Mitigating Congestion at Sags with Adaptive Cruise Control Systems

Alexandros E. Papacharalampous*, Meng Wang*, Victor L. Knoop*, Bernat Goñi Ros*,
Toshimichi Takahashi†, Ichiro Sakata‡, Bart van Arem*, *Member, IEEE* and Serge P. Hoogendoorn*
*Dept. Transport and Planning, Fac. Civil Engineering and Geosciences, Delft University of Technology
Stevinweg 1, 2628 CN, Delft, The Netherlands
Email: a.papacharalampous@tudelft.nl
†Vehicle Dynamics Laboratory, Toyota Central R&D Laboratories Inc.,
41-1 Yokomichi, Nagakute-shi, Aichi 480-1118, Japan
‡Technical Centre, Toyota Motor Europe, Hoge Wei 33, 1930, Zaventem, Belgium

***Abstract*—Sags are segments of the road where there is a significant change in gradient from downhill to uphill in a short distance. Empirically, it has been observed that drivers do not compensate adequately for the changing grade resistance force at sags, which limits vehicle acceleration. As a consequence, congestion forms at sags. This paper proposes and compares the implementation of Adaptive Cruise Control (ACC), Traffic State-Adaptive ACC (TSA-ACC), and Cooperative ACC (CACC) at sags. The controllers are implemented in a traffic simulation environment with a single-lane road stretch and a platoon of 200 vehicles of which 10% follow the movements set by the controller and 90% follow the normal driving rules. The simulation results show that all controllers reduce the travel time of the equipped vehicles and have significantly positive effects on the total travel time of the platoon. TSA-ACC produces the most travel time savings. The findings of this paper show that the proposed controllers can be used to improve the performance of traffic flow at sags.**

I. Introduction

Sags are segments of the road where there is a significant change in gradient from downhill to uphill in a short distance. It has been observed that capacity at sags is lower in comparison to flat segments [1]. According to [2], 39% of the bottlenecks in Japanese highways can be attributed to sags. This share is the highest among other infrastructure-related reasons for the creation of bottlenecks [2]. The reduced capacity causes traffic to breakdown sooner, in terms of traffic flow, than in normal, i.e., no sag conditions. The emerging congestion further reduces the capacity of the bottleneck [1].

Generally, vehicles equipped with ACC systems accelerate and decelerate more efficiently than human driven vehicles [3]. Vehicles with ACC do not fall into inattentiveness errors and have a shorter reaction time than human drivers [4]. Additionally, the acceleration of those vehicles is not influenced by changes in gradient; they adjust their acceleration solely on the basis of the behaviour of their predecessor.

The objective of this paper is to demonstrate how in-vehicle control strategies can mitigate congestion at sags and reduce vehicles' travel time. To achieve this objective, three controllers will be presented: Adaptive Cruise Control (ACC), Cooperative Adaptive Cruise Control (CACC) and Traffic State-Adaptive ACC (TSA-ACC). Those control concepts have not yet been specifically applied to sags. This paper will show that their implementation could lead to significant savings in total travel time.

The performance of the controllers is tested with microscopic traffic simulation in a scenario with a single-lane highway stretch containing a sag and a limited number of controlled vehicles (10% of vehicles are controlled). The effectiveness of each controller is evaluated by analysing the reduction in total travel time in comparison to the no-control scenario and to the case where 10% of the drivers are supported by the ACC controller.

The paper is structured as follows. First, a literature review on the behaviour of drivers at highway segments with sags is presented, including findings of previous research studies that are of interest in the formulation of the controllers. Next, the mathematical formulation of the controllers is presented. The experimental setup is described in section IV. Section V presents the results of the evaluation of the controllers. Finally, sections VI and VII contain a discussion on the fulfilment of the objectives and the conclusions that were drawn from the presented research work respectively.

II. Literature Review

When flow immediately upstream of the bottleneck becomes higher than the capacity of the bottleneck, then congestion forms. Sags form an infrastructural bottleneck; the bottleneck is always at the same location, generally 0.5-1 km downstream of the lower point of the sag [5].

The congestion-induced capacity drop at sags is approximately 10-15% [1], [6]. Free flow capacity and queue discharge rate at sags have been calculated to be approximately 20% lower than their equivalent values in flat segments [7], which shows that traffic conditions at sags are very susceptible to breakdown. Another characteristic of the congestion patterns at sags is that they are typically oscillatory [6].

The main reason for the capacity reduction at sags appears to be that drivers fail to accelerate enough to compensate for the increased gravitational pull that is exerted due to the change in gradient [8]. As a result, the driver's behaviour changes in two ways: *i)* drivers reduce speed [5], [9] and *ii)* drivers maintain a longer spacing (distance headway) than expected if one takes into account their speed [10], [11].

Various measures have been proposed to mitigate congestion at sags. These measures can be divided into four categories [7]. The first category of measures involves increasing the free flow capacity of sags. An example is equipping vehicles with ACC systems so that they can accelerate more efficiently [3]. The second category includes measures that aim to increase queue discharge rate. For instance, this can be achieved with Variable Message Signs (VMS) that give information to drivers about the location of the head of the queue and encourage them to recover speed after leaving congestion. This kind of measure has been found to increase the queue discharge rate by 1-7% [12], [13]. The third category of measures concerns the prevention of traffic perturbations. For example, some of those measures aim to discourage drivers from performing lane changes towards the densest lanes [6] and to prevent the formation of long platoons [14]. The fourth category of measures are based on the concept of Mainstream Traffic Flow Control (MTFC). MTFC can be implemented through Variable Speed Limits that create a slow moving area upstream of the sag in order to reduce the inflow to the sag [7].

To conclude, it is clear that sags account for a large number of traffic jams in some highway networks. Therefore, the motivation for reducing the negative effects of sag bottlenecks is clear. Traffic management concepts based on ACC have been tested at sags [3] but an operational comparison with other more advanced measures, such as CACC, is missing. This paper focuses on the comparison of more advanced control concepts based on vehicle automation systems.

III. Controller Formulation

This chapter contains the mathematical formulation of the acceleration models and information on the control objectives of each controller. Their design is based on the categories of measures for mitigating congestion at sags that are described in the previous section. ACC is a measure of the first category. CACC belongs to the first, second and third categories. TSA-ACC belongs to the first, second and fourth categories of measures. Finally, it should be noted that none of the controllers requires information from the infrastructure in order to operate.

A. Adaptive Cruise Control (ACC)

The ACC system operates in two modes: cruising mode and following mode. In cruising mode, the ACC system aims to maintain a user-defined speed. In following mode the system attempts to maintain a desired gap. It is assumed that the host vehicle speed, spacing and relative speed with respect to the preceding vehicle are available from on-board sensors. In this paper, it is assumed that there is no delay or error in the information from on-board sensors.

The proposed ACC controller is a non-linear state-feedback controller that is an improved version of linear state-feedback control laws that are widely studied, i.e. the constant time gap policy [15], [16]. The ACC controller is proposed based on the design of a flexible Model Predictive ACC controller [17], but simply in the efficient state-feedback fashion.

The acceleration control law for ACC vehicle i is expressed as follows:

$$a_i^{\text{ACC}} = \begin{cases} k_1(v_{\text{input},i} - v_i) + k_2\frac{\Delta v_i}{s_i}, \text{ if } s_i \le r^{\text{ACC}} \\ k_1(v_0 - v_i), \text{ if } s_i > r^{\text{ACC}} \end{cases} \tag{1}$$

where a is acceleration, s is distance gap, v is speed, i denotes the vehicle index, Δv_i is the relative speed with respect to the preceding vehicle $i-1$ ($\Delta v_i = v_{i-1} - v_i$), k_1 and k_2 are the feedback gains and r^{ACC} is the on-board sensor detection range. For a radar-based system, r^{ACC} is typically 150 m.

Variable v_{input} is a gap-dependent desired speed that is an input to the acceleration model and is determined by:

$$v_{\text{input},i}(s_i) = \min\left(\frac{s_i - s_0}{t_d}, v_0\right) \tag{2}$$

where t_d is the desired time headway, s_0 is the minimum gap at standstill and v_0 is the free speed.

The control law is subject to three constraints:

1) non-collision constraint ($s_i > 0$);
2) physical speed range ($0 \le v_i \le v_{\max}$);
3) admissible acceleration range ($a_{\min} \le a_i \le a_{\max}$).

The proposed ACC controller takes the sensor range explicitly into account. When there is no preceding vehicle detected within the sensor range, the ACC controller regulates the acceleration to match the free speed. When a vehicle is detected in range, the first term of the control law regulates the acceleration to a gap-dependent speed. The gap-dependent speed is proportional to the current gap with respect to the predecessor and is no larger than the free speed. The second term of the control law gives large deceleration when the controlled vehicle approaches the predecessor with small gaps.

B. Cooperative ACC (CACC)

The CACC controller uses Vehicle-to-Vehicle (V2V) communication to anticipate downstream traffic conditions. The V2V communication range is assumed to be 300 m for typical short range communication technologies. It is assumed that no communication delay and errors occur.

The CACC controller extends the basic ACC controller by including an additional multi-anticipative term [18], [19]. This implies that the CACC-vehicle reacts to the behaviour of not only the direct predecessor, but also of multiple downstream vehicles. If there is no CACC-vehicle in the V2V communication range, the CACC controller calculates the target acceleration in the same way as the basic ACC controller (see (1)). If there are CACC-vehicles within the communication range, then the acceleration is calculated as follows:

$$a_i^{\text{CACC}} = a_i^{\text{ACC}} + k_3 \sum_{j=i-2}^{N} \frac{v_j - v_i}{x_j - x_i} \tag{3}$$

where j denotes indices of the CACC vehicles downstream of the direct predecessor $i-1$, x denotes the position of vehicles and k_3 is a feedback gain.

By including the multi-anticipation term, controlled vehicles behave as follows. If the controlled vehicle detects a speed reduction (increase) of another CACC-vehicle downstream of its current position, then it decelerates (accelerates) as well. That deceleration (acceleration) is stronger the closer the controlled vehicle is to the CACC-vehicle upstream. In that sense, vehicles "anticipate" that they will decelerate or accelerate when moving downstream.

C. Traffic State-Adaptive ACC (TSA-ACC)

The TSA-ACC controller estimates the traffic state that the vehicle is in by means of on-board detectors; then, it adjusts the value of control parameter t_d (desired headway) based on the traffic state. More specifically, the TSA-ACC controller increases the desired headway when the vehicle approaches the upstream front of a jam (jam tail), and decreases the desired headway when the vehicle is in congested traffic and right after it crosses the downstream jam front (jam head). The logic behind it is as follows. First, the increase in desired headway makes the controlled vehicle decelerate. The following vehicles are forced to decelerate as well, which reduces the inflow to the jam. Inflow control can mitigate or even dissolve congestion at sags [7]. Second, when the desired headway decreases the flow within the queue increases (since flow is equal to the reverse of headway). An increased outflow from the queue leads to total travel time savings.

The TSA-ACC controller needs to be able to estimate the traffic state. A vehicle-based traffic-state detection algorithm is proposed for this purpose. The algorithm uses an exponential moving average (EMA) of the vehicle speed to identify the traffic state. The formula used to calculate the EMA of the speed for each vehicle at each discrete time instant is:

$$v_{\text{EMA}}(t_{k+1}) = (1 - e^{-\frac{\Delta t}{\tau_r}})v(t_{k+1}) + e^{-\frac{\Delta t}{\tau_r}} v_{\text{EMA}}(t_k) \tag{4}$$

where t_k is the time instant of control time step k (it holds that $t_k = k\Delta t$, where Δt is the control time step length) and τ_r is the relaxation time.

From (4), it follows that the influence of vehicle speeds older than the time instant $t - \tau_r$ decreases exponentially.

The vehicle-based traffic-state detection algorithm estimates the traffic states as follows:

1) If $v_{\text{EMA},i} > v_{\text{free}}$, vehicle i is in free flow conditions.
2) If $v_{\text{EMA},i} < v_{\text{cong}}$, vehicle i is in a jam.
3) If $v_i - v_{\text{EMA},i} < -\delta v$, vehicle i is approaching the upstream front of a jam.
4) If $v_i - v_{\text{EMA},i} > \delta v$, vehicle i is leaving the jam (crossing the jam head).

If none of the above states is detected, then the controller implements the default value of desired headway.

IV. Experimental Setup

A. Simulation Configuration

The controllers were evaluated using microscopic simulation. The longitudinal driving behaviour of non-controlled vehicles is modelled in the same way as described in [7]. The car-following model that is used in the simulations takes into account the effect of the vertical curve [7]. The goal of the controller's application is to reduce the travel time of all the vehicles that traverse the test segment. The penetration rate of any of the aforementioned controllers is 10% or, in other words, out of all the vehicles in the test segment, 10% are controlled. The penetration rate is chosen to represent the current ACC penetration situation in developed countries. The travel time savings for the controlled vehicles and non controlled vehicles are also considered separately.

The controllers were simulated in a single-lane segment with no on-ramps or off-ramps. The segment starts with a downhill section which gradient is equal to -0.5% and length is 3 km. The sag's vertical curve has a length of 600 m. In this distance, the gradient changes linearly from downhill to uphill. The sag segment is followed by an uphill segment which has a length of 2 km and a gradient of +2.5%. The travel time of the vehicles is defined as the time they need to traverse the total length of the segment, which is equal to 5.6 km.

A total of 200 vehicles were simulated using a simulation time period of 700s. Additionally, the controlled vehicles were placed randomly in the platoon per random seed. A total of 20 random seeds of controlled vehicles were used to evaluate the travel time per controller. It should finally be noted that the initial conditions of all vehicles were the same for every simulation run. Vehicles enter the network with a constant free flow speed of 120 km/h and a headway of 1.2 s.

B. Controllers Parameter Tuning and Application

Each controlled vehicle receives an acceleration value from the ACC or CACC controllers every 0.05 s, which is the control time step and is equal to the simulation time step. Initially, the ACC controller calculates the input speed, determines if the preceding vehicle is within range r^{ACC} and calculates acceleration from (1). Consequently, the controller compares the calculated acceleration to the maximum ($a_{\text{max}} = 1.4$ m/s^2) and minimum ($a_{\text{min}} = -8$ m/s^2) acceleration values. If the calculated acceleration is higher than the maximum or lower than the minimum then the acceleration becomes equal to a_{max} or a_{min} respectively. Finally, the controller determines if the no-collision constraint is violated, i.e., whether the vehicle's net spacing is less than s_{min}. Operationally it is more suitable to set s_{min} to a higher value than 0 because if the controller reacts to spacing being less than 0, then the vehicles will have already collided. This value is set to be $s_{\text{min}} = 10$m. If the spacing is less than s_{min}, the following equation is applied for calculating acceleration a of vehicle i:

$$a_i = \max\left(-\frac{(v_{i,t} - v_{i-1,t})^2}{2 * s_{i,t}}, a_{\text{min},i}\right) \tag{5}$$

where, v is the speed of the vehicle, s is the spacing (distance headway) and t is the simulation time step.

The CACC controller determines the acceleration in a similar fashion with the addition of a step prior to the comparison to the minimum and maximum values and after calculating the acceleration from (1). More specifically, the controller determines if there are CACC controlled vehicles within the range r^{CACC}. If vehicles are found within range, then the controller requests the values of position and speed of these vehicles, calculates the multi-anticipation term shown in (3) and adds the value to the previously calculated acceleration.

From the ACC and CACC, it was expected that the image of the congestion in a speed-contour plot would be similar to a no-control scenario. The reason for this hypothesis is that ACC and CACC controlled vehicles behave in part similarly to human drivers, yet more efficiently. Additionally, the CACC controller should operate similarly to ACC; given the low penetration rate, total travel time savings of CACC compared to ACC should be minimal. Both controllers improve the traffic operations by handling the acceleration tasks more effectively. Also, vehicles with any of the two aforementioned controllers should always keep the smallest possible spacing given the speed of the predecessor. To verify these assumptions, first it has to be proven that: *a)* the total travel time is smaller than in the no-control scenario; and *b)* controlled vehicles keep shorter headways downstream of the sag than non-controlled vehicles.

Since each controlled vehicle performs more efficiently than the non-controlled vehicles, the effects of the decrease in travel time should be additive when more vehicles cross the section. In other words, the vehicles further upstream in the platoon should have more travel time gains than vehicles that are in the front of the platoon. If that expectation proves true, then intuitively it means that larger platoons will have higher travel time gains.

The TSA-ACC controller has the advantage of reacting to traffic conditions instead of having a continuous and uniform operation in comparison to ACC and CACC. The operation of the TSA-ACC is the following: when the vehicle is entering the jam, the desired headway is increased from the default value of 1.2 s to 3 s and the vehicle decelerates and gains distance from the predecessor. A high enough value for the desired headway should cause a disturbance/slow moving area upstream of the initial tail of the congestion. This assumption can be tested by the speed contour plot from when only the state of approaching the jam is active. Therefore, the testing should break down the effects of each state by examining them separately as well as in total.

When the vehicle enters the jam, it reduces its desired headway to 0.6 s which causes the vehicle to accelerate and keep a lower spacing with their predecessor. When the vehicle is again in free flow, the desired headway takes again the default value which is 1.2 s. Fig. 4 shows the states that are detected by each controlled vehicle.

In general, decreasing the desired headway for all controlled vehicles for all the length of the simulation time will greatly reduce travel time. Nevertheless, reducing the desired headway can lead to unsafe situations for the drivers [4] and also may destabilize traffic when it is operating at close to capacity conditions [20]. For these reasons, it is proposed to keep the desired headway low only when in congestion and when leaving the congestion where the speeds are low and both drivers and controlled vehicles will have time to react to suddenly changing conditions. In addition, reducing the desired headway in the aforementioned cases will not interfere with traffic operations; traffic will not break down due to the lowered headway since lowering the desired headway is triggered by the congestion.

Finally, as [4] notes, a comfortable experience for the driver suggests low accelerations or, more specifically, minimal changes in acceleration. To avoid the sudden changes in acceleration, two methods were implemented. First, in the acceleration model of ACC, a higher weight was given to the relative speed by increasing feedback gain parameter k_2 (see (1)). This resulted in vehicles following the speed and acceleration of the preceding vehicles more smoothly. This method is applied for all controllers. Second, in the TSA-ACC, where the sudden changes of the desired headway resulted in major changes of the acceleration, a linear application of the desired headway was implemented. In other words, when the vehicle detected that it has to change the desired headway, it did so in a linear fashion over a predefined time interval. The time interval depends on the thresholds chosen for the state detection while some values that were commonly used in the simulation procedure and yielded the requested results range between 4-8s.

V. Results

This section contains the results that have been obtained from the simulations by applying the different controllers. Only for viewing purposes, the figures that are presented in this section have been generated from a predefined set of vehicles. Vehicles *10, 20, 30,..., 190* are controlled vehicles. Vehicle *6* is also a controlled vehicle. By choosing an equal number of non-controlled vehicles between all pairs of controlled vehicles, we ensure that there are minimal interactions between the controlled vehicles. The aforementioned configuration of controlled vehicles (equidistant from each other within the platoon) is not included in the simulation runs for determining average total travel times.

A. Normal ACC - Base scenario

The bottleneck of the sag area causes vehicles to decelerate when they exit the vertical curve. The congestion that has formed has a positionally fixed head and it propagates backward with a speed that depends on the inflow of the segment.

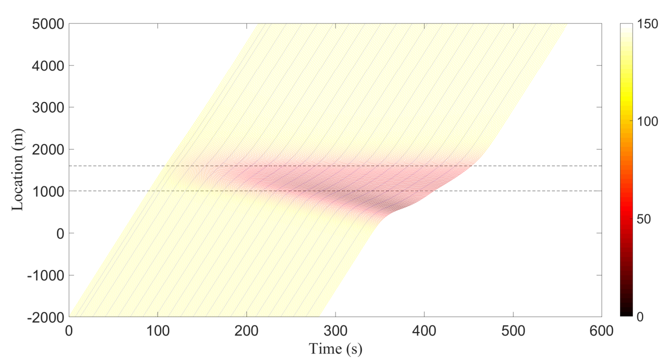

Fig. 1. Speed Contour plot with ACC controlled vehicles

In Fig. 1, the two dashed lines show the start (bottom) and end (top) of the sag area. Just upstream of the sag area and after some time from the appearance of the congestion there seems to be an area of even lower speeds than those observed within the sag, the characteristics of which are congruent to the form of a stop-and-go wave. This stop-and-go wave is ever more prominent in the no-control scenario (no controlled vehicles) which in turn means that ACC smooths out the traffic operations in the sag area. In general, the addition of ACC controlled vehicles resulted in time savings of approximately 10 veh·min in total travel time (an average of 3 s per vehicle).

Fig. 2 illustrates the travel time savings per vehicle in comparison to the no-control scenario. It shows that the existence of ACC controlled cars has an additive effect on travel time saving, as hypothesized. The most downstream controlled vehicle in the platoon saves an amount of travel time. The following non-controlled vehicles have travel time savings which are a direct effect of the leading controlled vehicle. The next controlled vehicle in the platoon also has travel time savings which are an accumulation of the time savings from its operation and from the upstream controlled vehicle. The increase in time savings is almost linear as seen from Fig. 2.

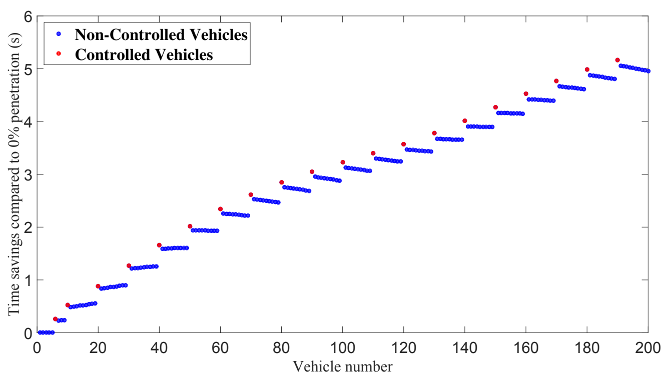

Fig. 2. Travel time savings compared to the no control scenario

B. Cooperative ACC

The results of CACC are similar to the ACC. Travel time for the CACC was improved by 0.4 veh·min compared to ACC or 10.4 veh·min compared to the no control scenario on average. Controlled vehicles behave more efficiently than non-controlled vehicles as is the case with ACC. This is argued since the basis of the CACC calculation of acceleration is identical to the ACC.

Nevertheless, the low penetration rate does not allow for the CACC model to operate effectively. When CACC controlled vehicles are in free flow conditions, the distance between controlled vehicles can be long enough to not allow communication. CACC controlled vehicles will be able to communicate with multiple vehicles when inside the jam where the distance headway between vehicles is low.

It is interesting to comment on the distribution of headways of the CACC (see Fig. 3). The headways were measured 2 km upstream of the sag where the vehicles had reached the maximum speed and they were no longer affected by the dynamics of the sag.

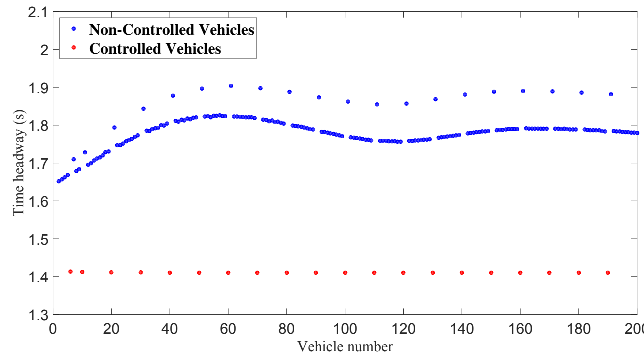

Fig. 3. Headways of vehicles 2km upstream of the sag

A first remark concerns the behaviour of the controlled vehicles. After exiting the congestion and achieving free speed, the controlled vehicles maintain the lowest possible headway. Therefore, controlled vehicles remain as close to their predecessor as possible depending on the value of the desired headway which is an input to the acceleration model. The value of the desired headway will be explored in the next subsection.

Second, there are non-controlled vehicles that have a higher headway than expected in comparison to the curve formed by the headways of the other non-controlled vehicles. These vehicles are the immediate followers of the controlled vehicles. The controlled vehicles are able to maintain a short headway from their predecessor more than a non-controlled vehicle could. Additionally, the non-controlled car responds to the acceleration slower than the controlled vehicle by a small degree. Therefore, the headway of the non-controlled cars is increasing since they fail to accelerate accordingly to the conditions in contrast to the controlled vehicles. When the non-controlled cars that are following a controlled car have reached maximum speed, it is no longer possible to decrease their spacing resulting in the higher headway seen in Fig. 3.

C. Traffic State-Adaptive ACC

First, it is important to determine whether the TSA-ACC can detect the states of traffic that it is currently in. The detection of the states per controlled vehicle is shown in Fig. 4, which demonstrates that the TSA-ACC can detect the states of traffic effectively.

The improvement in travel time from implementing the TSA-ACC controller is 18 veh·min and the average travel time savings for the controlled vehicles are approximately 5.66 s. The effects of the TSA-ACC were evaluated by breaking down the strategies of the controller and examining the effects of each state on the segment's traffic. The first strategy which is to increase the desired headway when approaching the congestion, is abbreviated TSA-ACC-Appr. The second strategy which is to decrease of desired headway when in

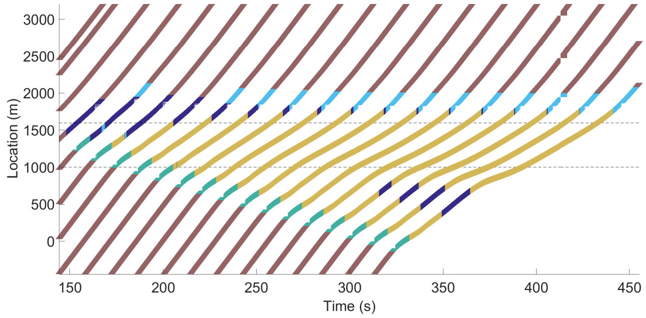

Fig. 4. Detection of states by vehicles equipped with TSA-ACC. Brown indicates free flow, green/cyan shows approaching the jam state, yellow indicates in congestion state, light-blue indicates leaving the jam and dark-blue is the fall-back state

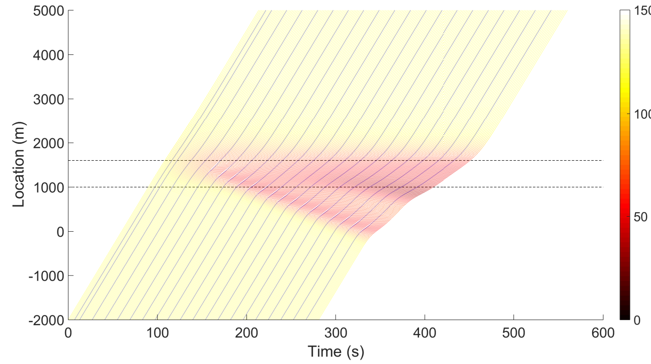

Fig. 5. Speed contour plot for implementing only the approaching strategy (increase of time headway) of TSA-ACC

congestion and when leaving the jam is abbreviated TSA-ACC-Cong. Both TSA-ACC-Appr and TSA-ACC-Cong are not new control concepts but are split here from each other for the sake of the analysis of their effects on traffic.

If the desired headway is altered only when entering the jam (TSA-ACC-Appr) then the difference from the normal ACC is that controlled vehicles decelerate upstream of the congestion. The deceleration of the controlled vehicles causes following vehicles to also decelerate and consequently to create a new slow moving area that resembles a stop-and-go wave upstream of the sag. The formation of the new slow moving area causes the inflow to the sag to reduce.

The reduction of the inflow causes the main congestion to spread over a larger area upstream (as seen in Fig. 5). Vehicles maintain a higher speed on average compared to the ACC case. However, the new slow moving area incurs extra travel time for the vehicles that cross it because they remain in less than free flow speeds for a longer length of the road. The resulting travel time savings are moderate compared to the ACC. The additional travel time savings of only increasing desired headway when a vehicle is approaching the jam compared to the ACC are 1.4 veh·min (11.4 veh·min compared to the no-control scenario). The individual travel time savings of the controlled vehicles compared to the no-control scenario are 3.64 s on average.

Furthermore, simulations indicated that increasing time headway above the value of 3s will on average reduce travel time savings. A possible reason why increasing desired headway causes less travel time savings may be that the region where the state "approaching the jam" is detected, is not large enough. Increasing the area can happen either by reducing the threshold of detecting the state, which will incur more false-positives, or by exploiting the communication capabilities of CACC, which is a matter of future research.

In the case of reducing the desired headway only in congestion and when leaving the jam (TSA-ACC-Cong), the travel time savings are greatly improved as hypothesized. More specifically, the total travel time savings are approximately equal to 18.6 veh·min and the average travel time of the controlled vehicles is approximately 6 s. This is a slight improvement in comparison to the original TSA-ACC controller. Therefore, we conclude that what makes the original TSA-ACC controller decrease the total travel time is primarily the strategy of the reducing the desired headway when controlled vehicles are in a queue or leaving it.

Fig. 6 summarizes the results of the total travel time savings for the controllers that were tested and also includes an error bar that indicates the range of the variation of the values. The travel time savings for each of the parts of the TSA-ACC controller (separately and in combination) are also included in the figure.

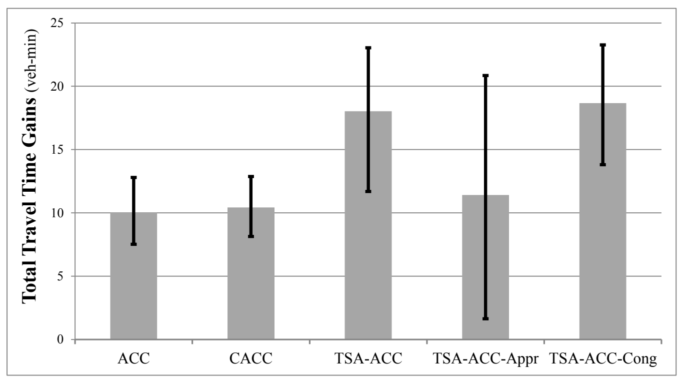

Fig. 6. Total Travel Time savings for all the examined controllers (and for each part of TSA-ACC) and their variation

VI. Discussion

The simulations in this paper do not include lane changes and only passenger cars are simulated while non-controlled passenger vehicles have no stochastic driving characteristics. In spite of those simplifications, the findings presented in this paper are important for understanding the effects of the controllers on traffic flow at sags. They provide insights on how the controllers work on controlled environments which is the basis for more realistic simulation testing.

The results show that all proposed controllers reduce the total travel time in comparison to the no-control scenario. The TSA-ACC controller produces a considerable improvement in total travel time in comparison to the ACC and CACC controllers. The results also show that the traffic-state detection algorithm used by the TSA-ACC controller is able to detect the states of traffic successfully. The CACC controller did not improve the total travel time too much compared to the ACC controller. It is expected that with higher penetration rates, the total travel time savings resulting from the implementation of CACC vehicles will be higher than the total travel time savings resulting from the implementation of ACC vehicles. This is argued because the density of CACC-vehicles will increase and more CACC vehicles will be detected by each controlled vehicle.

Regarding the performance of the TSA-ACC controller, it is found that the strategy that has the highest impact on total travel time is decreasing the desired headway in congestion and when leaving the jam. Increasing the desired headway when approaching the jam leads to an improvement in total travel time albeit with great variability (see fig. 6) depending on the position of the controlled vehicles within the platoon. When the two strategies are combined, the gain in total travel time is slightly lower than with the first strategy alone.

VII. Conclusions

This paper evaluated and compared the effectiveness of three different controllers in mitigating congestion at sags. The controllers are Adaptive Cruise Control (ACC), Cooperative ACC (CACC) and Traffic State-Adaptive ACC (TSA-ACC). The proposed controllers have not been applied specifically to sags before. Those controllers were tested with microscopic simulation of a single-lane highway with 10% controlled vehicles randomly distributed in traffic. The effectiveness of the controllers was evaluated primarily by analysing the total travel time resulting from their implementation.

All controllers produced a reduction in total travel time compared to the no-control scenario. More specifically, the ACC and CACC controllers reduce the total travel time by 10.0 and 10.4 veh·min, respectively. TSA-ACC is the controller that leads to the greatest improvement in total travel time in comparison to the ACC scenario; the implementation of TSA-ACC produced an 18 veh·min improvement in total travel time compared to the no control scenario and 8.0 veh·min compared to the ACC controller.

Further research is necessary to evaluate the performance of the controllers in multi-lane networks under various conditions. These conditions can be different vehicle categories, traffic heterogeneity and different geometric characteristics of the sag. The position of the controlled vehicles within the platoon may also have effects on the generated/altered traffic conditions and will be examined in future work. Finally, it would also be interesting to examine controllers that may result from the application of the traffic state adaptive strategy in combination with V2V communication.

Acknowledgement

This research was sponsored by Toyota Motor Europe.

References

[1] Koshi, M., M. Kuwahara, and H. Akahane. *Capacity of sags and tunnels on Japanese motorways* ITE Journal, Vol. 62, No. 5, 1992, pp. 17-22.

[2] Okamura, H., S. Watanabe and T. Watanabe, *An empirical study on the capacity of bottlenecks on the basic suburban expressway sections in Japan* in Proc. of the 4th International Symposium on Highway Capacity, June 2000.

[3] Ozaki, H., *Modeling of Vehicular Behavior from Road Traffic Engineering Perspectives* in Traffic and Granular Flow '01, Berlin:Springer, 2001, pp. 281-292.

[4] Kesting, A., M. Treiber, M. Schönhof, and D. Helbing, *Adaptive cruise control design for active congestion avoidance* Transportation Research Part C: Emerging Technologies, Vol. 16, No. 6, 2008, pp. 668-683.

[5] Brilon, W., and A. Bressler, *Traffic Flow on Freeway Upgrades* Transportation Research Record: Journal of the Transportation Research Board, No. 1883, Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 112-121.

[6] Patire, A.D., and M.J. Cassidy, *Lane changing patterns of bane and benefit: Observations of an uphill expressway* Transportation Research Part B: Methodological, Vol. 45, No. 4, 2011, pp. 656-666.

[7] Goñi Ros, B., V.L. Knoop, B. Van Arem, and S.P. Hoogendoorn, *Mainstream Traffic Flow Control at Sags*, Transportation Research Record, No. 2470, 2014, pp. 57-64.

[8] Yoshizawa, R., Y. Shiomi, N. Uno, K. Iida, and M. Yamaguchi. *Analysis of Car-following Behavior on Sag and Curve Sections at Intercity Expressways with Driving Simulator* International Journal of Intelligent Transportation Systems Research, Vol. 10, No. 2, 2011, pp. 56-65.

[9] Furuichi, T., S. Yamamoto, M. Kotani, and M. Iwasaki, *Characteristics of spatial speed change at motorway sag sections and capacity bottlenecks* presented at the 82nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2003.

[10] Goñi Ros, B., V. L. Knoop, B. van Arem, and S. P. Hoogendoorn, *Car-following Behavior at Sags and its Impacts on Traffic Flow* presented at the 92nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2013.

[11] Koshi, M., *An Interpretation of a Traffic Engineer on Vehicular Traffic Flow* in Traffic and Granular Flow '01, Fukui, M., Y. Sugiyama, M. Schreckenberg, and D. E. Wolf, eds. Berlin: Springer, 2001, pp. 199-210.

[12] Xing, J., H. Takahashi, and T. Takeuchi, *Increasing Bottleneck Capacity through Provision of Bottleneck Location Information* presented at the 11th World Conference on Transport Research, Berkeley, California, 2007.

[13] Sato, H., J. Xing, S. Tanaka, and T. Watauchi, *An Automatic Traffic Congestion Mitigation System by Providing Real Time Information on Head of Queue* presented at the ITS World Congress, Stockholm, Sweden, 2009.

[14] Hatakenaka, H., T. Hirasawa, K. Yamada, H. Yamada, Y. Katayama, and M. Maeda, *Development of AHS for traffic congestion in sag sections* presented at the ITS World Congress, London, U.K., 2006.

[15] Shladover, S. E., D. Su, and X.-Y. Lu, *Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow* Transportation Research Record: Journal of the Transportation Research Board, No. 2324, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 63-70

[16] Van Arem, B., C. J. G. van Driel, and R. Visser, *The Impact of Cooperative Adaptive Cruise Control on Traffic-Flow Characteristics* IEEE Transactions on Intelligent Transportation Systems, No. 7, 2006, pp. 429-436

[17] Wang, M., W. Daamen, S. P. Hoogendoorn, and B. van Arem, *Rolling horizon control framework for driver assistance systems Part I: Mathematical formulation and non-cooperative systems* Transportation Research Part C: Emerging Technologies, No. 40, 2014, pp. 271-289

[18] Wilmink, I. R., G. A. Klunder, and B. van Arem, *Traffic flow effects of Integrated full-Range Speed Assistance (IRSA)* in Proc. IEEE Intelligent Vehicles Symposium, 2007, pp. 1204-1210

[19] Wang, M., W. Daamen, S. P. Hoogendoorn, and B. van Arem, *Rolling horizon control framework for driver assistance systems. Part II: Cooperative sensing and cooperative control* Transportation Research Part C: Emerging Technologies, No. 40, 2014, pp. 290-311

[20] Treiber, M., A. Kesting, and D. Helbing, *Understanding widely scattered traffic flows, the capacity drop, and platoons as effects of variance-driven time gaps* Physical Review E, Vol. 74, No. 1, 2006.