussed more on the effects along the considered corridor under more generic circumstances and did not produce a favourable traffic performance outcomes. As a result of this analysis of case context, an interesting research avenue opens up to question if the truck platooning in different global contexts has a major effect on traffic flow performance?

6.4. Policy recommendations

This research offers insights into traffic flow effects of truck platooning on traffic and on the platoons themselves. It also results in a number of recommendations for policy in regard to the application of truck platooning in practice.

In the considered case, truck platooning was found to have a small negative effect on traffic flow performance. However, the effect may be considered marginal and acceptable. The negative effect for near congested or congested traffic flow was large and therefore a recommendation could be made to not allow truck platooning under these traffic states, unless a relevant or specific algorithm is applied. However, there is little relevance to allow truck platooning in congestion as the main emission and energy consumption effects are not present. Furthermore, there are strong indications that drivers in truck platoons are reluctant to platoon under (near) congested traffic states (Yang et al., 2018), therefore such a recommendation may be trivial in any case. Such a restriction on truck platooning may be achieved by not allowing truck platooning within certain peak periods on specified corridors in which congestion or very busy traffic could be present. Furthermore, restricting truck platooning below a certain traffic speed may also be considered in cases of unexpected congestion. However, further research would be required to investigate the consequence of this.

As no positive effect on traffic flow performance was found, we recommend that the main focus of truck platooning should remain on the emission and energy consumption gains and care should be taken when assuming potential traffic flow gains as is sometimes mentioned by policymakers. Other research has shown that under certain circumstances traffic flow gains may be possible, but a generic context of these gains remains unclear and was not found in this research. When building a business case for truck platooning, we found no significant gain from traffic flow performance benefits.

A final recommendation considers platooning strategies. As far as this research can validly comment on platooning strategies, we find no substantial concerns in allowing truck platoon sizes of two or three trucks, or allowing gap settings between trucks in the range of 0.3–0.7 s in regard to the traffic flow. However, further considerations will obviously be required regarding safety of such strategies. The considered size of platoons is restricted in this paper based on assumptions and current and foreseen policy. However, further research that explicitly looks at ideal and feasible platoon sizes in mixed traffic is also recommended.

Summary of main policy recommendations:

- Truck platooning should not be allowed in saturated traffic flow (near congested)
- Truck platooning should not mainly focus on traffic flow gains, but on the main emissions objective
- More research is required to determine the specific context of potential traffic flow effects
- Platoon lengths of two or three trucks are not significant for traffic flow
- Gap settings also do not overly affect traffic flow, but should be considered more for safety

7. Conclusions

This research focusses on studying the effects of truck platooning on traffic flow performance. Truck platooning has been increasingly considered for application, with the main benefits of lower energy consumption and lower emissions being the main draw. Other possible gains are mentioned such as driver employment efficiency and interestingly also traffic flow performance gains. Little substantiated proof exists in regard to traffic flow benefits as a business case is built to promote and encourage the introduction and further development of truck platooning. As with most developments in the spectrum of vehicle automation, quantitative evidence of potential effects are difficult to give due to the technologies not existing sufficiently in practice and uncertainties on the future technological development, set-up and behavioural adaptation.

In this contribution, we summarised the current state of the art in regard to truck platooning and considered the current state of the art to be able to give simulated estimates on the potential traffic flow effects. An existing and state of the art simulation model, LMRS-IDM+, was extended to allow the main relevant effects of interaction between manual vehicles, trucks and platooning trucks to be accurately simulated. The main advances that were included are adapted synchronisation behaviour, courtesy lane changes, right-keeping for trucks, and the platoon system itself, including CACC and platooning strategies. The developed model was applied in an experimental case on a main trucking corridor in The Netherlands, which is also part of a trans-European ITS corridor. Scenarios considering traffic state, truck gap settings, platoons sizes, and the share of equipped trucks were simulated. These returned information regarding the total traffic performance, the performance of traffic at ramps, and the ability of a platoon to remain platooning.

The experiment allows the effects on traffic flow to be demonstrated. The experiment showed that truck platooning may have a small negative effect on the total traffic flow performance, which is especially affected by the number of equipped and platooning trucks. For traffic states in traffic with traffic demand below 80% of capacity, the effect remained small, however for scenarios which included congested traffic, a large negative effect was found on traffic flow in all sub scenarios. The ability of inflowing traffic to merge at on-ramps was found to be mainly affected by the percentage of equipped trucks and to a lesser extent also to the maximum platoon size as well as busier traffic. These conclusions are not surprising and are similar for the number of recorded disengagements of platoons at ramps. The applied gap setting for platooning trucks did not significantly affect the merge time, while a higher gap did lead to a higher number of cut-ins. The ability of trucks to platoon was positively affected by a greater percentage of equipped trucks and by larger platoon sizes. Shorter gap times also slightly improved the ability of trucks to remain in platooning formation.

Recommendations are made for improvement in modelling truck platoons through active platooning strategies and more fine-tuned behavioural adaptation, both of which rely to a large extent on knowledge that can only be obtained as truck platooning systems are further implemented. Policy recommendations are also made and mainly focus on restricting truck platooning to traffic states that are not near congested or congested, from a viewpoint of traffic efficiency. Furthermore, gap settings and platoon lengths of two or three trucks may not need to be regulated from a traffic flow perspective, however from a safety perspective there may be issues. A final potential discovery is made that the effect of truck-platooning on traffic performance made significantly differ in the European context to that in the American context. Recommendations are made to investigate this further.

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