# Rule based control for merges: assessment and case study

Nagalur Subraveti, Hari; Knoop, Victor; van Arem, Bart

**DOI**
10.1109/ITSC.2018.8569221

**Publication date**
2019

**Document Version**
Final published version

**Published in**
2018 IEEE Intelligent Transportation Systems Conference, ITSC 2018

2018 21st International Conference on Intelligent Transportation Systems (ITSC)
Maui, Hawaii, USA, November 4-7, 2018

# Rule based control for merges: assessment and case study

Hari Hara Sharan Nagalur Subraveti, Victor L. Knoop, and Bart van Arem, *Member, IEEE*

*Abstract*— **Merging areas are a common bottleneck source on motorways. In order to tackle congestion at these locations, efficient traffic management and control is vital to best utilize the available space. However, before the application of any traffic control measures, a thorough analysis of the effectiveness of the designed control action needs to be evaluated. The paper presents insights for the assessment of rule based traffic control at motorway merges. The methodology is then applied to a case study wherein an advisory system using rule based control for motorway merges considering mixed traffic is evaluated. With the aim to reduce travel times at merging sections, advices from the control system influencing the longitudinal behavior of mainline vehicles were generated. The advisory system was tested in a microsimulation tool for various penetration rates of controlled vehicles on the mainline. The effect of implementing the control action, side-effects of the design, risks involved and the overall role in improving or deteriorating the merging situation are then discussed. This can hence help in further developing any rule based control systems at motorway merges.**

## I. Introduction

Congestion on motorways has become a common phenomenon across the world. One of the common bottleneck locations on motorways are the merging sections where an on-ramp merges into the mainline. These merge areas are prone to congestion due to conflicts between the ramp flow and the mainline traffic because both are vying for the same space downstream of the merge area. Congestion at ramps can lead to oscillations, capacity drop, queue spill backs leading to congestion at off-ramps, loss of travel time etc. [1], [2], [3]. Systems such as ramp-metering have been applied to control the flow coming from the ramps and avoid or delay the onset of congestion on motorways. With emerging technologies like vehicle-to infrastructure (V2I) communication and advanced driver assistance systems (ADAS), it is possible to develop a more active traffic management strategy which can improve the traffic flow at these merge bottlenecks [4]. However, before the application of any traffic control measures, a thorough analysis of the effectiveness of the designed system needs to be performed. Several control approaches exist to solve the various control problems. Feedback control, optimal and model predictive control, rule-based/knowledge-based systems, artificial neural networks are some examples of the various approaches that have been employed for traffic control. Computational complexities relating to the rule based control systems are quite low and they are comparatively easy to implement and evaluate [5] and hence, rule based control systems are quite popular and have been used in multiple studies. The design process of rule-based control systems involve many assumptions and if improperly designed, can lead to a worse traffic performance. The current work presents an approach for the assessment of rule based traffic control at motorway merges. This will contribute to a well-motivated control strategy including the risks involved in the implementation of such control strategies which will be helpful in examining the design easily in case the system does not perform as expected.

To demonstrate the methodological approach presented, an advisory system using rule based control is constructed and evaluated at a merging section. In order to facilitate the merging process, a rule is designed to create gaps on the mainline by controlling a certain percentage of the vehicles on the mainline of a two-lane motorway. The rule is designed to influence the longitudinal behavior of the mainline vehicles. Since lateral control involves multiple vehicles from different lanes, the case study is restricted to longitudinal control only. The advisory system is implemented in a microsimulation tool to evaluate the traffic performance and the role of the control action applied. The effect of implementing this control action, the side-effects originating from this, risks involved and the overall role of the control strategy in improving/deteriorating the traffic situation are discussed. Technical requirements and specifications of the communication systems and the in-car system used in the case study are not discussed and out of the scope of this study.

The paper first presents a literature review of rule based control for merging. This is followed by a section discussing the general approach for the assessment of rule based control systems for motorway merges and insights into the merging situation. The subsequent section then illustrates this with an example of an advisory system used for traffic control of a two-lane motorway using a rule based system. Finally, the conclusions, limitations and scope for future work are discussed.

## II. Literature Review

This section presents a review of the various studies which use rule based traffic control at motorway merges.

Early works on merging control were related to the Automated Highway Systems project in the 1990s which considered the problem of an automated vehicle merging into a platoon of automated vehicles from an on-ramp. Several studies related to this project employed various techniques for merge control such as regulating the speed profile of the merging vehicle, formation and preservation of gaps on mainline, controlling a string of vehicles etc. Later works like [6], [7], [8] dealt with algorithms for (C)ACC

This research was performed in the Taking the fast lane project which was funded by the Applied and Technical Sciences (TTW).

The authors are with the Department of Transport and Planning, Faculty of Civil Engineering and Geosciences, Delft University of Technology, 2628, Delft, The Netherlands (e-mail: h.h.s.nagalursubraveti@ tudelft.nl).

equipped vehicles, cooperative merging, in-car advisory systems, VSL etc. As the scope of this paper is restricted to rule based control, only studies based on or related to this type are reviewed here. For a more comprehensive review on a variety of control concepts related to merging, the authors refer to [4].

Most of the studies on rule based systems focus on longitudinal control such as [9], [10], [11], [12], [13] etc. In [9], a cooperative merging algorithm was developed for mixed traffic flow consisting of ACC and manually driven vehicles. With the aim to create gaps on the mainline large enough to allow the ramp vehicles to merge in without appreciable slowdown, the mainline vehicles were directed to adjust their speed and position with respect to the preceding vehicles not only on the same lane but also in the other lane before reaching the merging section. Simulations of a single lane road with an on-ramp for different penetration rates of ACC vehicles showed an improvement in the traffic performance, especially at higher penetration rates. Negligible improvements were found when demand neared the capacity. [10] presented a decentralized merging assistant for mixed traffic scenarios with the aim to stabilize the traffic flow around the merging areas and limit the changes in speed. When the assistant predicted conflicts between the mainline and ramp vehicle, it controlled the acceleration of the vehicle based on certain constraints and created a gap for the ramp vehicle. Scenarios involving complete manual traffic, with CACC and CACC combined with the merging assistant were evaluated. Although the conditions for which the assistant was designed is not mentioned in the study, it can be inferred that it worked well in free-flow conditions with limitations in the congested state. Results showed that there was no significant improvement in travel times with and without the merging assistant considering 100% CACC penetration rate though the stability improved compared to the manual traffic scenario. Hence it is not clear if the improvement compared to the 0% case is due to CACC or the merging assistant or a combination of both. [11] evaluated a merging situation using microscopic dynamic traffic management. In the merging situation, when a ramp vehicle is expected to arrive at the same time as a platoon of vehicles on the mainline, one of the vehicles in the platoon is advised to increase headway and create a sufficient gap for the ramp vehicle. Results from microscopic simulations showed considerable improvements in throughput, travel time loss and the number of shock waves. [12] developed an in-car advisory system that gave advices on lane, speed and headway. Although the paper does not explicitly consider merging scenarios, the distribution advice principle deals with the congestion problem associated with merging. Depending upon the flows on different lanes, vehicles on the shoulder lane are advised to yield to the merging traffic and the merging traffic are advised to synchronize their speeds with the mainline flow. Simulation results reported showed a positive effect of the advisory system on traffic performance at high penetration rates though the road layout evaluated consisted of multiple bottlenecks such as lane drops, off-ramps, on-ramps etc. and the effect of the rule specific to merging case is unclear. [13] designed a merging assistant which creates gaps to facilitate the merging process using macroscopic theory. Assuming the possibility of V2V and V2I communication, the control strategy is combined with existing ramp meter techniques. Vehicles on the shoulder lane are induced to move in platoons which are separated by empty gaps which are filled by the ramp vehicles released by the ramp metering. The penetration rate of cooperative/controlled vehicles was considered to be 100% and the gaps created by the merging assistant were assumed to be preserved for the ramp vehicles. With the system operating only in the free flow state of the fundamental diagram, the authors observe promising results with respect to reducing congestion using the merging assistant.

One of the few studies dealing with lateral control of vehicles is [14] which used a lane change advisory control upstream of ramps to encourage early lane changes and create more space for the merging vehicles. The authors assume the availability of complete and detailed vehicular information via INTELLIDRIVE which supports V2V and V2I communication. Improvements in total travel time and vehicle kilometers travelled were found at higher penetration rates.

In most of the studies, though the control action deals with the merging vehicle and its corresponding vehicle on the mainline, other vehicles on the mainline are also influenced. In [10], [11] and [13], the effect of deceleration of the controlled vehicle on the upstream traffic is neglected. Similarly in [14], influence of lane changes on other vehicles and induced lane changes are not discussed. In low demand situations, these systems can display benefits to the network (such as improved stability) but when the demand is high, they can have adverse effects. There is a lack of control systems where the response to a control action is restricted to a few vehicles and influencing them does not affect the other vehicles in a major way. Very few studies discuss the side-effects of implementing the control actions which can make it difficult to understand if any positive/negative effects arising from the implementation of the control can directly be linked to the rule or any unexpected/induced behavior due to the rule. Factors such as the frequency with which the rule is being applied, whether it is being applied in conditions in which it is intended to work, if it is performing as it is intended to are also rarely discussed. This is relevant as an understanding of this not only helps in the design of any control systems, it also helps in the easy evaluation of systems in case of failures.

## III. Considerations For Control Assessment

In the assessment of rule based control actions, several steps and factors in each step which may influence the performance, have to be carefully considered. This section presents the various components to be taken into consideration in order to approach the design in a structured manner.

### *A. Identification of the undesired situation*

The first step in the design of a control system is the formulation of the traffic problem that needs to be solved. Congestion at merging areas arise due to the conflicts between the traffic flow on the mainline and on-ramps. Lack of sufficient gaps for the oncoming ramp vehicles leads to either forced merging where ramp vehicles execute a forced lane changing maneuver causing vehicles on the mainline to

decelerate strongly leading to disturbances or merging at lower speeds which again affects the traffic on mainline. Anticipatory or cooperative behavior of mainline traffic (such as yielding/lane changes) can also add to disturbances at merging sections. Systems such as ramp-metering control the on-ramp flow entering the mainline. Most of the existing algorithms on merging control aim to create gaps on the mainline to facilitate the merging process and increase the throughput. It is important to hence identify the factors that can be controlled which can lead to a better merging process. The objective of the control strategy is to create a sufficient gap for the on-ramp vehicle to merge into by the time it reaches the merging point. Control systems relating to problems such as high merging and mainline demand, poor weather conditions, spillbacks from off-ramps are not discussed here because the factors causing them can either not be controlled (as in the case of weather) or require control at higher/network level (controlling inflow to the merge areas). This work mainly deals with the design of control systems that assist the merging process. Considering this, the factors that can be controlled include the speeds of the vehicles, lane change decisions, accelerations etc.

### B. *Choosing the control direction*

Vehicles on the mainline can be influenced in either the longitudinal or lateral direction in order to create gaps and facilitate the merging process. Longitudinal movements can be controlled by modifying the vehicle speeds while lateral movement control indicates the lane changing process. For modifying speeds, intervention points that can considered include acceleration, spacing, desired speed etc. In terms of lateral control, other aspects have to be taken into consideration such as traffic flow on the other lane, available gaps, trade-offs between disturbances caused by lane changes and creation of gaps etc. The variables that can be controlled in lateral direction include the timing of lane change, location, decision to change lane. Since lateral control involves multiple vehicles from different lanes, it requires more complex algorithms and control over a group of vehicles. Conditions required for smooth lane changes are not very frequent especially in moderate and high demands and hence lane change advisories can in fact have a negative impact in such conditions.

### C. *Traffic state and measurements*

An important step in the formulation of the control rule is the identification of measurements required to perform the necessary action. Information regarding the traffic can be obtained from loop detectors from which the data can be processed using estimation techniques to give the traffic state. Similarly, communication systems such as V2V (vehicle-to-vehicle) and V2I (vehicle-to-infrastructure) can also be assumed. Assumption of such systems allows for more flexibility in the control strategy formulation since detailed information is available and it is easier to describe the traffic state. Of course, problems such as communication latencies, range and frequency of the communication systems exist in these cases, but for simplicity these can be neglected. Information regarding the state of both the mainline and ramp traffic is required. For longitudinal control, if the mainline vehicles are advised to increase headways to create gaps, then information regarding the location, speed and current headway is required.

### D. *Conditions where control is expected to work*

Specification of the conditions under which the control action is expected to work is important. This relates to the scope of the study. Working out under which conditions the control action is expected to solve the considered objective will be helpful in creating scenarios for testing the action and later while analyzing the performance of the design. It is always better to restrict the scope rather than focus on a more generalized problem. If the objective is to stabilize the traffic flow on the mainline from the effect of the merging of ramp vehicles, then the control action may be better suited to work in free flow conditions compared to congested conditions. A factor to consider while deciding upon the conditions under which the control action is expected to work is to evaluate the frequency with which these conditions are met. For example, if the control action is to advise vehicles to change lane from the inner to outer lane, then the number of times a gap is available on the target lane to allow such lane changes should be evaluated. If the density on the target lane is already too high, then there are very few gaps available and hence these conditions are rarely met and thus no and very few gaps are created for the merging vehicles which will not affect the traffic performance in a major way. So, it might be better if such a control strategy is employed in a free-flow/ relatively moderate flow conditions where the rule has a better chance to perform. A rule designed to work in free-flow conditions may not yield positive results when the demand is too high and hence while testing, suitable demand profiles need to be considered.

### E. *Assumptions and constraints*

During the design of the control system, certain assumptions might be considered and it is important to outline these assumptions and the impact they play. Completely automated traffic is an assumption. Similarly, availability of complete information regarding the traffic state is an assumption. When gaps are created using the control action, it might be assumed that these gaps are preserved and these gaps are not filled by vehicles other than the ramp vehicles. Another aspect to consider during the design phase is the constraints related to the control variables. If the control variable is speed of the mainline vehicles, then it is necessary to ensure that the speed does not exceed the speed limits of the road. Also, a lower limit should be considered because if the speed of the vehicles is reduced greatly just in order to create a gap, performance on the mainline might be affected.

### F. *Location/timing of the advice*

In terms of advisory control, the selection of location and timing of the advice is very important. Ideally, sufficient gaps should be available before the ramp vehicles reach the acceleration lane. Hence, any control should be performed at a suitable distance upstream of the merge point. For example, advices which concern with the deceleration of a select few vehicles have to be given at an appropriate time/location for them to be effective without affecting the stability of traffic flow. If the controlled vehicles slow down quite near to the merging zone, then deceleration rates are

important. If high deceleration rates are selected, slowing down of the vehicles may cause a disturbance to the traffic upstream due to sudden speed changes. Similarly, if the vehicles are advised far ahead to slow down and create gaps, vehicles from the left may change lane and occupy the gaps created for the merging vehicles. The effect on throughput and total travel time due to the slowing down of vehicles quite far ahead is another factor that needs to be considered. This again relates to the constraints set on the control variable.

### G. Performance Indicator

In order to evaluate the performance of the control action, appropriate performance indicators have to be selected. When the goal of the control is to achieve stability, indicators such as length of traffic jams, its duration and the number are far better criteria to judge. Similarly, if the goal is to achieve a higher output, cumulative curves can be used to analyze the performance. When delay minimization is the objective, travel times/vehicle distance travelled can be an indicator. Of course a combination of these indicators can also be used but the primary one should always be related to the objective that needs to be achieved. For example, if stability is the main objective, simply analyzing travel times may not give a clear indication of the effectiveness of the control action. Hence trajectories, duration of any jams observed etc. will be helpful in this case. For the case study in the next section, the performance indicator chosen was travel time. In the case of merging, the number of gaps being created and their size is another important parameter that can indicate to the performance of the control.

## IV. Simulation Set-up

Based on the components presented in the previous section, a rule based advisory system is designed and implemented. Considering the design of the control action, a suitable analysis tool needs to be selected for evaluation. Generally, simulation based analysis is preferable before the application of the control to field analysis. The choice of simulation tool depends on the objective of the control action. If the control is to be applied on an aggregate level such as controlling flows entering from ramps, macroscopic models are well suited. However, if the control action targets individual drivers, then microscopic models are the best choice. This section gives a brief overview of the microsimulation tool used and the simulation setup chosen followed by the description of the designed rule in the next section. The main objective of the designed rule based control system is to create gaps on the mainline by influencing the longitudinal behavior of vehicles on the outside (shoulder) lane and facilitate a smoother merging process. The microsimulation tool considered in this case for performing the simulations was MOTUS (an open-source microscopic traffic simulation package) [15]. MOTUS offers the opportunity to extend the existing classes or implement new classes which can help in maintaining control over the actions. Being stochastic, it offers the opportunity for different simulation runs with different random seeds which can yield different results. The longitudinal model used in MOTUS is IDM+ [16], an adapted version of the Intelligent Driver Model (IDM) proposed in [17], where the acceleration of a vehicle is given by (1) and (2).

$$\dot{v} = a \cdot \min\left[1 - \left(\frac{v}{v_{des}}\right)^4, 1 - \left(\frac{s^*}{s}\right)^2\right] \quad (1)$$

and,

$$s^* = s_0 + v.T + \frac{v\Delta v}{2\sqrt{a.b}} \quad (2)$$

where,

| | |
|---|---|
| $\dot{v}$ = acceleration | $v_{des}$ = desired speed |
| $s^*$ = desired spacing | $\Delta v$ = approaching rate to the leader |
| $s_0$ = stopping distance | $T$ = desired headway |
| $a$ = maximum vehicle acceleration | $b$ = comfortable braking deceleration |

The lateral model in MOTUS is the LMRS model used in [16], where the desire of a vehicle to change lane is a function of three incentives which are a) Gaining speed b) Maintaining route to reach destination and c) Keep-right bias - driving in the right most lane (for right hand traffic). Relaxation phenomena in merging, observed in [18], is usually not considered in many microscopic models. But in case of LMRS, it is included.

*Lane change desire=f(Speed, Route, Keep-right)* (3)

Depending upon the lane change desire, lane changes are classified into free, synchronized and cooperative lane changes. Taking into account the urgency of mandatory lane changes, the voluntary incentives (speed and keep-right) can be (partially) ignored. The demand on the mainline was varied from 1500 veh/h/lane with a maximum flow of 2000 veh/h/lane. Inflow to the ramp starts 100 seconds after the start of simulation (so that mainline vehicles can reach the merge area). Ramp flow was kept at a constant value of 750 veh/h. No heavy vehicles were considered in the simulation.

At each time step (0.5 s), MOTUS calculates the position, speed, acceleration and various other properties of each vehicle in the simulation. Separate classes with new functionalities were added in MOTUS which also extended some of the properties of existing classes. A typical Dutch motorway with an on-ramp is chosen as the network for study as shown in Fig. 1. A 2-lane motorway of length of 6.5 km with a single lane on-ramp of 1 km with a speed limit of 120 km/h was considered similar to the speed limits on Dutch motorways. The total simulation running time was 9000 seconds.

When control advices generated from the designed rule require the Controlled Vehicles (CV) to decelerate in order to create gaps, there is the possibility of vehicles changing lanes from the left to the right because of the speed gain and keep-right incentives of the LMRS model used in MOTUS. But in reality, vehicles rarely change from the left lane (especially around the merging sections) as a courtesy to the vehicles trying to merge from the ramp [19]. Hence, lane changes from the left lane to the right lane were prohibited in the simulations to avoid such occurrences.

It is hard to judge the effect of the control strategy considering total travel time (TTT) as the only indicator. In order to better understand the effect of the rules on the traffic

performance, some additional indicators are extracted from the simulation results to get a clear picture of how the rule works. These are: the number of times the control action was applied and the time at which they were applied. The number of times the control action was applied gives an understanding of the frequency with which conditions are met. Timing of the advice is helpful in understanding if the rule was applied in free flow or congested conditions and if it was able to avoid or delay the onset of congestion by comparing the controlled scenario with the no-control case. This will also help to understand if the system is being provided with enough advices (or) being overloaded with advices and when advices can be avoided even though the rule is applicable.

Simulation runs for 10 random seeds were performed in order to evaluate the designed control action. The penetration rates of the CV on the right lane were varied from 0% to 100% for each random seed. In the simulation tool, when a vehicle is unable to maintain its route or exceeds a lane, it is deleted from simulation. In the simulation runs, this situation occurred in two cases for a particular random seed.

## V. CASE STUDY

### A. Description of the rule

Since there is a requirement of readily available gaps to be created for the ramp vehicles to merge into, the rule influences the longitudinal control of the vehicles on the shoulder lane by increasing the spacing between the vehicles when there is an expected conflict. So, if it is found that an on-ramp vehicle and a vehicle on the shoulder lane are expected to arrive at the merging point at around the same time, the vehicle on the shoulder lane is advised to reduce its speed and increase its spacing with respect to the immediate downstream vehicle. In simulations, the expected arrival times to the merging point are rounded to the nearest decimal and compared for potential conflicts. Similar rule/logic has been applied in studies such as [10], [11] though they differ in the criterion of speed control. Expected travel times are calculated based on constant speed heuristics.

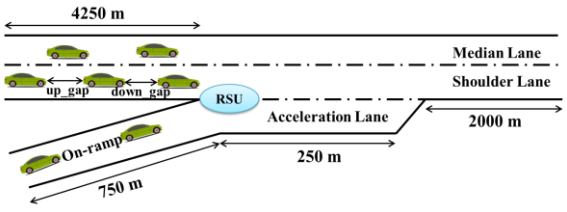


Figure 1. Scenario for the rule

Another criterion for the controlled vehicles to satisfy for the rule to get executed is for the upstream and downstream space headways to meet certain conditions. The reasoning behind the rule is that by influencing a certain vehicle, the traffic upstream should not get highly disturbed. If mainline vehicles are always advised to slow down to create gaps, flow on mainline can be highly disturbed (especially in high demand situations). Hence, the controlled vehicles are advised to slow down if sufficient spacing exists with respect to the upstream vehicle and gap to the downstream vehicle is comparatively less. So, in order for the rule to be executed, (4) needs to be satisfied.

$$down\_gap < G_C < up\_gap \quad (4)$$

where, down_gap and up_gap are the downstream and upstream space headways for the controlled vehicle as indicated in Fig. 1. $G_C$ is a parameter indicating the gap chosen when CVs are required to decelerate. In this case, the value of $G_C$ is taken as 60 m. If $G_C$ is too large, then sufficient gaps upstream and downstream of the CV is available for the ramp vehicle and the ramp vehicle is expected to merge without any problem. Smaller values can lead to the criterion being met with a very high frequency as well as disturbing other vehicles due to smaller gaps. Slowing down of CVs with high frequency can affect the traffic operations on the mainline in a negative manner.

The vehicle is controlled to decelerate till the point where its immediate upstream follower does not have to decelerate at a rate greater than 0.5 m/s$^2$. Since the ramp vehicle has the same Expected Arrival Time (ETA) as the mainline vehicle, it either has to reduce speed and merge in the up_gap or accelerate and merge in the down_gap. The gap between the CV and its follower is large enough (>=60 m) for merging to occur. (In simulation, ETA is given by the current simulation time plus time to reach merge point assuming constant speed rounded to the nearest decimal). Merging in the up_gap can cause the follower of the CV to decelerate which can be avoided using the rule. It must be remembered that the aim of the rule based control is to create gaps on mainline to facilitate merging. The responsibility of merging in the gap created lies with the ramp vehicle. Another assumption in the design of the rule is the presence of controlled vehicles only on the shoulder lane of motorway.

### B. Traffic state/measurements

According to the design of the rule, speed and position of the various vehicles with in a certain range of the merging point are required. In order to calculated the expected arrival times, current speed and location of both the mainline and ramp vehicles are needed. And calculation of space headways require the position of the vehicles as well as their lengths. Hence assuming the possibility of V2I communication, a Road Side Unit (RSU) is considered to be present at the intersection of the on-ramp and the shoulder lane of the motorway. The RSU is assumed to be able to gather relevant information (such as speed, location, lane etc.) of all the vehicles on all the lanes within a certain distance upstream of it. Here the distance is taken as 500 m. The RSU then sends all the information to a centralized control centre which processes the information to generate suitable advices to be sent to the controlled vehicles. Since the RSU can communicate only with the vehicles which are in its range (500 m), the vehicles are advised on their speed in the range of 3750-4250 m in the considered network. Once they go out of the range of the RSU, they drive as in the case of no control i.e. they revert back to their original desired speed.

### C. Control action

As the evaluation of the rule is done using simulations, the responses to the given advices is integrated in the simulation by adapting the desired velocity of the drivers.

Thus, when the CVs in the detection range of the RSU are advised to decelerate, the desired velocity term in (1) is lowered to a suitable value. Typically, in normal scenarios, the desired velocity of the drivers is taken as 120 km/h. For the network in Fig. 1, $v_{des}$ of the CV is modified to $v_{md}$ as shown in (5).

$$v_{des} = v_{md} \text{ (=60 km/h); if CV within RSU range} \quad (5)$$

Thus, when the CV is in the RSU range and meets the designed criteria, the desired velocity is lowered to $v_{md}$. As can be seen from Fig. 2, lowering the desired velocity of the vehicle to $v_{md}$ (60 km/h here) does not lead to the speed of the CV being drastically reduced. Considering the criterion designed, it can be seen that the speed reduction of the CV is around ~15 km/h. And if there are no constraints, it slowly regains its original speed taking the initial desired speed (of 120 km/h) into consideration. And considering the gap $G_C$ to the upstream vehicle, the speed reduction of the CV does not cause the upstream vehicle to reduce its speed by much (~5-8 km/h). This lowers the impact of the deceleration of the CV on upstream traffic while creating a gap.

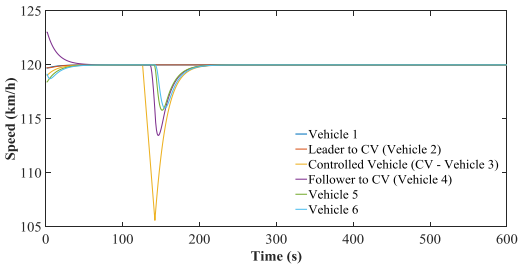


Figure 2. Effect of $v_{md}$ on speed of CV

## D. Results and discussions

*Conditions where rule is expected to work:* Since the goal of the control action is to reduce travel times at merging sections, the performance indicator used is TTT. In free-flow conditions, the rule is not expected to have much of an impact since it only affects the merging order. In moderate to heavy demand conditions, due to less availability of gaps, the designed rule is expected to work as it leads to the formation of more gaps for the ramp vehicles to merge into. For 4 random seeds, analysis of the speed contour plots showed that the network never experiences congested conditions and variations in travel times compared to the base scenario were negligible with the rule rarely being applied. Therefore the rule did not provide a considerable impact on traffic operations. The average TTT for these 4 seeds was found to be 196.56 veh-h with a maximum average reduction in TTT of 0.0017 veh-h (for 50% penetration rate). Hence these seeds are not considered for detailed analysis. The TTT for different penetration rates and its variation (for the remaining six seeds) is shown in Fig. 3. It can be observed that for lower penetration rates (<30%) of CVs on the shoulder lane of mainline, there is negligible difference in TTT. It increases at 50% and lower TTT values are found at higher penetration rates (>80%). On average, a reduction of 6 veh-h of TTT was observed compared to the no control scenario.

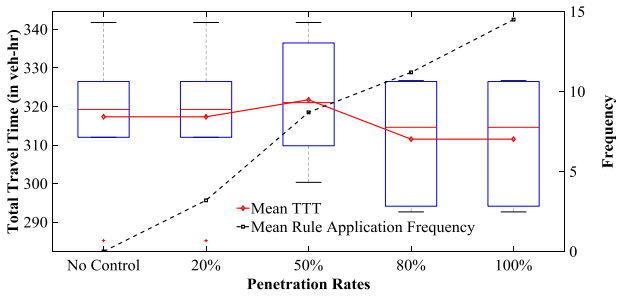


Figure 3. TTT and Rule Application Frequency for different penetration rates

*Frequency with which conditions are met*: Since, there does not seem to be a huge difference in the TTT following the application of the control action, the frequency with which the criteria for the rule to be executed is evaluated. Fig. 3 shows the average number of times the rule was applied for different penetration rates.

It can be seen from Fig. 3 that the number of times all necessary criteria were satisfied for the rule to be executed is quite small. Considering the different seeds, the maximum number of times the rule was executed was 19 for the 100% penetration rate. This can also be related to small reduction in TTT observed across different seeds and penetration rates. For the rule to create a significant impact, the control action needs to be applicable more number of times. Hence either the scenario that is analyzed in the simulation needs to be changed so that the criteria is met with more number of times or the criteria itself needs to be looked into. In this case, these were the three criteria:

i. Equal ETA to the merging point
ii. Upstream gap is greater than 60 m
iii. Downstream gap is less than 60 m

As mentioned earlier, the rule is expected to be more helpful in moderate/congested conditions rather than free-flow conditions. Hence, the time and location at which the control action was executed are evaluated to observe the conditions under which it occurred which will give a clearer understanding. Fig. 4 shows the speed contour plots for a particular case with the location and timing of the advices (indicated by the black dots). Comparing the no control scenario to the case with 100% penetration rate of controlled vehicles on the mainline, it can be seen that the area of congestion in the no control case is slightly more spread out. The number of stop-go waves in the no control scenario is also slightly higher compared to the 100% case.

*Side-effects of the control action*: The advices for the controlled vehicles are generated in a 500 m section upstream of the RSU. From the speed contour plots in Fig. 4, it can be seen that there have been a number of times when the vehicles were advised quite near to the merging point (~4100-4200 m). These controlled vehicles hence did not have enough time to decelerate and create a sufficient gap leading to the ramp vehicle to merge as it would in the absence of the control action. This just leads to the unnecessary slowing down of a certain percentage of vehicles on the mainline without affecting the merging process in any way.

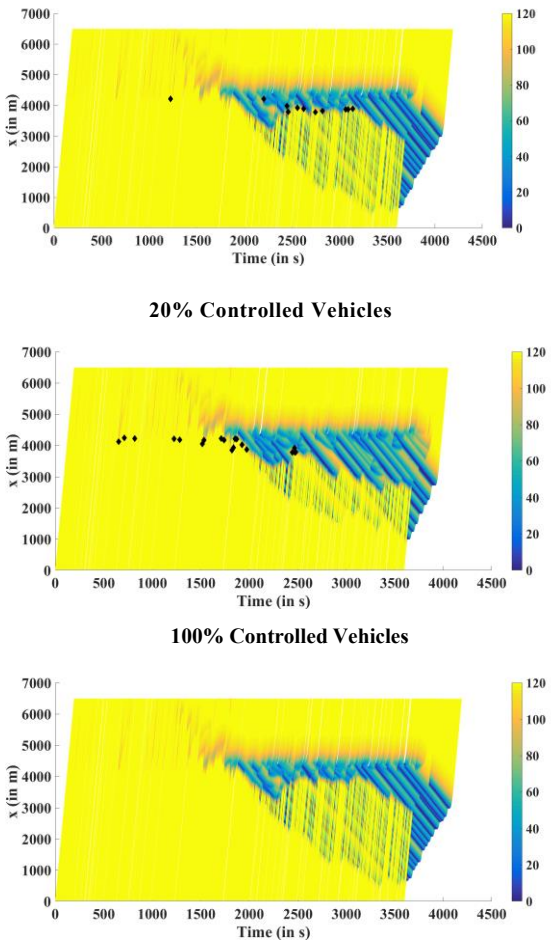


Figure 4. Speed Contour Plots

If this occurs in heavy demand conditions where vehicles are controlled to slow down quite near to merge point, this may lead to additional disturbances. This leads to the point of suitable location and timing of the advice. Early advices leads to a more smooth process of creating gaps for the ramp vehicles.

The control action is applicable in cases of expected conflicts which are based on the predicted travel times of the mainline and ramp vehicles. During heavy congestion on ramps/mainline, there can be multiple pairs of conflicting vehicles on one lane for a single vehicle on the other lane i.e. if demand on mainline is high with vehicles at near standstill and demand on ramp is comparatively low, a ramp vehicle on mainline which has higher speed can have conflicts with multiple vehicles on the mainline which are in a queue. Thus there are cases where multiple mainline vehicles are advised to decelerate for a single conflicting ramp vehicle.

Although lane changes were prohibited from the median lane to the shoulder lane to avoid vehicles occupying the gaps meant for ramp vehicles, it was found that when congestion sets in on the shoulder lane and traffic becomes standstill, controlled vehicles from the shoulder lane changed to the median lane when conditions allowed. This affects the frequency of rule application especially in the case of low penetration rates. For example if the penetration rate is considered to be low (say 20%), and many of them change lane to the median lane, then there are very few possibilities of applying control action to these vehicles.

The control action in simulation is executed by adapting the desired velocity of the advised vehicles. If these vehicles are in congested condition and travelling at lower speeds (< 60 km/h), then adapting the speed to 60 km/h does not have any effect. As per the car-following model used in the simulation tool, in congested conditions, the desire to maintain a safe headway predominates the desire to maintain a speed. Hence application of the rule to vehicles which are travelling below speeds to which the desired velocity is adapted to should be carefully considered. The advised speed to the CVs should rather be dependent on the speed at which they are driving than using single constant value for speed reduction.

## VI. Conclusions

The paper presents an approach to the design of rule based control systems for motorway merging sections and illustrates this with an example of a rule based advisory system influencing the longitudinal behavior of mainline vehicles on the shoulder lane. Initially, various steps to be considered in the design of rules are presented. Following a structured approach to the design can be helpful in diagnosing the system in case it does not perform as expected. Factors such as the direction of control, measurements/information needed for formulation of control strategy, traffic conditions for the rule to be effective etc. that need to be considered and things that can go wrong in the later stages of design evaluation are highlighted. Using this approach, a rule based advisory system is designed and tested in a microsimulation tool. The aim of the rule was to create gaps by influencing certain percentage of vehicles on the mainline without much affecting the remaining traffic. On evaluation, it is found that at high penetration rates, a slight reduction in TTT (1.9%) was found and but no effect was observed at lower penetration rates. Further analysis based on the factors described in the approach indicated some flaws in the design and the side-effects of implementing the control action. The location and timing of the advice played in important role in determining the performance of the rule. Since there were cases where the rule was applied to close to the merging point, the vehicles did not have much time to prepare for the gap creation process. Similarly, the manner in which the control action is implemented in simulation was another factor that played an impact on the overall performance. In the case of the example, deceleration of controlled vehicles occurred by adapting their desired velocity which was found to be ineffective at lower speeds of the vehicles. It was also found that there were cases when the vehicles were unnecessarily advised to decelerate. Overall, although the implementation of the control rule did not lead to the worsening of conditions, it also did not improve in a significant way. The frequency with which the conditions are met is limited which may be a reason for the negligible role of the rule.

The rule was designed with the intention to not influence upstream traffic much but due to the rigidity of the criteria,

the frequency with which the rule was applied greatly reduced. Rule based mechanisms need to have conditions which are frequently met and hence designed criteria should not be too rigid. If multiple criteria are designed in order to trigger the application of the rule, the control action is rarely activated. Parameter settings while considering the design of criteria also plays an important role in determining the frequency with which conditions are met. Of course, overloading the system with advices and excessive interference is not preferable and hence a proper trade-off needs to be considered. When rule based systems are applied to a certain percentage of vehicles, its effect on the non-controlled vehicles and their interaction must be carefully considered. There may be cases where the designed rule might not work as it was intended to but improvements in traffic performance can still be found. Hence, suitable performance indicators must be considered to understand the actual effect of the rule on traffic performance.

This work is restricted to design of longitudinal rule based control of mainline vehicles. Additional factors may have to be considered while designing lateral control actions. Only a single scenario (demand profile) was evaluated in simulation. Hence, analysis for different demand profiles needs to be performed to achieve a clear understanding of the working of the designed rule. Consideration of such a structured approach can provide a framework for developing any rule based control systems at motorway merges.

## REFERENCES


[1] S. Ahn and M. Cassidy, "Freeway traffic oscillations and vehicle lane-change maneuvers," *17th International Symposium of Transportation and Traffic Theory*, pp. 1–23, 2007.

[2] L. Leclercq, J. A. Laval, and N. Chiabaut, "Capacity drops at merges: An endogenous model," *Transportation Research Part B: Methodological*, vol. 45, no. 9, pp. 1302–1313, 2011.

[3] R. L. Bertini and S. Malik, "Observed dynamic traffic features on freeway section with merges and diverges," *Transportation Research Record*, vol. 1867, pp. 25-35, 2004.

[4] R. Scarinci and B. Heydecker, "Control Concepts for Facilitating Motorway On-ramp Merging Using Intelligent Vehicles," *Transport Reviews*, vol. 34, no. 6, pp. 775–797, 2014.

[5] L. D. Baskar, B. De Schutter, J. Hellendoorn, and Z. Papp, "Traffic control and intelligent vehicle highway systems: a survey," *IET Intelligent Transport Systems*, vol. 5, no. 1, p. 38, 2011.

[6] V. L. Knoop, A. Duret, C. Buisson, and B. Van Arem, "Lane distribution of traffic near merging zones influence of variable speed limits," in *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, 2010, pp. 485–490.

[7] D. Marinescu, J. Čurn, M. Bouroche, and V. Cahill, "On-ramp traffic merging using cooperative intelligent vehicles: A slot-based approach," in *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, 2012, pp. 900–906.

[8] S. Sivaraman, M. M. Trivedi, M. Tippelhofer, and T. Shannon, "Merge recommendations for driver assistance: A cross-modal, cost-sensitive approach," in *IEEE Intelligent Vehicles Symposium, Proceedings*, 2013, pp. 411–416.

[9] L. C. Davis, "Effect of adaptive cruise control systems on mixed traffic flow near an on-ramp," *Physica A: Statistical Mechanics and its Applications*, vol. 379, no. 1, pp. 274–290, 2007.

[10] R. Pueboobpaphan, F. Liu, and B. Van Arem, "The impacts of a communication based merging assistant on traffic flows of manual and equipped vehicles at an on-ramp using traffic flow simulation," in *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, 2010, pp. 1468–1473.

[11] W. Daamen, B. Van Arem, and I. Bouma, "Microscopic dynamic traffic management: Simulation of two typical situations," in *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, 2011, pp. 1898–1903.

[12] W. J. Schakel and B. Van Arem, "Improving traffic flow efficiency by in-car advice on lane, speed, and Headway," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 4, pp. 1597–1606, 2014.

[13] R. Scarinci, A. Hegyi, and B. Heydecker, "Definition of a merging assistant strategy using intelligent vehicles," *Transportation Research Part C: Emerging Technologies*, vol. 82, pp. 161–179, 2017.

[14] H. Park and B. L. Smith, "Investigating Benefits of IntelliDrive in Freeway Operations: Lane Changing Advisory Case Study," *Journal of Transportation Engineering*, vol. 138, no. 9, pp. 1113–1122, 2012.

[15] MOTUS (2015), http://homepage.tudelft.nl/05a3n/.

[16] W. Schakel, V. Knoop, and B. van Arem, "Integrated Lane Change Model with Relaxation and Synchronization," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2316, pp. 47–57, 2012.

[17] M. Treiber, A. Hennecke, and D. Helbing, "Congested traffic states in empirical observations and microscopic simulations," *Physical Review E - Statistical Physics, Plasmas, Fluids, and Related Interdisciplinary Topics*, vol. 62, no. 2, pp. 1805–1824, 2000.

[18] B. Sultan, M. Brackstone, B. J. Waterson, and B. Boer, "Modeling the dynamic cut-in situation," *Transportation Research Record*, no. 1803, pp. 45–51, 2002.

[19] V. L. Knoop, M. de Baat, M. Keyvan-Ekbatani, H. Taale and S.P. Hoogendoorn, "Strategy-Based Driving Behaviour on Freeways: Findings of Test-Drive and On-Line Survey Study", in *the 96th Annual Meeting of the Transportation Research Board,* Washington D.C., 2017.