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Traffic control algorithms for mixed vehicle traffic – A simulation-based investigation

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Abstract

A library of software tools, that implements various motorway traffic control algorithms in a generic way for any network topology given by the user, has been developed and integrated with the advanced simulation environment VSimRTI. The control algorithms have been thoroughly assessed via comprehensive simulation investigations involving a large variety of penetration rates for CAVs, infrastructure types and capabilities, and traffic conditions (free flow, critical, congested). The most promising strategy appears to be an ACC parameter adaptation strategy that is presented together with the simulation evaluation results for a test site at Girona (Spain).

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Keywords: Traffic control; ACC parameter adaptation; Simulation-based evaluation.

1. Introduction

Peak-hour traffic congestion has become one of the most challenging problems in modern societies causing severe infrastructure degradation and underutilization. Longer travel times, lower speeds and extended congestion in the network, are only a few of the direct consequences. An efficient way to influence traffic performance and alleviate traffic congestion on motorways is the development and implementation of appropriate traffic control strategies utilizing vehicle automation and communication systems (Markantonakis et al., 2019). In the near future, vehicles equipped with such systems are expected to revolutionise the ordinary features and capabilities of

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conventional vehicles (Diakaki et al., 2015). Vehicle original equipment manufacturers (OEMs) are investing heavily in automation, while software is becoming a critical component of vehicles. At the same time, traffic and road authorities are seeking new technology solutions to increase safety and to reduce traffic congestion, fuel consumption and emissions. These solutions are often dependent on the vehicle's potential to recommend, support or even execute appropriately designed traffic control tasks and the ability of the infrastructure to provide various types of support for drivers and vehicles. Therefore, there is a need to prepare the road infrastructure to support the coexistence of conventional and automated vehicles, targeting the transition period when the penetration rate of connected automated vehicles (CAVs) will gradually increase.

A number of control strategies, targeting maximum throughput at motorway bottleneck locations, was developed by the DSSL group within the FP7 ERC project TRAMAN21 (www.traman21.tuc.gr). These include an adaptive cruise control (ACC) parameter adaptation strategy, a mainstream traffic flow control (MTFC) strategy and a lane-change advice (LCA) strategy. The first control strategy changes in real time the driving behaviour (specifically the employed time-gap and possibly also the acceleration strength) of ACC-equipped vehicles in motorway sections according to the prevailing traffic conditions in order to improve traffic flow efficiency (Spiliopoulou et al., 2018; Manolis et al., 2020). The second control strategy employs mainstream traffic flow control using variable speed limits as an actuator (Markantonakis et al., 2019), when approaching areas with a particular infrastructure layout, e.g. a lane drop or an on-ramp merge area, in order to establish optimal traffic conditions. The third control strategy delivers appropriate lane-changing actions to selected connected vehicles using a feedback-feedforward control law (Markantonakis et al., 2019). The basic goal of the LCA strategy is to achieve a desired distribution of vehicles among the lanes in the immediate proximity of a bottleneck, so as to exploit the capacity of each and every lane, thus increasing the overall cross-lane capacity (see Roncoli et al. (2016), (2017) for more details). Preliminary simulation investigations demonstrated that the proposed strategies improve the motorway traffic flow efficiency significantly, even for low penetration of CAVs.

A library of software tools, that implements the control algorithms in a generic way for any network topology given by the user, has been developed recently within the H2020 project INFRAMIX (www.inframix.eu). Extended simulations have been performed using the advanced simulation environment VSimRTI (Protzmann et al., 2017). The control algorithms have been integrated with the simulation environment and have been thoroughly assessed via comprehensive investigations involving a large variety of penetration rates for CAVs, infrastructure types and capabilities, and traffic conditions (free flow, critical, congested).

Several of the developed tools will soon reach maturity allowing for their immediate practical usage, e.g. at the project's test sites, as well as further exploitation. Based on the simulation evaluations conducted within INFRAMIX, the most promising appears to be the ACC parameter adaptation strategy and is the one chosen to be presented in more details in what follows. Compared to previous publications of the DSSL group on this strategy (Spiliopoulou et al., 2018; Manolis et al., 2020), the investigations presented next include a new microscopic simulation environment, a more realistic mixture of traffic, a more realistic model for the required communication between vehicles and the infrastructure, and different options utilised to examine the minimum requirements from an infrastructure point of view.

2. The ACC parameter adaptation strategy

The existence of vehicles equipped with ACC systems is now a reality, and their use will be expanded in the near future. ACC systems enable drivers to adjust the desired maximum speed and the desired time-gap to the leading vehicle when following slower vehicles. These systems apply automatically the appropriate acceleration or deceleration of the vehicle, based on real time measurements and driver's parameterisation. They are mainly designed to increase safety and comfort, thus some conservative values for the ACC system parameters may be used, i.e. comparatively large time-gaps and low accelerations. However, such conservative parameter values may eventually lead to degradation of the static and dynamic road capacity compared to conventional manual-driving vehicle traffic. The higher the penetration rate of ACC-equipped vehicles, the more pronounced will be the influence of their driving style on the overall traffic flow.

In contrast to the vast literature on ACC and cooperative ACC (CACC) systems, which focuses on the design, functionality or architecture of these systems, there is a comparatively small number of investigations related to the impact of ACC and CACC systems on traffic flow. These works aim to capture this impact under different settings (mainly different time-gaps) and penetration rates, using either microscopic simulation (e.g. Ioannou and Stefanovic, 2005; Shladover et al., 2012) or macroscopic approaches (e.g. Ngoduy, 2013; Delis et al., 2016). However, these studies do not systematically examine how the ACC settings should be specified to improve the overall traffic performance. For a more comprehensive literature review, as well as for a discussion on studies that advance towards the direction of specifying the ACC settings either offline or online, see Manolis et al. (2020). The latter paper presents a simple but effective ACC-based control strategy, which aims to adjust in real time the ACC parameters of equipped and connected vehicles based on the prevailing traffic conditions. The main philosophy behind the proposed concept is to: (i) leave the ACC parameters at their driver-selected values if traffic flow is clearly under-critical so as to limit interventions only to traffic situations that call for efficiency increase; and (ii) change the ACC parameters gradually as appropriate to improve the flow efficiency when critical traffic states are imminent or present. The proposed control strategy depends only on real-time measurements of mean speed and flow. It is actually activated only when, where and to the extent needed. For the sake of understanding and completeness, the control strategy is presented in what follows.

Consider a motorway with both manually-driven and ACC-equipped vehicles. The ACC-equipped vehicle drivers may introduce their desired ACC system parameters, i.e. desired speed, v_d , and minimum time-gap, T_d , but the time-gap is subject to change if the control strategy orders different values. The motorway is considered to be divided into segments, and the traffic management centre (TMC) applies the proposed control strategy at every motorway segment i . In particular, at every control interval t_c , the strategy receives real-time measurements of the exiting flow q_i and mean speed v_i of every segment i . This information may be obtained through conventional spot detectors. The proposed strategy has two goals which are presented below.

The first goal is to determine in real time the time-gaps of the ACC-equipped vehicles that lead to the increase of the static and dynamic road capacity, only where and when it is needed. To achieve this, the strategy calculates the suggested time-gap as a function of the current segment flow, $T_i[q_i(k)]$, as shown in Fig. 1(a). As long as the segment flow is low (i.e. $q_i \le Q_1$), the maximum time-gap, T_{max} , is suggested, since traffic is not critical. Beyond this lower limit, as the flow increases, the strategy gradually decreases the suggested time-gap value, while for high flow values (i.e. $q_i \ge Q_2$) the strategy suggests the minimum time-gap T_{min} . Note that the suggested time-gap value is reduced to the minimum value before the flow reaches the nominal capacity of the segment, Q_{cap} . In this way, the strategy aims to delay, or even prevent, the formation of congestion, by maximizing timely the segment's capacity. It should be also noted that the adopted function $T_i[q_i(k)]$ of time-gap versus flow must be non-increasing, but can have any form deemed appropriate, e.g. deliver only a (high or low) number of discrete time-gap values, rather than being continuous, as the stepwise function shown in Fig. 1(b). This will be, in fact, the form to be used in the simulation investigations presented below. If, despite the intended capacity increase, the segment becomes congested (e.g. due to even higher arriving demand or due to a shockwave arriving from downstream), then the strategy releases its operation at the congested segments, by suggesting the maximum time-gap T_{max} for safety reasons. The suggested time-gap will be applied only if it is lower than the individual time gap setting. The above control decisions are summarized by the following relation that determines the suggested time-gap,

$$T_{stg,i} = \begin{cases} T_i\left[q_i(k)\right] & \text{if } v_i(k) > v_{cong} \\ T_{max} & \text{else} \end{cases} \tag{1}$$

where $k = 1,2,\ldots$, is the discrete time index, and v_{cong} indicates the congestion limit. The control strategy decisions are calculated at the TMC and are disseminated to the ACC-equipped vehicles, e.g. via V2I communication. To avoid possible oscillations, the flow and speed measurements are sufficiently smoothed before being used, e.g. using an exponential filter.

The second goal of the proposed control strategy is the maximization of the discharge flow during congestion at the location of active bottlenecks (dynamic capacity). It is empirically known that the discharge flow at the head of a congested area is lower than capacity, and the second goal is to mitigate this capacity drop. The strategy first identifies the location of active bottlenecks. More specifically, if two consecutive segments $i-1$ and i , have a speed difference higher than a threshold Δv, and the mean speed $v_i(k)$ of the downstream segment i is higher than the congestion speed v_{cong}, while the mean speed of the upstream segment, $v_{i-1}(k)$, is lower than v_{cong} , this indicates

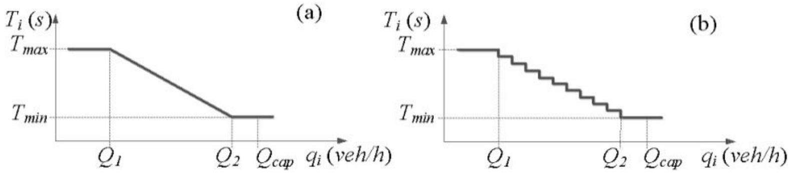

Fig. 1. Calculation of the suggested time-gap value using: (a) a linear, or (b) a stepwise function.

that these two segments are located just upstream and just downstream of the head of a congested area, i.e. that an active bottleneck has been identified. The discharge flow at the congestion head can be increased by suggesting the minimum time-gap T_{min} applied by ACC-equipped vehicles driving within the two mentioned segments. These extended control decisions are implemented via the following relations:

$$\begin{aligned}&\text{If } v_i(k) > v_{cong} \text{ and } v_{i-1}(k) < v_{cong} \text{ and } \left[v_i(k) - v_{i-1}(k)\right] > \Delta v \\ &\text{then } T_{stg,i}(k) = T_{min} \text{ and } T_{stg,i-1}(k) = T_{min}\end{aligned} \tag{2}$$

Again, speed measurements are sufficiently smoothed before being used in order to avoid possible oscillations or false alarms, e.g. due to moving shock waves. The suggested time-gap $T_{stg,i}$ for each control period is determined by (1) and (2). The ACC-equipped vehicles receive the suggested time-gap, but they apply it only if their individual time-gap setting is higher than the time-gap suggested by the controller. Note that ACC-equipped vehicles update their time-gap settings with a frequency that may be higher than at every control interval due to crossing of segment boundaries. Based on extensive simulation investigations, it has been found that the Q_1 and Q_2 values, as well as the size of the motorway segments and the control interval have minor impact on the performance of the strategy.

3. The VSimRTI simulation environment

Microscopic simulations were carried out using VSimRTI (V2X Simulation Runtime Infrastructure), which is a comprehensive framework for the assessment of new solutions for cooperative intelligent transportation systems. The following models are coupled within VSimRTI (see also Fig. 2):

- Map: The geometry of the road on a microscopic basis.
- Road traffic: Vehicle movements on the highway resembling real traffic patterns.
- Communication: Different communication paths including ITS-G5 and cellular communication (LTE-V2X, 5G).
- Road infrastructure: Includes variable message signs (VMSs) for speed limits and lane assignments for CAVs, various road detectors, as well as road side units (RSUs) used for the ITS-G5 communication with the vehicles.
- Traffic management and services: Collect position data from vehicles and distribute advices.
- User behaviour: Reacting on variable message signs and advices via in-vehicle information (IVI) messages.
- Vehicle applications: Includes differentiation in driving behaviour of CAVs and conventional vehicles. CAVs can furthermore react to advices via IVI messages on their own.

Additionally the control algorithms have been directly integrated with the TMC in the simulation environment. Figure 2 illustrates the models included in the microscopic simulations. More detailed information about the models can be found in public deliverable of the INFRAMIX project (www.inframix.eu).

Apart from trailers and motorcycles, three types of vehicles (cars) can be considered within VSimRTI:

- conventional vehicle (CV): vehicle with SAE level of automation equal to 0, 1, or 2 which does not communicate with the TMC-model;
- connected conventional vehicle (CCV): vehicle with SAE level of automation equal to 0, 1, 2 or 3 which communicates through wireless messages with the TMC-model (via cellular or ITS-G5 communication);
- connected automated vehicle (CAV): vehicle with SAE level of automation equal to 3, 4, or 5 which communicates through wireless messages with the TMC-model (via cellular or ITS-G5 communication).

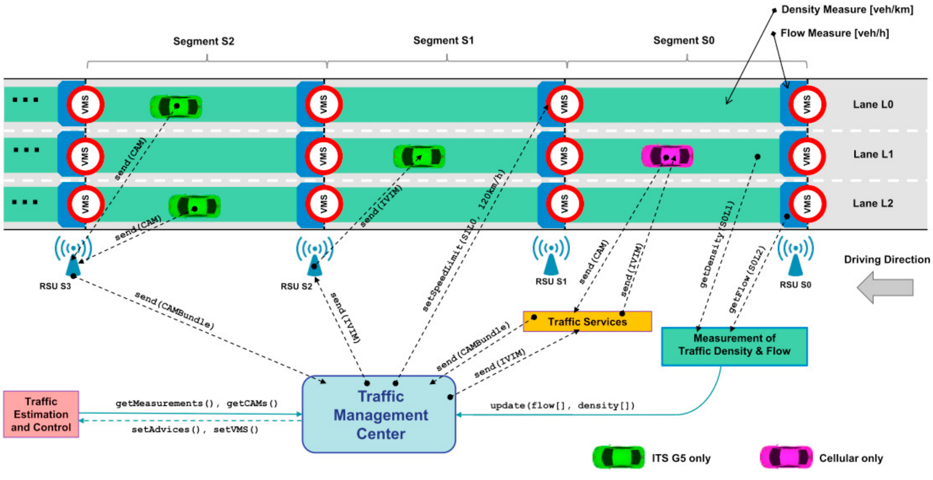

Fig. 2. Overview of all models included in the microscopic simulation.

4. Network description and simulation set-up

The INFRAMIX test site at Girona (Spain), along the highway AP7, was the basis of the microscopic simulation evaluations for traffic efficiency. In order to simulate vehicle traffic on highways, VSimRTI uses the microscopic traffic simulator SUMO v1.5.0 (sumo.dlr.de/docs). Modelling the road traffic for the microscopic simulations was one of the main challenges that has been accomplished following a two-step process. On the basis of real toll data provided by Autopistas (www.autopistas.com), a large-scale simulation scenario along the highway AP7 has been created with more than half a million vehicles during a 24 h period. This scenario has been calibrated to match the real traffic as close as possible utilising the IDMM car-following model (Treiber and Helbing, 2003). Since the Spanish test site at Girona covers only a small part of AP7, the large-scale scenario has been cropped to a 19 km stretch using novel techniques implemented in the simulation framework. This final simulation scenario allows focusing the experiments and evaluation on the test site only and enables simulations faster than real time for a simulation period of three hours (8am to 11am). The considered highway stretch, shown in Fig. 3, includes 3 on-ramps and 2 off-ramps and is divided into 38 segments with a length of about 500 m each. Segments 1 to 4 have 3 lanes, while all other segments have 4 lanes. The simulation step for SUMO is set to 0.5 sec.

The penetration rate of CVs, CCVs and CAVs (CV-CCV-CAV) can be parametrized individually. The following six configurations have been considered to reflect typical and future market penetrations (100-0-0, 94-4-2, 85-10-5, 70-20-10, 55-30-15, 30-45-25). CVs are selected to have SAE level 0, CCVs are selected to have SAE level 3, while CAVs are selected to have SAE level 5. Communication between vehicles and the TMC is modelled with ITS-G5 via RSUs which are located along the road. Messages are sent to the vehicles in a range of about 200 m from the RSUs every 5 sec. These messages contain advices for 10 downstream segments. In order to investigate what are the minimum requirements from an infrastructure point of view, three different cases have been considered for RSU coverage:

- Full RSU coverage: RSUs are placed at the entry of each segment, i.e. every 500 m.
- Mid RSU coverage: RSUs are placed every 4th segment, i.e. every 2 km.
- Low RSU coverage: RSUs are placed every 10th segment, i.e. every 5 km.

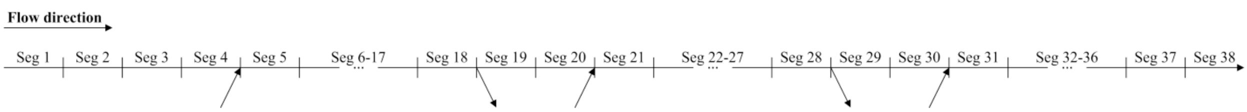

Fig. 3. INFRAMIX test site at Girona (Spain), along the highway AP7.

In the simulations, vehicles are using a range of different default time-gap values, sampled from a normal distribution with a mean value μ and a standard deviation $\sigma = 0.05\mu$, while any values out of the $[\mu - 2\sigma, \mu + 2\sigma]$ range are truncated. The mean value μ is different per category of vehicle. More specifically, the mean value is selected to be equal to 1.1 sec for slow CVs and CCVs, 0.9 sec for fast CVs and CCVs, and 1.4 sec for slow and fast CAVs.

CAVs (SAE level 5) are supposed to be equipped with ACC systems and apply automatically any advice for the time-gap setting if it is lower than their default setting, while CCVs (SAE level 2) are equipped with ACC systems that are activated manually (with a probability of 50% and a delay of 5 seconds) by the drivers if the time-gap advice received through communication is lower than the one applied manually.

5. Simulation investigations

This section presents the simulation results obtained for the no-control case as well as for the control case where the ACC-parameter adaptation strategy is applied. For each one of the investigated cases, the six CV-CCV-CAV configurations discussed above are considered, while for each configuration, 10 simulation replications with different seeds were carried out and the respective average value of delay encountered by the vehicles is reported and compared.

5.1. No-control case

The average vehicle delay for the no-control case is reported in Table 1 for all CV-CCV-CAV configurations. The resulting speed contour plots for all cases are presented in Fig. 4. Due to the conservative parameter values used by CAVs, the static and dynamic road capacity is degraded when increasing their penetration rate. As a result, congestion is created at the merge area of the most downstream located on-ramp and the average vehicle delay increases. The congestion duration and extend are increasing with the increase of the penetration rate of CAVs.

5.2. Control case: The ACC parameter adaptation strategy

The parameters of the control strategy are set as follows: $t_c = 30$ sec, $v_{cong} = 50$ km/h, $Q_1 = 1200$ veh/h/lane, $Q_2 = 1800$ veh/h/lane, $T_{max} = 1.6$ sec, while three different cases (1.2, 1.0 and 0.8 sec) are considered for the value of the minimum suggested time-gap, T_{min}. The strategy suggests discrete time-gap values with increments of 0.2 sec. Table 1 includes the results for all control cases. It can be observed that for all RSU coverage cases and all minimum suggested time-gap values considered, improvements are reported over the no-control case for all CV-CCV-CAV configurations; see also the bar-chart presented in Fig. 5 for the improvements reported as a percentage over the no-control case. In fact, when the minimum time-gap suggested by the controller is either 1.0 or 0.8 sec, i.e. lower than the one applied on average by CVs, the average vehicle delay achieved per CV-CCV-CAV configuration is lower than the no-control case for the 100-0-0 configuration (i.e. only CVs). As a result, any future market penetrations of

Table 1. Average vehicle delay for all cases considered and for all CV-CCV-CAV configurations.

Average vehicle delay (sec)	CV-CCV-CAV configurations					
	100-0-0	94-4-2	85-10-5	70-20-10	55-30-15	30-45-25
No-control case	133.0	134.2	140.7	150.8	168.4	214.7
Full RSU coverage, T_{min} = 1.2 sec	133.0	133.0	133.0	137.1	144.3	147.6
Full RSU coverage, T_{min} = 1.0 sec	133.0	129.4	128.7	124.4	119.7	118.0
Full RSU coverage, T_{min} = 0.8 sec	133.0	126.6	119.3	109.8	103.2	97.9
Mid RSU coverage, T_{min} = 1.2 sec	133.0	133.1	137.3	138.7	143.4	147.4
Mid RSU coverage, T_{min} = 1.0 sec	133.0	129.4	127.8	122.3	120.7	118.6
Mid RSU coverage, T_{min} = 0.8 sec	133.0	126.2	119.6	109.6	103.9	98.6
Low RSU coverage, T_{min} = 1.2 sec	133.0	133.8	136.4	137.7	143.2	147.5
Low RSU coverage, T_{min} = 1.0 sec	133.0	129.8	127.6	123.8	120.9	120.8
Low RSU coverage, T_{min} = 0.8 sec	133.0	125.9	119.8	111.4	106.4	100.8

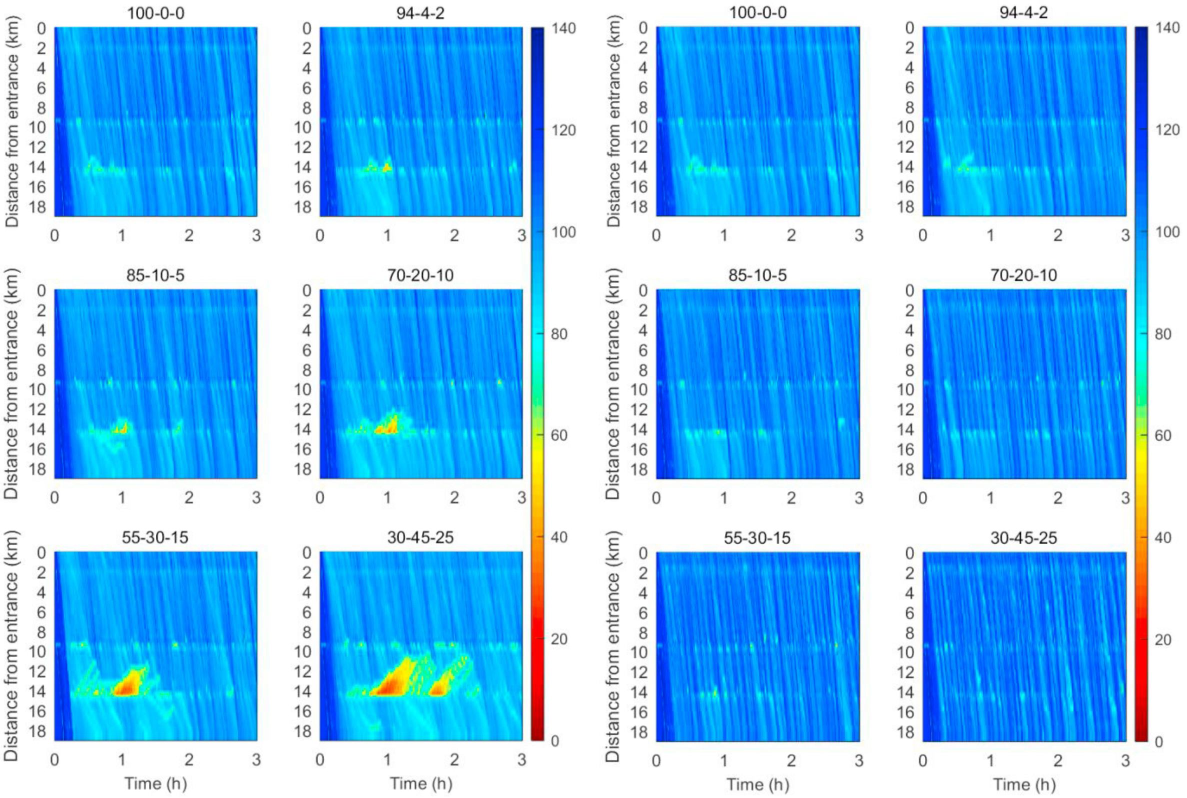

Fig. 4. Speed contour plots (km/h) for the no-control (left) and control (Full RSU coverage and T_{min}= 0.8 sec; right) cases for all CV-CCV-CAV configurations.

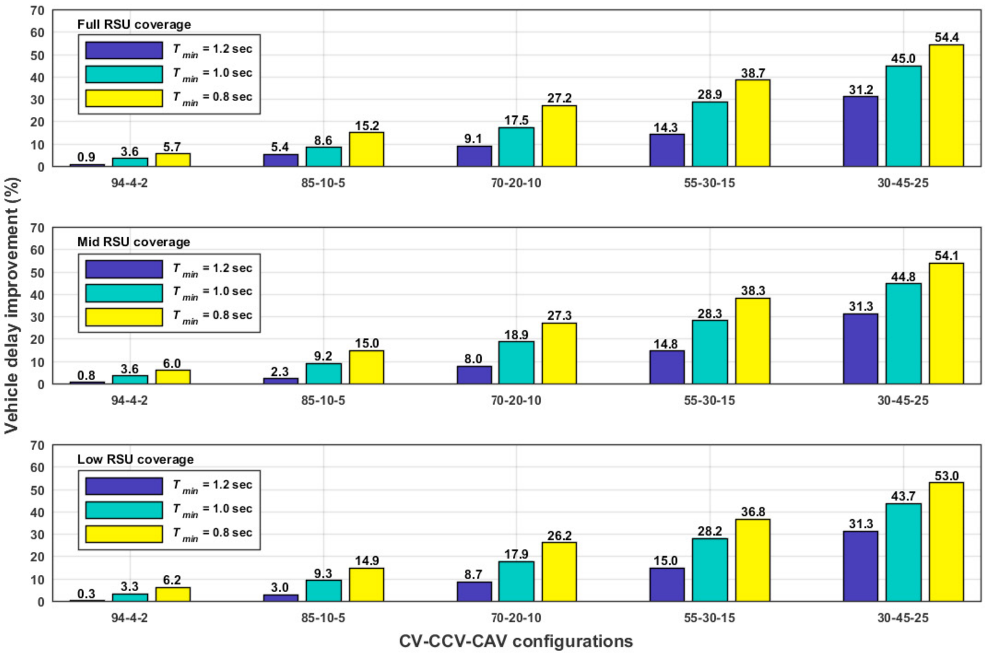

Fig. 5. Bar chart for the vehicle delay improvements (%) over the no-control case for all control cases and all CV-CCV-CAV configurations.

CAVs will be in a position to avoid degradation and even improve the current situation only if CAVs use on average lower time-gaps when necessary. This improvement over the corresponding CV-CCV-CAV configuration and over the 100-0-0 configuration is also observed in the speed contour plots presented in Fig. 4 for the control case with full RSU coverage and $T_{min} = 0.8$ sec.

In order to investigate what are the minimum requirements from an infrastructure point of view, apart from the full RSU coverage case we also considered control cases with mid or low RSU coverage. Although we expected to observe lower performance for the mid and low RSU coverage cases, as vehicles may have outdated information when they actually arrive at a segment and apply the advice, we can see that performance remains at the same level compared to the full RSU coverage case.

6. Conclusions

A library of software tools, that implements various motorway traffic control algorithms in a generic way for any network topology given by the user, has been developed recently within INFRAMIX. The library has been integrated with the advanced simulation environment VSimRTI. The control algorithms have been thoroughly assessed via comprehensive simulation investigations involving a large variety of penetration rates for CAVs, infrastructure types and capabilities, and traffic conditions. The most promising strategy appears to be the ACC parameter adaptation strategy that was presented in more details together with the evaluation results.

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