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A Low Market Penetration Rate friendly Variable Speed Limit System based on a PID Controller under Connected and Automated Vehicle Environment

E. Fauchet¹, P.A. Laharotte², K. Bhattacharyya³, A. Ladino⁴ and N.-E. El Faouzi⁵

Abstract—With the emergence of Connected and Autonomous Vehicles (CAV) and the development of Intelligent Transport Systems (ITS), new traffic control strategies have emerged. This paper focuses on the application of a Variable Speed Limit (VSL) system used in a connected environment. The speed control is activated by roadside telecommunication antennas, while its implementation relies on a moving bottleneck created by two CAVs: a controller and an agent regulated by a PID controller. The speed restriction is evaluated by applying heuristics, based on traffic theory and referred to as SPECIALIST in the literature. The originality of the method is based on the application of the speed restriction through 2 CAVs side by side on a 2-lane highway segment rather than through the CAV distributed in a disparate way on the network. The resulting system ensures efficient control even at low Market Penetration Rates (MPR) of the CAVs in the traffic stream.

I. INTRODUCTION

A. Context

Traffic management aims to optimise the flow of vehicles along a set of road infrastructures organised in a network. The purpose is generally to match supply (the capacity of the infrastructure) with local demand (the quantity of vehicles in circulation) by limiting congestion. Various strategies have been developed to regulate traffic flows, ranging from traffic signal control [1] to dynamic lane management [2]. One of the objectives is to limit or eliminate the propagation of a shockwave, occurring due to incidents (accidents, bad weather, etc.) or to constraints (bottleneck, insertion lane, etc.) on the network. The challenge is to limit the risk of accidents caused by these stop-and-go movements and to optimise travel times while reducing fuel consumption. The objective follows three fields of action: safety, traffic efficiency and the environment. The usual action process consists in detecting an event on the network, characterising

it and, if necessary, anticipating its spatial and temporal propagation in order to apply an adequate regulation upstream. To meet this need, the usual and popular strategy consists of dynamically detecting a shockwave on a fast lane and applying a speed limit to vehicles upstream of the congested area. In the literature, this approach is called Variable Speed Limit (VSL) ([3], [4], [5]). With the deployment of Cooperative Intelligent Transport Systems (C-ITS) and, consequently, Connected and Autonomous Vehicles (CAV), new implementation processes are available [6], notably by taking advantage of CAV acting as a traffic sensor and strategy enforcement tools. Such approaches use current traffic conditions such as speed or flow to determine how fast drivers should drive to avoid the congested area. Thus, the flow of vehicles entering this area is reduced to prevent the shockwave from spreading or even resolving it.

B. State-of-the-art

The first VSL systems were developed based on a reactive approach ([3], [4], [5]), i.e. the control is triggered by pre-selected threshold values of traffic indicators based on expert knowledge. This type of strategy has shown its efficiency in homogenising speeds and stabilising traffic by reducing speed differences between drivers. They thus improve safety on the network. The main limitation is the delay of the system activation. By the time the system is triggered, traffic conditions have often already reached breakdown. So, the VSL systems, based on proactive approaches and developed subsequently, focus on estimating the propagation of traffic states on the road network [7]. Researchers have used models (e.g. Model Predictive Control (MPC) [8]) to predict future traffic conditions and to anticipate the shockwaves propagation due to an incident rather than reacting to it. In addition to these proactive processes, approaches based on Artificial Intelligence (AI) have also been developed, in particular those based on Reinforcement Learning (RL) [9], [10]. Their use is particularly justified for identifying and determining the activation policy of speed reduction.

In the next stage, some contributions have also been made regarding the way to implement the speed control strategy in practice. Initially, VSL systems based on a proactive or Reinforcement Learning approaches relied on Loop Detectors (LD) to estimate the current traffic conditions of the network, and on Variable Message Signs (VMS) to deliver the control and apply the speed limit. This is the case of the SPECIALIST algorithm [7], [11]. However, as LD-

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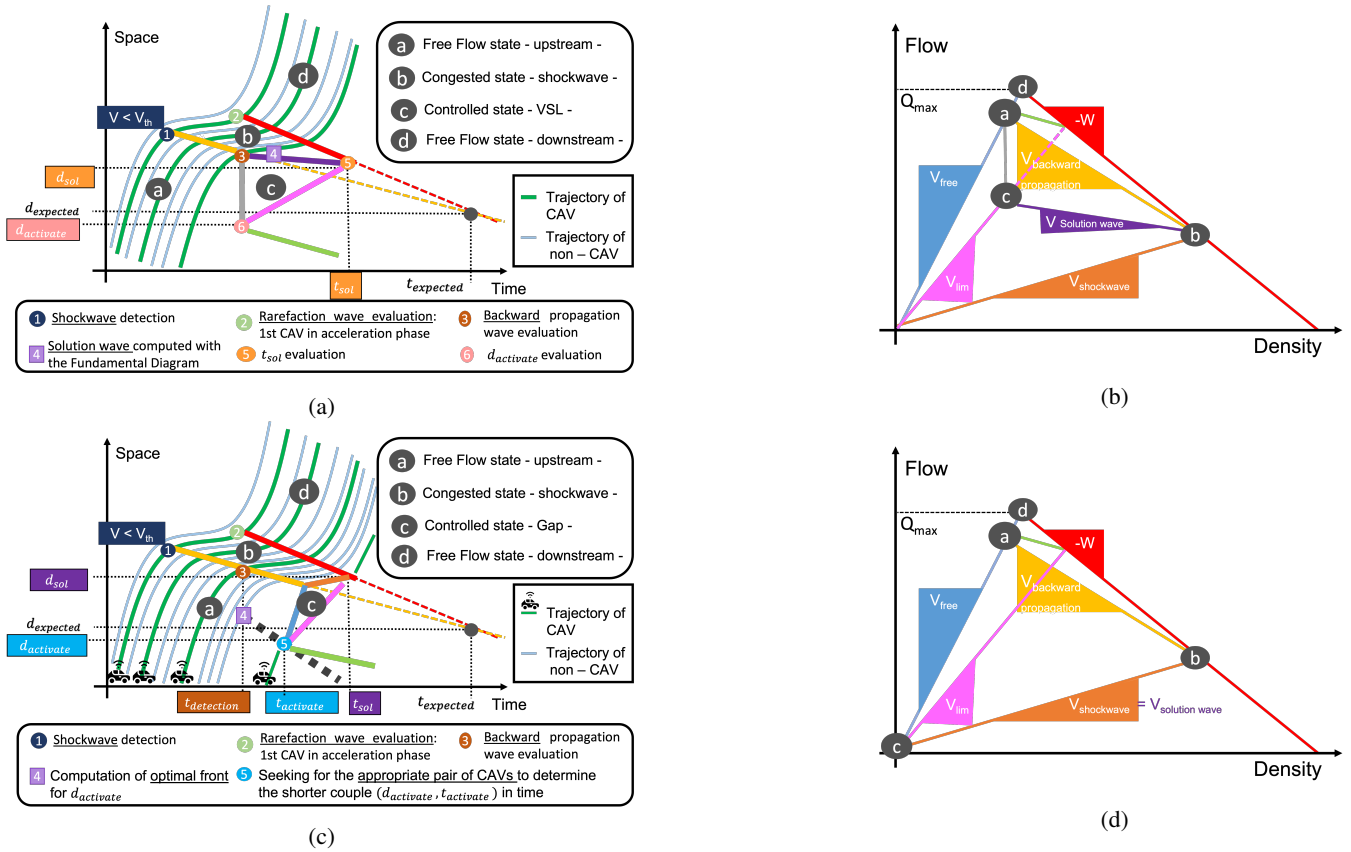


Fig. 1: Kinematic Wave based illustration of the Variable Speed Limit approaches, inspired by SPECIALIST algorithm [7]: (a) Space-Time diagram and (b) Fundamental Diagram of the Full CV-based VSL approach versus (c) Space-Time diagram and (d) Fundamental Diagram of the Moving Bottleneck (MB) CV-based approach.

based systems cannot provide continuous information (due to the discrete positions of the sensors on the network), they can ensure an effective control system only if the sensors are densely located. As a consequence, the installation and maintenance cost of the system is high. In this context and with the development of C-ITS, a more recent study [8] has proposed to take advantage of connected environments (e.g., I2V technology) by using information collected from CAVs in addition to those from Loop Detectors. It enables to generate a continuous information along the network and a reduction in the costs associated with LD by reducing their number. However, control is still provided by the VMS. Another study [12] proposed to exploit the potential of a telecommunication network not only to collect data from the CAVs (in addition to the LD) and estimate traffic conditions, but also to deliver control and impose speed limits thanks to Road-Side Units (RSU) and Infrastructure-Vehicle communication (I2V).

A VSL system was introduced by the authors in a previous work [13], where the traffic state estimation and subsequent control relies entirely on CAV, RSU and I2V communication. As opposed to the previous approaches, known as Eulerian approaches because they are based on LD (i.e., stationary sensors), this approach is entirely based on the Lagrangian indicators from the CAVs (i.e., mobile

sensors). The individual trajectories of the CAVs are used to estimate and predict the traffic conditions on the network in a continuous manner for better activation of the VSL system. The potential of the communication provided by the CAV and RSU is also exploited to ensure better speed limit triggering while reducing the costs associated with the use of LD and VMS. The application shows that such a VSL system satisfies comparable performance with a VSL system based on Eulerian approach. Nevertheless, its performances tends to decrease for low CAV penetration rates. Therefore, to address this concern, we propose to explore a new approach based on the slaving of two CAVs to create a Moving Bottleneck [14], [15] imposing a speed restriction on all vehicles upstream of a congested area. Hereafter, such strategy is called CV-based Moving Bottleneck (MB) VSL. The underlying concept is to solve the shockwave downstream by creating a short gap with a density of zero vehicles thanks to a controlled Moving Bottleneck.

While the Moving Bottlenecks (MB) are widely studied in the literature to model slow vehicles (e.g. Public Transport) according to traffic flow theory [14] or to feature the impact of Moving Bottlenecks on road capacity [15], only few studies ([16], [17], [18]) have considered the Moving Bottlenecks as a traffic control strategy, but none has developed or explored the full sequence of processes to effectively imple-

ment it in practice in the context of Connected Vehicles. The introduced CV-based Moving Bottleneck (MB) strategy is outlined below as a proactive VSL approach, estimated from traffic flow theory considerations: the SPECIALIST approach [7]. Nevertheless, the same strategy could be applied using other congestion wave detection processes and activation policies such as those generated by RL approaches.

C. Positioning : Connected Automated Vehicles acting as moving bottleneck for Traffic Control

While the potential of I2V communication and CAV for the development of new traffic regulation strategies is documented in the literature [19], the future deployment of only a few CAVs already promises the development of new methods previously infeasible due to the low compliance of human drivers [20]. For example, connected and automated cars acting as moving bottleneck on a fast lane can be considered as traffic regulation agents. Indeed, by controlling their speed, vehicles upstream will be forced to respect this limit as they are blocked by a moving traffic jam.

This type of strategy has recently been deemed to show potential for regulating traffic in a single-lane network [16], where a CAV (or several CAVs) that brake(s) upstream of a congestion area make(s) it possible to homogenise the traffic.

In another study [17], a single CAV acting as a moving bottleneck is used to improve the traffic conditions on the network, but specifically on the lane where a fixed bottleneck occurs. The CAV speed is therefore considered as a control variable to affect the traffic upstream of the congestion with the help of a Model Predictive Control (MPC). This strategy helped in the reduction of fuel emissions and travel times when congestion is observed. The lane changes of upstream vehicles potentially induced by the slowing down of the CAV(s) are, however, not considered.

Eventually, to apply a VSL system on a 3-lane motorway, [18] proposed to use a platoon of CAVs creating a mobile traffic jam on the 3 lanes. The formation of this platoon is considered possible thanks to V2V communication but the practical implementation of the platoon is neither specified nor studied.

The main contribution of this paper is in developing a method for a multi-lane highway segment (applied with 2 lanes) to ensure that 2 CAVs meet and remain side by side to form a MB (of 2 CAVs on 2 lanes) through the implementation of a PID (Proportional, Integral, Derivative) control loop [21]. While the first CAV, called controller, is setting the pace by following the speed instructions provided by the Road-Side Unit through I2V communication, the second CAV, called agent, aims at reaching the controller and following its pace thanks to the implementation of the PID loop. In this connectivity context, it is assumed that the CAVs are equipped with V2X technologies enabling the communication with the Road-Side Units and between connected cars. The controller and its agent are selected and paired by the Road-Side Unit, then communicating through V2V technology to deploy the VSL strategy, feed the PID

control loop and synchronize themselves to move side-by-side, and act together as a moving jam. The underlying objective here would be to take advantage of the equipment and cooperativeness of CAVs for an original application of the VSL system. The control is not delivered to the full set of available CAVs on the road network, but only to a subset (here, a pair) of CAVs carefully and automatically identified and selected by the Road-Side Unit. The RSU centralised the traces left by Connected Vehicles to identify shockwaves, then trigger the VSL process composed of four main steps: (i) computing a solution to determine the activation distance of the VSL, (ii) seeking for a relevant pair of CAVs (controller, agent), (iii) pairing and determining the meeting point of the controller and its agent, then (iv) requesting the application of speed instructions to the controller. It is expected from this strategy that it ensures a higher compliance with the speed limit even at low penetration rates by forcing all vehicles upstream of the mobile traffic jam to comply with the instruction without having received it directly. The findings suggest that it is expected to observe equivalent performance for any scenario having a Market Penetration Rate (MPR) greater than or equal to 30 %. The performances for even lower penetration rates are, in fact, mostly sensitive to the speed limit solution that may be difficult to generate due to the small quantity of available CAV's trajectories.

The main contributions of this paper are the following:

- the refinement of a shockwave detection process [13], inspired by the SPECIALIST approach [7], but only based on traces left by CAVs: especially, a gap-based process is introduced to apply the Variable Speed Limit (VSL) strategy.
- the introduction of a selection process to identify the relevant pair of CAVs used as traffic regulators.
- the introduction of a PID-based process to merge 2 CAVs driving side-by-side to generate a moving bottleneck.

The remainder of this paper is organised as follows: section 2 presents the methodology used, section 3 illustrates the results obtained, and section 4 discusses the conclusions and perspectives from this work.

II. METHODOLOGY

A. Implementation of the VSL system: a 3 step process

As illustrated in Figure 1 (a) & (b), the VSL system developed previously [13], called Full CV-based VSL, is based on the Kinematic Wave Theory according to the traditional approach of Lighthill-Whitham-Richard (LWR) [22] used to model macroscopic traffic dynamics. It describes the flow conservation law ($\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0$) at time t and location x and assumes that a strong relationship exists between flow $q(x,t)$ and density $\rho(x,t)$. This relationship, called Fundamental Diagram, follows a concave curve, simplified as triangular. The Full CV-based Variable Speed Limit system is composed of 3 main steps:

- *Step 1* consists in detecting a shockwave on the network thanks to the data generated from the CAVs, i.e. thanks

STEP 3 : VSL application based on PID controller with 2 CAVs side-by-side

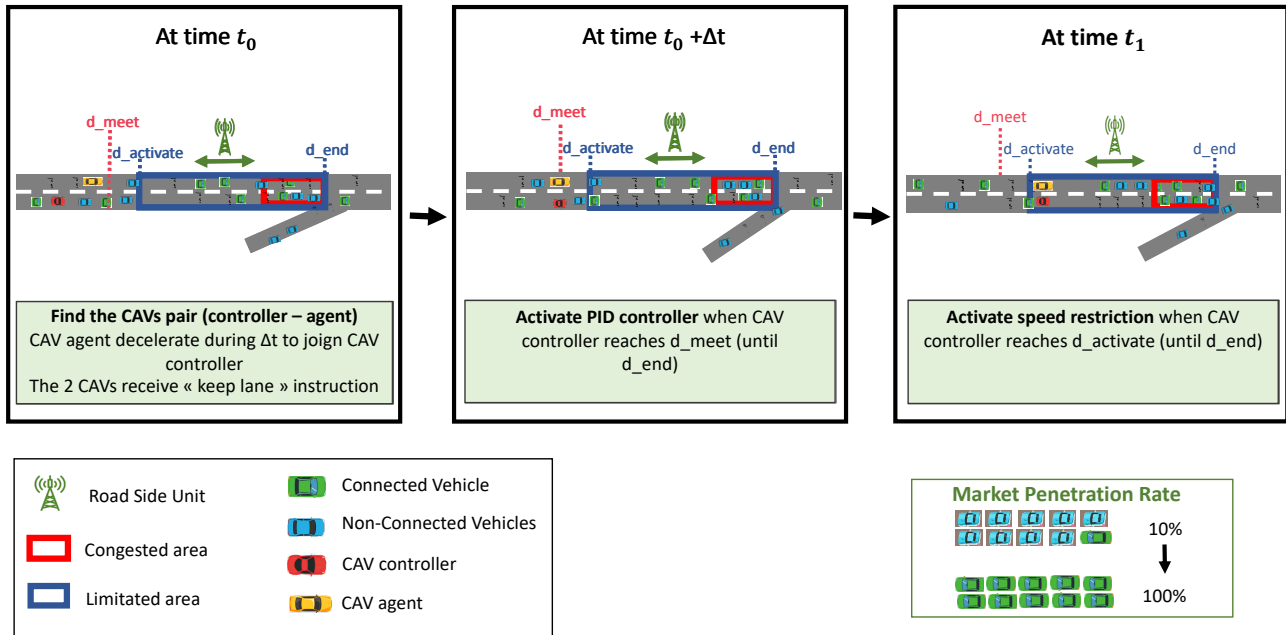


Fig. 2: Step 3 of the VSL system - Speed restriction application based on PID controller with 2 CAVs side-by-side

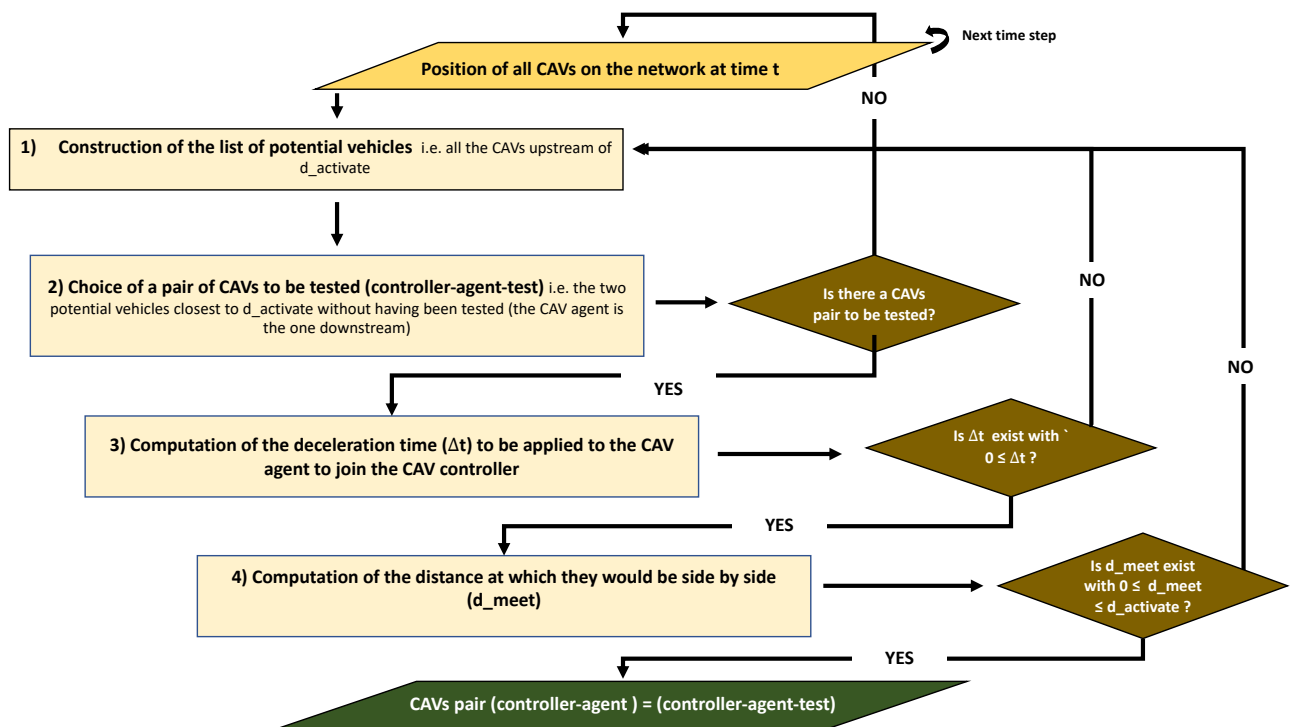


Fig. 3: Process to find the ideal pair of CAVs (controller-agent)

to the speed and position of each available CAV at each time step. We consider that a shockwave is propagating on the network when i) at least 3 CAVs have a speed lower than the threshold speed and ii) the first of them eventually reaches an acceleration phase (*a.k.a.* rarefaction wave), thus delimiting the congestion zone. (levels 1 to 3 on Figure 1 (a))

- *Step 2* consists in finding, if possible, a solution allowing to solve the shock wave. We therefore look for the distance and time of application of the speed restriction on the network ($[d_{activate}, d_{end}]$, $[t_{deb}, t_{end}]$). (levels 4 to 6 on Figure 1 (a))
- *Step 3* consists in delivering the control by applying this speed restriction at the distance and time computed in step 2.

In the MB CV-based strategy, a moving bottleneck (MB) is built and used as a traffic regulator. Thus, it requires to slightly adapt the process, as illustrated in Figure 1 (c) & (d). While the detection process of the shockwave remains unchanged, its resolution is based on a gap created between downstream vehicles and the controlled CAVs. According to kinematic wave theory, the characteristics of the gap with zero-density, illustrated by state C on Figure 1 (c), directly result from: (i) the slope of the backward propagation wave (yellow line), (ii) the average speed in the shockwave (orange line), (iii) the free flow speed (blue line), and (iv) the applied speed limit (pink line). From the shockwave detection time ($t_{detection}$), an optimal front of potential activation distances ($d_{activate}$) emerges and evolves with the expected time of activation. Then, the challenge lies in identifying the appropriate pairs of upcoming Connected Automated Vehicles able to cooperate in order to drive side-by-side before reaching the front of activation distances. The pair of CAVs with the shorter activation time ($t_{activate}$) should be selected to apply the speed limit instructions at distance $d_{activate}$.

Thereafter, for the sake of simplicity and comparability of the results between VSL systems, it is assumed that the step of shockwave resolution (step 2) is known and shared between the VSL systems under comparison (Full CV-based VS MB CV-based VSL). Only the 3rd step differs between VSL systems. It enables to remove the stochasticity impact due to the computation of solutions based on the position of Connected Vehicles. In the subsequent section, the study focuses on the main contribution of the MB CV-based VSL system, *i.e.*, the performances of the CAVs pairing process with regard to the effective Market Penetration Rate. Instead of enforcing the speed limit to any available CAVS in the activation area, the MB CV-based VSL targets only 2 CAVs, which can synchronize together to form a moving bottleneck and thus slow down the vehicles located upstream of a congested section.

B. Applying Speed Limitation to 2 CAVs side by side

As described in Figure 2, the third stage of the new VSL system (MB CV-based VSL) is broken down into 3 sub-stages:

- 1) Find the best pair of CAVs (controller-agent) that can join each other side by side before reaching $d_{activate}$ (*i.e.* the pair with the shorter activation time $t_{activate}$) and to whom the speed limit shall be applied between $d_{activate}$ and d_{end} .
- 2) Apply a servo loop to bring the two vehicles together: from d_{meet} to d_{end} , a PID control is applied to both vehicles to keep them side by side
- 3) Apply the speed restriction from $d_{activate}$ to d_{end} to the CAV leader.

C. Search for the vehicle pair (controller-agent)

As illustrated in Figure 3, the process of selecting the two CAVs is divided into 4 steps:

- 1) *Building the list of potential vehicles:* The list of candidate vehicles for the CAV pair (controller-agent) is established. To belong to the list, the vehicles must be CAVs and be upstream of $d_{activate}$.
- 2) *Selection of a pair of CAVs (controller-agent) test:* The selection process is carried out by scanning through the list of candidate pairs starting from those closest to the application distance of the speed reduction $d_{activate}$. For a given candidate pair, the most upstream of the two vehicles is designated as the controller and the other as the agent. It is, therefore, the agent that will decelerate to catch up with the controller while the controller does not change its speed. Also, at the end of the process, the controller vehicle must be in the right lane and the agent in the left lane. If this is not the case, they are instructed to change lanes.
- 3) *Computation of the deceleration time (Δt) to be applied to the agent so that it joins the controller.* At time t_0 , we have:

- Position and speed of the controller vehicle: x_{c_0} and v_{c_0} .
- Position and speed of the agent vehicle : x_{a_0} and v_{a_0} .

At time $t_1 = t_0 + \Delta t$, we have:

- Position and speed of the controller vehicle: x_{c_1} and v_{c_1}
- Position and speed of the agent vehicle : x_{a_1} and v_{a_1} .

We are looking for the position d_{meet} at which the two CAVs will be side by side (if it exists), *i.e.* $d_{meet} = x_{c_1} = x_{a_1}$. Now we have :

$$x_{c_1} = x_{c_0} + v_{c_0} \Delta t$$

and

$$x_{a_1} = x_{a_0} + v_{a_0} \Delta t - 1/2 f \Delta t^2$$

with f as the deceleration value.

Hence :

$$\begin{aligned} x_{c_1} &= x_{a_1} \\ \iff -1/2 f \Delta t^2 + (v_{a_0} - v_{c_0}) \Delta t + x_{a_0} - x_{c_0} &= 0 \end{aligned} \quad (1)$$

We solve this second degree trinomial to find the deceleration time (if any) Δt for which the two CAVs will have the same position at t_1 .

- 4) *Compute the position where the two CAVs (controller-agent) meet (d_{meet}):* If a positive solution exists for Δt , then we calculate d_{meet} with :

$$d_{meet} = x_{c0} + v_{c0} \Delta t \quad (2)$$

If d_{meet} is positive and less than or equal to $d_{activate}$, then our candidate pair of CAVs (controller-agent) becomes our pair (controller-agent).

Otherwise, we test another test pair (controller-agent) from the list. If there are no more vehicles to test in the list of potential vehicles, we wait for the next time step and reconstruct a new list.

D. Application of a speed restriction to the controller CAV and PID control to the agent CAV

Once the best controller - agent pair is found, both CAVs need to coordinate to meet at d_{meet} and remain side-by-side until d_{end} . To achieve this purpose, we apply :

- 1) *A PID loop control* to the agent vehicle, between d_{meet} and d_{end} , with the objective of minimising the distance between the 2 CAVs: the PID's role is twofold: (i) offset the gap between the 2 CAVS, and (ii) offset the speed differences between the 2 CAVs, when they meet at d_{meet} until they reach d_{end} ;
- 2) *A command to prohibit lane changes* for the 2 CAVs between d_{meet} and d_{end} ;
- 3) *A command with a speed restriction* to the controller vehicle between $d_{activate}$ and d_{end} .

A Proportional Integral Derivative (PID) controller [21] is a closed control loop for applying a correction to a control function. It is used here to control the space between the controller and the agent CAV. At each time step, an error term ($e(t)$) is measured which is equal to the difference between the desired distance between the two CAVs (set value SP) and the actual distance (measured value $PV(t)$), so we have

$$e(t) = SP - PV(t)$$

. Three components interact with each other:

- The Derivative component (D) based on the speed (derivative) at which the action is taken to reach the target instruction
- The Integral component (I) based on the cumulative impact (integral) of the actions that have already been taken to reach the target instruction
- The Proportional component (P), proportional to the error term

To calculate the acceleration/deceleration value $u(t)$ to be applied to the agent vehicle, the PID is applied to the error term. This gives us:

$$u(t) = k_p * e(t) + k_i * \int_0^t e(t') dt' + k_d * \frac{\partial e(t)}{\partial t} \quad (3)$$

the control function, at time step t , with k_p , k_i and k_d the coefficients of the proportional, integral and derivative terms.

We use the Ziegler Nichols method [23], [24] to calibrate these constants. We consider only the proportional action which we increase until the output signal of the closed loop, $u(t)$, oscillates in a stable and regular way. The aim is to find K_u , the maximum gain, and, T_u , the oscillation period of the closed loop. We apply our PID to 2 CAVs on a 2-lanes corridor so that they remain side by side, considering only the proportional component which we increase until the acceleration value to be applied to the agent CAV oscillates in a regular and stable way. We start from

$$K_u = 0.005$$

and we obtain

$$K_u = 0.020$$

and

$$T_u = 73.8s$$

. Then, the PID constants are calculated with:

$$k_p = 0.3 * K_u$$

$$k_i = 1.2 * K_u / T_u$$

$$k_d = 3 * K_u * T_u / 40$$

III. RESULTS

Once the PID is calibrated, our approach (MB CV-based VSL with PID) is ready for evaluation and comparison to an alternative strategy: the Full CV-based VSL. The analysis is performed thanks to a traffic micro-simulation framework, called SUMO [25], which can replicate the driving behaviour (lateral and longitudinal) of a road user and its interactions with the surroundings. The microscopic traffic simulator is composed of several component layers interacting with each other: (i) the environment layer describing the road configuration and the demand supply, (ii) the agent layer including feature related to any active agent from drivers and cars to road manager, (iii) the sensor layer, and (iv) the communication layer. The communication layer (V2X, I2V) is developed in Python and operated through a TCP-based client/server architecture, called Traffic Control Interface (TraCI). At each time-step, vehicle-state data are collected from SUMO through the help of TraCI. Then, new instructions can be provided based on different VSL logics to alter the current vehicle state within the same timestep. The simulation framework is calibrated the same in order to improve its ability to replicate the local traffic conditions [26].

A. Scenario under consideration

The network under consideration is described in Figure 2 is an 11km section of a two-lanes motorway with an insertion lane at the 9th km. Here, the analysis is only concerned with how to deliver VSL control, so we set the speed limit solution for all scenarios to the solution found when the environment is fully connected (100 % penetration rate). Therefore, we fix [$d_{activate}$, d_{end}], [t_{deb} , t_{end}]). For the fixed speed limit solution, scenarios are considered with Market Penetration

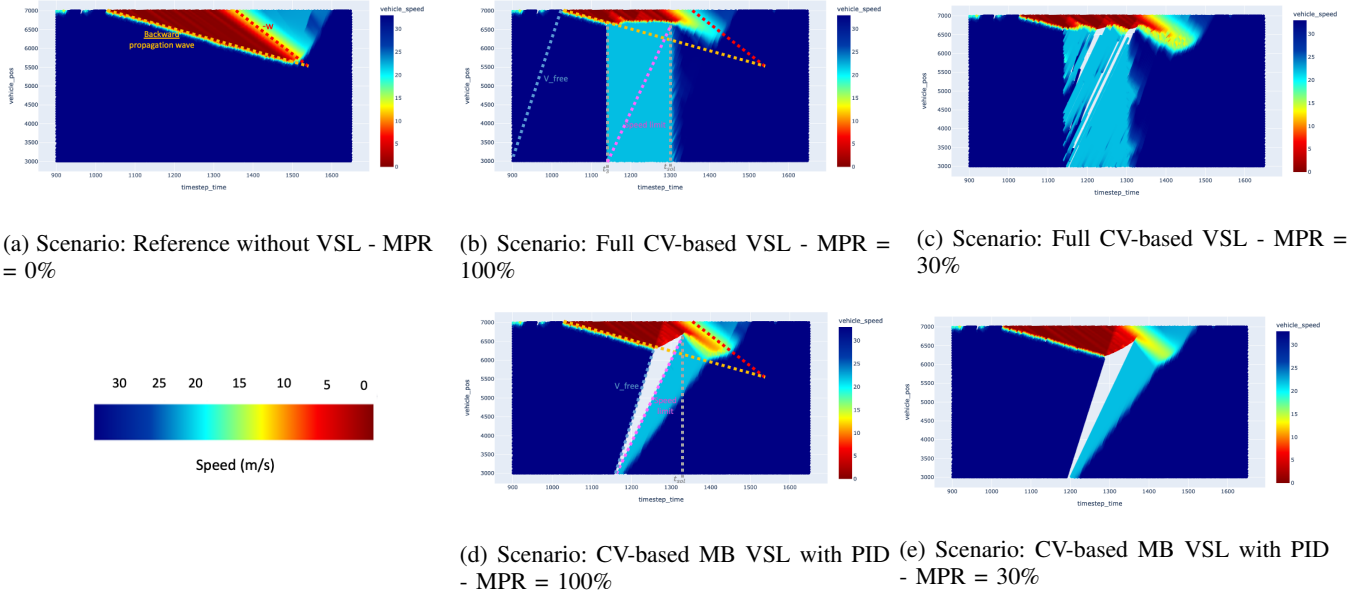


Fig. 4: Space-Time Diagram according to applied Variable Speed Limit strategy

TABLE I: Average Travel Time (ATT) of vehicles in function of the VSL system application and the Market Penetration Rate (MPR)

ATT(s)	0%	100%	75%	50%	30%	20%
Full CV-based	112	95	96	100	101	101
MB CV-based	112	103	104	104	105	105

TABLE II: Indicators for triggering the speed restriction in the case of the Moving Bottleneck (MB) CV-based approach: $d_{triggering}$ the distance between $d_{activate}$ and d_{meet} and Δt the time for the two vehicles to meet side by side

MPR	100%	75%	50%	30%	20%
$d_{triggering}$ (m)	39	77	77	499	376
Δt (s)	0	15	15	21	26

Rate (MPR) of CAVs varying between 0% (baseline) and 100% (a fully connected environment). To cover mixed traffic cases with low connected environment, the MPR takes the following discrete values (20%, 30%, 50%, 75%, 100%).

B. Performance of the introduced system

For the different penetration rates considered and for the two methods applying the VSL system, the following results are obtained:

- The average travel times of vehicles observed on the network in seconds (Table I)
- The space-time diagrams for MPR = 0% (Figure 4a), MPR = 30% and MPR = 100% (Figures 4c and 4e)
- The indicators for triggering the speed restriction in the case of the Moving Bottleneck (MB) CV-based approach with $d_{triggering}$ the distance between $d_{activate}$ and d_{meet} and Δt the time for the two vehicles to meet side by side (Table II).

Both applications of the VSL system show, for all scenarios considered, a reduction in average vehicle travel times compared to the baseline without control (MPR=0%) (Table I). It is worth-mentioning that, as expected, the MB CV-based with PID VSL provides more stable performances (Standard Deviation - StD = 0.84) with Market Penetration Rate variations than the original approach (StD = 2.88).

Furthermore, Figure 4 illustrates the performances of the CV-based Variable Speed Limit approaches to solve the shockwave. Especially, it highlights:

- the stability of the performances of the introduced approach with regard to the Market Penetration Rate of CAVs ;
- the differences of implementation between both VSL approaches (Full CV-based versus MB CV-based): while the Full CV-based approach will have an immediate impact on the shockwave, some delays are observed in the MB CV-based approaches due to the elapsed time to create a gap as it is shown in Table II with Δt the delay needed for the 2 CAVs to meet side-by-side and $d_{triggering}$ the distance to travel before the triggering of the speed restriction. This might explain the limited benefits of the MB CV-based approach with regard to Travel Time gains, since we computed in this study the activation distance to solve the shockwave according to the Full CV-based approach outputs.

IV. CONCLUSIONS AND PROSPECTS

We introduced in this paper an original approach, called Moving Bottleneck CV-based Variable Speed Limit system, dedicated to the application of VSL to damp shockwaves. This approach consists of forming a mobile jam by keeping side-by-side two Connected and Automated Vehicles using a PID controller. The purpose is to create a gap between

controlled CAVs and downstream vehicles to break the propagation of a downstream congestion shockwave. The main contribution lies in the implementation of the strategy that relies on V2X communication to broadcast information, while the PID is built to ensure the deceleration of one CAV to build the mobile front and ensure the stability of the front until they reach the congested area. Such an implementation process enables to ensure a fair control with regard to the penetration rate of CAVs.

The performances of the introduced methods are compared to the ones of an alternative approach [13]. As expected, a strong improvement in terms of homogeneity of the travel times, when the penetration rate of CAVs vary, is highlighted with the new approach. However, the absolute benefits in travel time are reduced in this study, which might be explained by the fact that the activation distance of the VSL was optimised for the reference [13] to avoid stochasticities due to the computation of the solution. Furthermore, the selection process of the pair of CAVs is built on the assumption that only one vehicle is controlled to decelerate and reach its partner. Such an assumption restricts the space of available solutions and might negatively affect the performances. Furthermore, the process of selecting and matching the 2 CAVs imposed that whatever the starting configuration of the 2 CAVS (i.e. position in relation to each other and their lane), the CAV controller must be downstream and on the right lane and the CAV agent upstream and on the left lane. Taking into account their starting configuration to designate which one is the controller/agent and their respective lanes would improve the efficiency of the matching process.

Future works might focus on:

- improving and evaluating the Moving Bottleneck CV-based methodology to properly define the distance and time of activation;
- exploring alternative algorithms to seek for an appropriate pair of CAVs by relaxing assumptions on available actions taken by the controlled CAVs;
- introducing the fuel consumption into the criterion related to the process of merging the two CAVs in order to limit over-consumption for the agent following the controller.

REFERENCES

- [1] D. Zhao, Y. Dai, and Z. Zhang, "Computational intelligence in urban traffic signal control: A survey," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 42, no. 4, pp. 485–494, 2011.
- [2] M. Hausknecht, T. Au, P. Stone, D. Fajardo, and T. Waller, "Dynamic lane reversal in traffic management," pp. 1929–1934, IEEE, 2011.
- [3] S. Smulders, "Control by variable speed signs: the dutch experiment," in *International Conference on Road Traffic Monitoring and Control (6th: 1992: London, England)*. 6th International Conference on Road Traffic Monitoring and Control, 1992.
- [4] S. Smulders and D. Helleman, "Variable speed control: state-of-the-art and synthesis," 1998.
- [5] B. Khondaker and L. Kattan, "Variable speed limit: an overview," *Transportation Letters*, vol. 7, no. 5, pp. 264–278, 2015.
- [6] F. Vrbanić, E. Ivanjko, K. Kušić, and D. Čakija, "Variable speed limit and ramp metering for mixed traffic flows: A review and open questions," *Applied Sciences*, vol. 11, no. 6, 2021.
- [7] A. Hegyi, S. Hoogendoorn, M. Schreuder, H. Stoelhorst, and F. Viti, "SPECIALIST: A dynamic speed limit control algorithm based on shock wave theory," in *2008 11th International IEEE Conference on Intelligent Transportation Systems*, pp. 827–832, IEEE, 2008.
- [8] L. Kattan, B. Khondaker, O. Derushkina, and E. Poosarla, "A probe-based variable speed limit system," *Journal of Intelligent Transportation Systems*, vol. 19, no. 4, pp. 339–354, 2015.
- [9] K. Kušić, I. Dusparic, M. Guériau, M. Gregurić, and E. Ivanjko, "Extended variable speed limit control using multi-agent reinforcement learning," in *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)*, pp. 1–8, IEEE, 2020.
- [10] K. Kušić, E. Ivanjko, M. Gregurić, and M. Miletić, "An overview of reinforcement learning methods for variable speed limit control," *Applied Sciences*, vol. 10, no. 14, 2020.
- [11] A. Hegyi and S. Hoogendoorn, "Dynamic speed limit control to resolve shock waves on freeways - field test results of the SPECIALIST algorithm," in *13th International IEEE Conference on Intelligent Transportation Systems*, pp. 519–524, IEEE, 2010.
- [12] E. Grumert and A. Tapani, "Using connected vehicles in a variable speed limit system," *Transportation Research Procedia*, vol. 27, pp. 85–92, 2017.
- [13] E. Fauchet, K. Bhattacharyya, P. Laharotte, and N. El Faouzi, "A variable speed limit strategy based on lagrangian traffic indicators resulting from connected vehicles: Application to the SPECIALIST algorithm," *Transportation Research Board Conference Proceedings*, 2022.
- [14] L. Leclercq, S. Chanut, and J. Lesort, "Moving bottlenecks in lighthill-whitham-richards model: A unified theory," *Transportation Research Record*, vol. 1883, no. 1, pp. 3–13, 2004.
- [15] X. Wei, C. Xu, W. Wang, M. Yang, and X. Ren, "Evaluation of average travel delay caused by moving bottlenecks on highways," *Plos one*, vol. 12, no. 8, 2017.
- [16] Y. Han, D. Chen, and S. Ahn, "Variable speed limit control at fixed freeway bottlenecks using connected vehicles," *Transportation Research Part B: Methodological*, vol. 98, pp. 113–134, 2017.
- [17] G. Piacentini, P. Goatin, and A. Ferrara, "Traffic control via moving bottleneck of coordinated vehicles," *IFAC-PapersOnLine*, vol. 51, no. 9, pp. 13–18, 2018.
- [18] Z. Li, X. Zhu, X. Liu, and X. Qu, "Model-based predictive variable speed limit control on multi-lane freeways with a line of connected automated vehicles," in *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*, pp. 1989–1994, IEEE, 2019.
- [19] J. Guanetti, Y. Kim, and F. Borrelli, "Control of connected and automated vehicles: State of the art and future challenges," *Annual reviews in control*, vol. 45, pp. 18–40, 2018.
- [20] Z. Li, M. Levin, R. Stem, and X. Qu, "A network traffic model with controlled autonomous vehicles acting as moving bottlenecks," in *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)*, pp. 1–6, IEEE, 2020.
- [21] M. Johnson and M. Moradi, *PID control*. Springer, 2005.
- [22] P. Richards, "Shock waves on the highway," *Operations research*, vol. 4, no. 1, pp. 42–51, 1956.
- [23] H. O. Bansal, R. Sharma, and P. Shreeraman, "PID controller tuning techniques: A review," *Journal of Control Engineering and Technology*, vol. 2, p. 10, 2012.
- [24] J. G. Ziegler and N. B. Nichols, "Optimum settings for automatic controllers," *Journal of Dynamic Systems, Measurement, and Control*, vol. 115, no. 2, pp. 220–222, 1993.
- [25] P. Lopez, M. Behrisch, L. Bieker-Walz, J. Erdmann, Y. Flötteröd, R. Hilbrich, L. Lücken, J. Rummel, P. Wagner, and E. Wießner, "Microscopic traffic simulation using sumo," in *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, pp. 2575–2582, IEEE, 2018.
- [26] H. Rakha, B. Hellinga, M. Van Aerde, and W. Perez, "Systematic verification, validation and calibration of traffic simulation models," in *75th Annual Meeting of the Transportation Research Board, Washington, DC*, Citeseer, 1996.