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Assessment of Proactive Gap- and Speed-Control Traffic Management Reducing Collision Risks

B. Ons[1], S. Maerivoet[1]

1. Transport & Mobility Leuven, Belgium

Abstract

Advanced technologies used in vehicles today, such as (Cooperative) Adaptive Cruise Control (CACC), are used in traffic simulation studies to model connected and automated vehicles (CAV). Time gap and speed regulation mechanisms are widely accepted in commercial (C)ACC systems. Through simulations with the microscopic traffic simulation model SUMO, we investigated a traffic management safety procedure in which CAVs were informed about the deceleration manoeuvres downstream and responded by increasing the control gap with the vehicle in front, or reducing the control speed gradually and temporarily. Traffic management (TM) was applied in different contexts with variations in the default control time gaps, traffic demands and mixture compositions. Simulations exposed that, depending on the traffic demand, the accidental risk decreased by TM for CAVs while the effects on throughput were minor. Our results demonstrate that TM applying brief active safety measures can increase safety while sustaining traffic flow efficiency.

Keywords:

Autonomous transport and platooning, Intelligent traffic and mobility management

Introduction

The deployment of automated functions in driving systems, referred to as Advanced Driving Assistance Systems (ADAS), led to the development of more advanced technologies and set forth progress towards connected and automated vehicles (CAV). The most advanced technologies implemented in today's cars such as (Cooperative) Adaptive Cruise Control are technologies that are also built into traffic simulation tools to simulate CAV models [8,13,14]. ADAS incorporates state-of-the-art safety-related technologies such as Forward Collision Warning (FCW), Automatic Emergency Braking (AEB), or Collision Avoidance Systems (CAS) in their automation software in one form or another. Accident risk decreases to a great extent when cars are using these safety-related ADAS [3]. These systems augment traffic safety as they signal the preconditions for a potential crash to the driver, timely augmenting the vigilance of the driver.

[1] bart.ons@tmleuven.be, sven.maerivoet@tmleuven.be

Road safety is believed to improve greatly with the deployment of CAVs in daily traffic. It is widely accepted that the main cause of road accidents is human error [12]. Automated vehicles can reduce the figures on road accidents with the removal of human error [10]. However, CAVs are still in a development-evaluation phase, with pilot projects such as the L3Pilot project, currently unfolding. There are still technical hurdles that would need to be overcome before CAVs can hold an accident-free promise. One of these technical hurdles is to increase the distance range in which on-board equipment such as lidar, radar, cameras, and sensors collect reliable data and provide decisive information to the automated system. This information should allow for anticipating any obstacles at any distance within the stopping distance. Today’s on-board sensor arrays feeding the ACC or AEB system have a detection horizon sufficient to avoid or mitigate accidents, but accidents can still happen depending on weather or road conditions. The stopping distance of a vehicle is the sum of the response time of the driver or the system and the braking distance of the vehicle. The stopping distance can be compared to the available distance given the detection range of the on-board equipment. For instance, assuming a detection range of 100 m from a stationary object approaching with the speed equal to 33 m/s, a response time of 1.3 s (the time of accumulating evidence, decision making and system response, and/or take-over time, see [16]) and an emergency deceleration of -8.5 m/s², the collision speed will be 12.2m/s (23.3 m/s for wet road conditions). Although on-board equipment are capable to pick up features at far distances, the area in which sensory input from on-board equipment is processed to reliable and relevant information is limited. The stopping distance can be longer than the sensory range making accidents inevitable. This is especially true if the vehicle is driving very fast, if roads are slippery, or if the line-of-sight is obscured at close range by trees, turns, or intersections. Therefore, AVs must be connected so they can exchange valuable information with the infrastructure (V2I) and with each other (V2V). The exchange of information between connected vehicles and the infrastructure allows for real-time traffic management. Traffic management of CAVs is a research topic that receives lots of attention lately (e.g. [1,2,5,9]). Connected and automated vehicles are on the edge of their market deployment. Tomorrow’s traffic composition will consist of mixes with connected vehicles, CAVs, and regular vehicles. Therefore, traffic management involving CAVs is usually simulated in mixed traffic conditions [15]. The interoperability of CAVs with other vehicles is one of the challenges that we will face in the near future.

In this study, a straightforward TM procedure including a policy on intelligent speed adaptation and intelligent gap-control is examined improving road safety. This procedure aims at reducing the risk of accidents by reducing the speed or increasing the headway of the target vehicle with the vehicle in front when the target vehicle approaches a context that is suspected to be less save. These actions are initiated if particular events corresponding to greater collision risks trigger a warning communication from a vehicle downstream to the vehicles upstream. Connectivity itself lies outside the scope of this study and the assumption is made that vehicles are connected with each other or indirectly through the infrastructure.

The study aims to investigate the effect of traffic management in which vehicles downstream give warnings to vehicles upstream for possible threatful downstream conditions, and the vehicles upstream lower their speed or increase their headway gradually, and temporally.

This article is composed of several sections build around two simulation scenarios. The first scenario is a straight motorway on which vehicles are encountering a simulation-controlled threatening event. The second scenario is a 10 km by 3 km imported realistic network in the neighborhood of the city of Turnhout in Belgium. This area has a motorway, two off- and onramps, secondary roads all featuring realistic traffic conditions. The traffic management procedure is explained in the “material and methods” section for each respective simulation together with the simulation setup. In the “result and discussion” section, the effects of the proposed TM procedure are demonstrated and discussed. We will elaborate on the results and conclude with the main findings and future steps in the conclusion section.

Simulation scenario 1

Material and methods

The TM procedure is tailored for motorways. The chain of events starts with the deceleration of a vehicle downstream to the speed below or equal to the threshold of 12 m/s. This event is signalled from the slow-moving vehicle to the moving vehicles in the upstream flow up to 600 m. All connected cars at high speed (>23 m/s) respond by increasing their headway with their leading vehicle. The headway can be expressed in the time it takes to drive the distance equal to the gap distance with the leading car. This is referred to as the time gap. All connected vehicles respond by increasing their time gap 3 times with 0.3 s, every 5 s. Then, the vehicles maintain their prolonged time gap followed by a normalisation repeating the same time gap steps backwards. Note that this procedure will anticipate the longitudinal moves of a traffic jam tailback as more connected vehicles arrive at the tailback and slow down. The extended time gap provides more time for the controllers to adapt to the slow-moving traffic and to avoid accidents. The main variable of interest is the effect of applying the proposed TM procedure. To verify the effect of the TM procedure, all simulation runs were carried out two times: one time with using TM and one time without. In the remainder of this study, “TM” refers to the condition with traffic management while the other condition is referred to as the “baseline”. We expect fewer events associated with accidental risk to occur for the TM condition compared to the baseline.

Simulations were conducted with the SUMO (Simulation of Urban Mobility) microscopic traffic flow simulator [6]. CAVs were equipped with the ACC model. This model was implemented in SUMO as described in [14], based on [8]. Simulating the ADAS systems using the SUMO traffic microsimulation model was preferred compared to using other tools. One of the advantages of this free and open-source tool is the TraCi (Traffic Control Interface) module. This provides access to the simulation while it is up and running. It allows to interfere in the simulation in the same way as a traffic management system would do in actual daily traffic. As such, this interface is used to detect the conditions under which the traffic management procedure should be activated, and it manages the steps of this procedure as described. The simulations are based on the main application cores from the Horizon 2020 TransAID project [7].

The ACC model has a virtual sensory range of 120 m. It is the distance to the leading car at which the controller progresses from the speed control mode to the gap control mode, thus perceiving and anticipating the leader in front. Note the existence of the CACC model in SUMO which assumes connectivity and performs adaptive movement control beyond any sensory distance limit. This model is not suitable in the current simulation setup. The CACC model does not have any sensory limit and would therefore disrupt the baseline.

The first KPI of interest concerns the assessment of traffic safety. To quantify this, a surrogate safety measure is used. Surrogate safety measures measure the accidental risk at a more fine-grained scale than the actual count of accidents. The term “surrogate” refers to the capability to replace the accidental statistics which often lack accuracy and quality. Accidents occur rare and actual counts are very small or zero. We used the surrogate safety measure: “Time-To-Collision (TTC)”. TTC is the time that a vehicle would take to collide with another vehicle if all vehicles would drive at a constant speed. Obviously, small TTC corresponds to high imminent accidental risk [4]. In the first simulation, the number of TTC events below the threshold of 1 second are counted. Safety improvements should not be achieved at the expense of traffic flow efficiency. The second group of KPIs of interest is flow-related. One is the throughput expressed by the average number of vehicles per hour (veh/h) driving in the simulation. The second one is the average network speed. A warm-up period of 600s was respected.

There are three contextual variations. One is the traffic demand ranging from 1800 veh/h, 3900 veh/h, and 6000 veh/h in the first simulation. The second contextual variation involves the vehicle mix composition of connected vehicle proportions ranging from 15 %, 35 % to 65 % of the total traffic fleet. These percentages can be thought of to represent different CAV deployment levels in the future. The fewer connected vehicles, the fewer cars that can be influenced by traffic management. In order to simulate the heterogeneity of daily traffic, two main clusters of human driver models were composed: a defensive driver model and an aggressive driver model. Parameters were randomly drawn from the models’ parametric distributions (See Table 1).

The vehicle mix was complemented with HGV (heavy good vehicles) and small trucks (LGV). The vehicle mix compositions are presented in Table 2. The parameter values are compliant with other studies (e.g. Shladover et al., 2012). The third contextual variation is the setting of the desired time gap or headway that CAVs wish to maintain with the vehicle ahead. This setting is important for the trade-off between safety and efficiency. This time gap was manipulated in successive steps of 0.2 s between 1 s to 2 s in the first simulation. In total, 270 runs were executed (3 demands x 3 mixes x 6 time gaps x 5 random seeds) with TM and 270 runs without TM in the baseline.

Figure 1. The first simulation use case.

The road network consists of a 6 km long three-lane motorway. After a warm-up period, a vehicle stops on the third lane and stay there for 600 s. TTC events are only counted during the stationary period (see Figure 1).

Table 1. Used vehicle parameters. (N(m,s)[min/max] denotes a sampled normal distribution with mean m, standard deviation s, and stated minimum and maximum values.

Definition	CAV automated	Defensive driver	Aggressive driver	Light goods vehicle	Heavy goods vehicle
Car following model	**ACC**	**Krauss**	**Krauss**	**Krauss**	**Krauss**
Time gap (*tau*, s)	1.0 – 2.0	N(2.0,0.2) [1.6,2.6]	N(1.3,0.2) [0.8,1.6]	N(2.0,0.3) [1.4,2.6]	N(2.0,0.3) [1.4,2.6]
Deceleration limit (*decel*, m/s²)	N(3.0,1.0) [2.0,4.0]	N(3.0,1.0) [2.3,3.7]	N(4.2,1.0) [3.2,5.2]	N(3.5,1.0) [2.0,5.0]	N(3.5,1.0) [2.0,5.0]
Acceleration limit (*accel*, m/s²)	N(2.0,1.0) [1.0,3.0]	N(1.7,1.0) [0.8,2.6]	N(3.2,1.0) [2.2,4.2]	N(1.5,1.0) [1.0,2.0]	N(1.5,1.0) [1.0,2.0]
brake (*emergencyDecel*, m/s²)	8.5	8.5	8.5	7.5	7.0
Response time cycle (*actionStepLength*, s)	0.4	1.3	1.3	1.3	1.3
Maximal speed (*maxSpeed*, m/s)	33.3	32	39	33.3	25.0

Table 2. Vehicle mix compositions.

Vehicle mix	CAV automated	Defensive driver	Aggressive driver	Light goods vehicle	Heavy goods vehicle
CAV (15%)	15%	37.5%	37.5%	5%	5%
CAV (35%)	35%	25%	25%	5%	5%
CAV (65%)	65%	12.5%	12.5%	5%	5%

Results and Discussion

The TTC results of the first simulation are depicted in Figure 2 for the default time gap setting of 1 s, split between connected vehicles participating in TM (left panel) and unconnected vehicles (right panel). The different colours represent vehicle compositions ranging from 15 % connected vehicles for the blue colour, 35 % connected vehicles for the red colours and 65 % connected vehicles for the yellow colour in the mixes. The main variable of interest is the applied TM procedure and its effect compared to the baseline. Generally, the more vehicles on the road, the more TTC events occur. When comparing vehicle mixes, in general, the higher the proportion of ACC vehicles, the fewer TTC events are occurring on average. Longer default time gaps resulted in fewer TTC events.

The TM condition is represented with full-colour bars while the baseline is represented by the adjacent striped texture bars. Both groups, connected and unconnected vehicles benefit in terms of safety. For high demands, the TM procedure reduced the number of TTC events for connected vehicles. In the right panel of Figure 2, TTC events tends to go down too despite the fact that no TM was applied on those vehicles. A tentative explanation is that regular cars also decrease speed when connected TM-guided vehicles are driving in front of them. In the mix composition of 65 % of connected vehicles (yellow colour, left panel), a demand of 6000 veh/s, and a default time gap of 1 s, adding up TM-guided and regular vehicles, the number of TTC events decreases from 108 to 48 on average. These results indicate that the number of head-tail near-accidents decrease by more than 50 % in simulated heavy traffic conditions. The TM procedure is especially effective in case of high demands because more vehicles are driving in ACC gap-control model. For lower demands, more vehicles are driving in free flow speed-control mode. In this mode, the TM procedure cannot take effect because there is no car in front. Extending the TM procedure to reduce speed might also affect safety for connected vehicles operating in the speed-control mode approaching at high speed a stationary or slow moving obstacle.

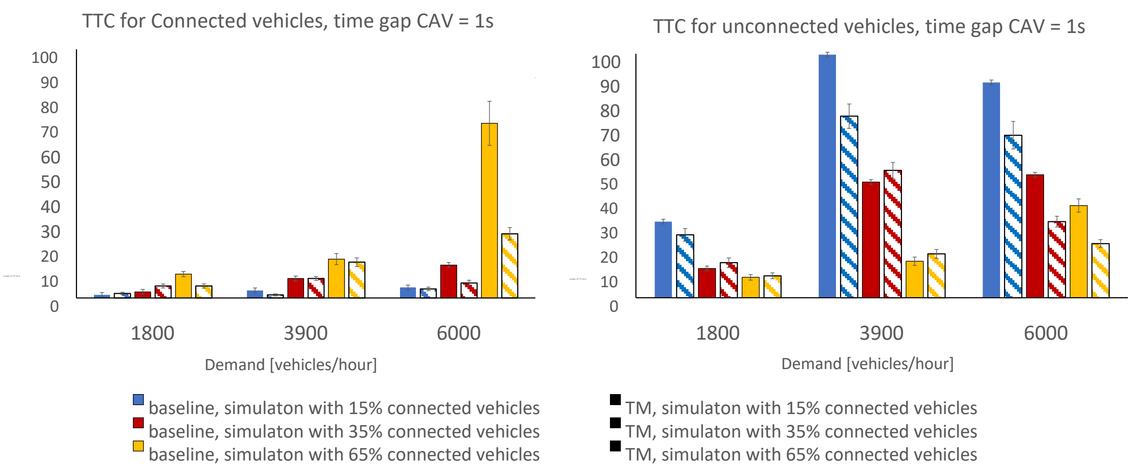

Figure 2. Counts of TTC events separated for CAV and the other vehicles.

The default time gap setting of 1.2 s provides similar results as Figure 2, but from 1.4 s to 2 s, the effect lowers and disappears. obviously, increasing the time gap from 1 s to 1.9 s by the TM procedure will buy relatively more time for the CAVs to anticipate than increasing the time gap from 1.6 s to 2.5 s.

Increasing time gaps might affect the throughput of traffic. A TM procedure with positive results on road safety should not be achieved at the expense of traffic flow efficiency. In the upper panels of Figure 3, the throughput is plotted against the default time gap in the ACC model. The panels from left to right represent different vehicle mixes with an increasing number of connected vehicles. Each colour line represents a different traffic demand. The simulation involving traffic management did not degrade in efficiency compared to the baseline. The TM conditions are plotted with dashed lines. These lines fall close to or on top of the solid lines representing the baseline. In the lower panels, the average speed is plotted for all simulation scenarios and no reduction of traffic efficiency is demonstrated. The TM procedure briefly lowers the time gap which results into an insignificant effect on the average speed. This contrasts with the default time gap settings during the entire simulation (depicted on the x-axis), resulting in major effects on throughput and average speed.

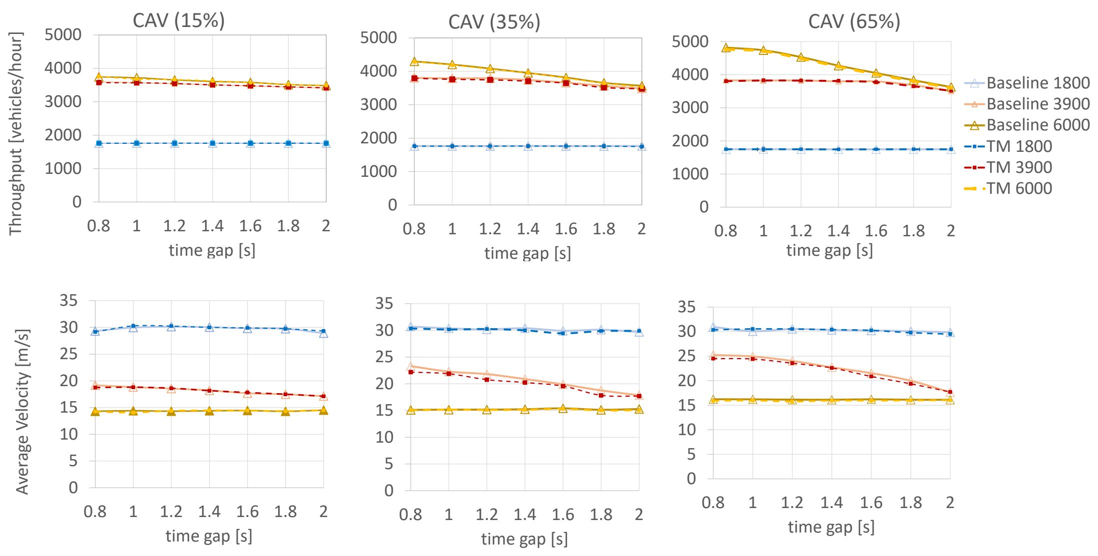

Figure 3. Throughput (veh/h) and mean speed against desired time gap for different demands and vehicle mixes.

Simulation scenario 2

With regard to the TM procedure in the first simulation, the TM procedure in simulation 2 includes managing the speed in addition to the time gap. The conditional events that trigger a car downstream to send a TM incentive to the vehicles upstream are a speed drop of 6m/s measured in an interval of two seconds, and a slow traffic progression at a speed below or equal to 5 m/s. Considering the first conditional event, a braking manoeuvre more intense than one would expect from a vehicle merely adjusting its speed to the traffic around it, can be an indication of an endangering context with possible impending collisions. In the second conditional event, an upfront vehicle driving at a low speed might indicate that the vehicle is hampered in traffic. For upstream vehicles, this might be an indication of a traffic jam ahead or an obstruction. If these conditional events are met, an incentive to adapt speed or increase time gap is signalled from the vehicle downstream to the vehicles upstream. We expect fewer TTC events to occur for the TM condition compared to the baseline.

Material and methods

A connected vehicle within a upstream range of 400m from a hampered CAV receives a TM incentive to increase the time gap in a identical way as in Simulation 1. In addition, connected cars moving at a speed above (>12 m/s) will also respond by reducing their speed in steps: first, the maximal speed is set from 33 m/s to 30 m/s; 4 seconds later, the maximal speed is set 2 m/s below the current speed; and this step is repeated. The vehicle will maintain its speed for 20 s and reverses the previous steps to normalise its speed. This action will affect vehicles driving in speed-control mode, leaving more time for the automated system to respond, while reducing the probability to be involved in an accident.

As in the first simulation, the same surrogate safety is used, and all simulation runs are carried out two times: one time with TM and one time without. Safety improvements might jeopardise traffic flow efficiency. Flow-related KPIs are also assessed. One of these KPIs is the throughput expressed by the average number of vehicles per hour leaving the simulation. The second one is the average travel time. A warm-up period of 100 s was respected.

There are three contextual variations. One is the traffic demand ranging from 6400 veh/h, 9600 veh/h, to 12800 veh/h that were inserted in the simulation from 6 different locations (see red dots in **Error! Reference source not found.**). The vehicle mix composition ranges from 0 %, 25 % to 50 % of TM guided vehicles in the total traffic fleet. The default time gap setting was constrained to 1s and 1.2s. In total, 180 runs were executed (3 demands x 3 mixes x 2 time gaps x 10 random seeds) with TM and 180 runs without TM in the baseline.

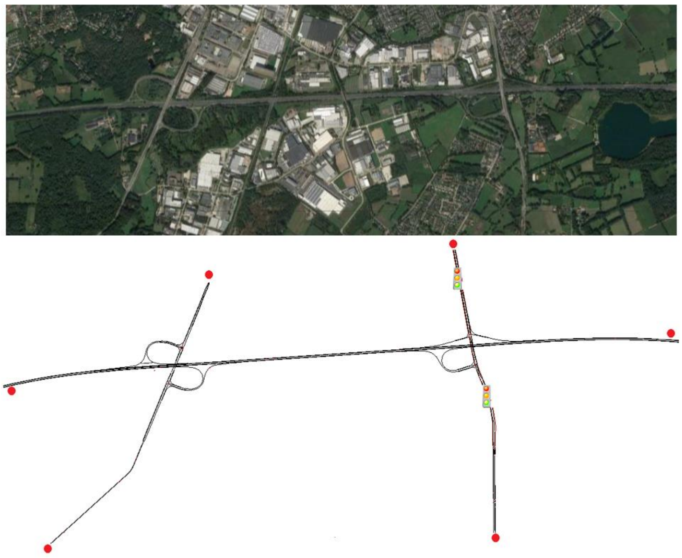

Figure 4. An aerial picture of the imported region in simulation 2 and the network extracted from the region.

The second simulation composes a more realistic setting. The simulation environment was imported using OpenStreetMap [11] and consists of a region in the neighbourhood of the Belgian city Turnhout (see Figure 6). The network is composed of one motorway and two secondary roads. The secondary roads pass the motorway laterally and are connected via off- and onramps. The area is about 10km by 3 km in size.

Results and discussion

Similar results (see **Error! Reference source not found.**) as to simulation 1 were obtained. The TM protocol is effective in reducing the total number of TTC events in general, and especially in the case of high demands with many CAVs in the traffic composition. In contrast to simulation 1, small improvements are also noticeable for lower demands and lower concentrations of CAVs, which suggests that fewer TTC events took place for the connected vehicles driving in speed-control mode having no vehicle in front of them. These results indicate tentatively that the extension of the time gap increase in the first simulation with the speed reduction in the second simulation has improved the TM procedure providing more safety. On- and offramps, traffic lights, and other structural nodes can potentially lead to stagnant traffic that turn into obstacles. This will stochastically lead to more TTC events. A TM procedure that encourages vehicles to reduce speed and leave more space in between can reduce the number of TTC events. In **Error! Reference source not found.**, it can be seen that the TM procedure sharply reduces the number of TTC events for CAVs, but also to a slighter extent for the other vehicles. In other words, the CAVs are better protected by TM and the near-accident probability of other road users tentatively goes down too.

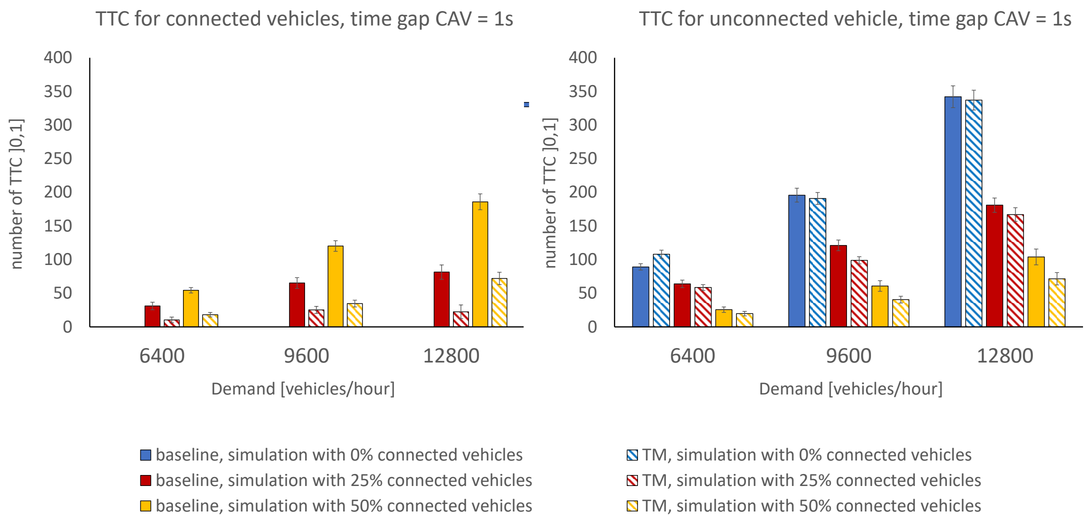

Figure 5. The number of TTC events split between connected and unconnected vehicles.

In the upper plots of Figure 6, the average throughput and average travel time is displayed. The throughput is defined as the number of vehicles that leaves the simulation per unit of time. As it takes a while before the simulation environment gets populated by vehicles, a warning up period of 500 s in each simulations run is respected. The throughput increases from the left panel to the right panel with higher penetration levels of CAVs. In contrast to the first simulation, the throughput tends to hamper slightly by applying traffic management. The throughput for the TM condition ranges from 92.5 % to 100 % of the corresponding baseline condition. Concerning the mean travel time depicted in the lower panels, time loss for an average vehicle is in the order of magnitude of a few seconds up to 20 s for a whole journey lasting 6 minutes on average. Especially the traffic mix with the high concentration of CAVs gives a higher time loss because of TM. This result demonstrates the need to apply the TM procedure with precaution. The traffic management measure should not be applied unnecessarily for the least bit of danger. The definition of imminent potential danger en route ahead needs finetuning.

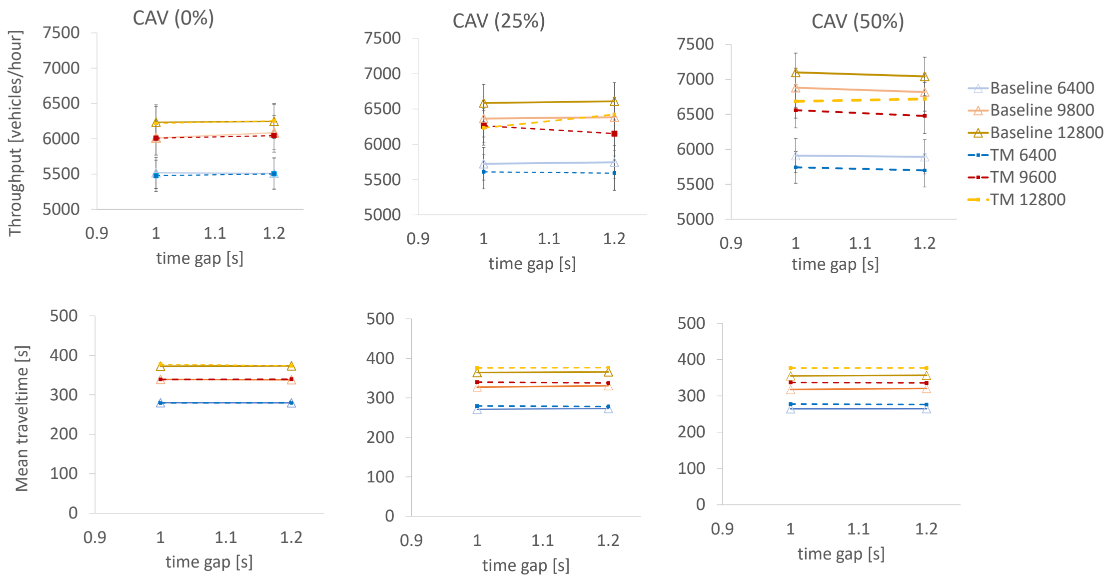

Figure 6. Throughput and mean travel time in simulation 2.

Conclusion

In this study, the microscopic traffic simulator SUMO was used to investigate the effect on safety, of a traffic management procedure that sends an incentive to vehicles upstream to slow down or to increase their headway if a vehicle downstream decelerates intensely or drives at low speed. This traffic management policy was tested by two scenarios. The simulation results demonstrate that the TM procedure reduces the number of near-accidents for the TM connected vehicles and to a lower extend for the unconnected vehicles. While the flow efficiency was not hampered in the first simulation scenario, the TM procedure caused slightly more congestion in the second simulation scenario. The procedure was tested in different contexts to evaluate the relationship between the effect of the TM procedure and the contextual variation. The safety improvement depends largely on the context: more reduction of near-accidents is obtained when more connected vehicles are involved and the default time gap settings are short.

Default ACC implementations combined with an on-board collision avoidance system make cars safer today. Safety can be augmented by connecting these cars and enrolling real-time dynamic traffic management. Traffic management procedures can improve road safety and traffic flow because they are based on traffic information from a wider area and broader traffic context than the detection area of on-board equipment. While the onboard controllers are designed to determine the imminent acceleration and deceleration of the vehicle, traffic management control can interfere indirectly, by altering controller settings such as the so-called desired speed or desired time gap. The term “desired” refers to the provisions that the controllers aim to maintain. Further research is required to finetune the proposed traffic management protocol and extend traffic management with a full set of generic traffic management procedures that improve traffic safety and traffic flow. This study is a step forward in achieving this goal.

Traffic management that allows vehicles to adaptively adjusts the time gap based on the prevailing traffic context holds great promise for making traffic safer and more fluent in the future. This study demonstrates that the traffic management parameters need to be tailored to the traffic context at hand. If this procedure is optimised, it can increas safety without deteriorating traffic flow, and conversely, it can counteract traffic deterioration while not jeopardising traffic safety. This can be done by controllers in vehicles that, with the help of traffic management and V2X, will be able to interpret the environment, and set their time gaps more adaptively.

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