Zero-Infrastructure, Decentralized Variable Speed Limit Control

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Abstract

Variable Speed Limit control can help avoid traffic jams before congestion forms. Vehicles upstream are required to decelerate at times in order to stop emerging congestion from propagating. This work proposes a fully decentralized, model-free, and infrastructure-free approach to Variable Speed Limit control, that employs connected vehicles as communication infrastructure, and as moving sensors and actuators. Dedicated Short Range Communication, consensus, and gossip algorithms, and a Bellman controller are components of this approach. The proposed method achieves significant improvements in traffic states, with up to 15% higher speeds, 5% lower density, and 8% higher flows. Significant improvements can be achieved at a compliance rate of at least 25% of all vehicles. Moreover, the approach is robust to gaps between platoons and recovers from periods of disconnection. The proposed method achieves traffic improvements similar to previous, centralized approaches, without the necessity of any infrastructure or model knowledge. `https://github.com/DerKevinRiehl/decentralized_vsl/`

Keywords: Automation and transportation; Connected vehicles; Variable Speed Limit; Decetranlized Control; Consensus Algorithm; Innovative data collection approaches; Artificial Intelligence applications to transportation

1 Introduction

The slower-is-faster effect [1] suggests vehicles upstream should decelerate (slow down) in order to enable conflict resolution downstream fast enough to avoid congestion forming. This idea is implemented in Variable Speed Limit control (VSL). VSL dynamically adjusts speed limits on highways to improve traffic flow and prevent congestion [2]. If implemented correctly, VSL can be an effective countermeasure against congestion on freeways, and significantly improve throughput and safety [3]. In practice, VSL can be challenging, due to complexities in real-time measurement of traffic & weather conditions, infrastructural requirements for sensors and electronic speed signs, public acceptance, and driver compliance [4].

Connected and automated vehicles (CAVs) introduce new opportunities to this context and allows the employment of vehicles both as moving actuators to harmonize traffic flow and alleviate congestion and as moving sensors. In previous studies, real-time traffic state information (flow, density, speed) is used to inform upstream vehicles that comply with a state feedback controller to reduce their speed if necessary [5], which however requires a communication and sensing infrastructure, accurate traffic state measurements, and model knowledge of the fundamental diagram.

Within this work, we propose an approach to VSL that is fully decentralized, model-free, and infrastructure-free. The approach requires nothing but connected vehicles, meaning the ability for vehicle-2-vehicle communication. The proposed method leverages Dedicated Short Range Communication (DSRC) [6] to implement a decentralized communication infrastructure, and makes use of vehicles as moving sensors for decentralized speed estimation with a combination of discrete-time consensus [7] and gossip algorithms [8]. Finally, compliant vehicles that follow suggestions act according to a Bellman, bang-bang control law [9], which does not require an understanding of the system model at any time.

The results of conducted micro-simulations show, that the controller approach can achieve significant improvements in traffic (+15% speed, -5% density, and +8% flow) when compared with an uncontrolled situation, even though the decentralized communication does not guarantee recent and accurate speed estimates at all times. The results are consistent for different compliance rates, where at least 25% of vehicles must participate in the control to achieve a significant traffic improvement.

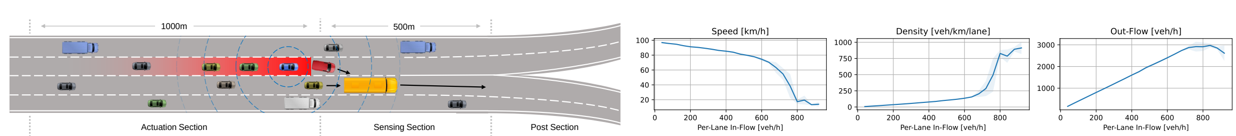

Figure 1: **Congestion Formation at Highway Bifurcation.** Impaired Speed, Density, and Out-Flow of ROI section (Sensing) for increasing per-lane in-flows.

2 Methods

Definitions: We consider a population of n vehicles on a multi-lane freeway segment. The freeway segment consists of three sections: actuation section, sensing section, and post section, as shown in Fig. 1. Vehicles in the actuation section serve as mobile actuators, follow a control law, and actively reduce their speeds to enable decongestion in the bottleneck. Vehicles in the sensing section serve as mobile sensors and estimate the speed of this section v^{ROI}. This section is also called the region of interest (ROI), it is where the congestion due to the bottleneck (bifurcation) happens. While vehicles in the previous two sections communicate, vehicles in the post section do not participate in any communication, sensing, or actuation. Each vehicle i has a physical maximum speed $\tilde{v}_i^{max}$, a real speed v_i and a section s_i that represents the section it is located on.

Communication Infrastructure: Our method employs connected vehicles that communicate vehicle-2-vehicle, leveraging DSRC technology. We assume a share α of all vehicles is connected, and a maximum possible communication distance $d_c = 200$m. The communication takes place in rounds, and each round takes t_r time. During each round r, each vehicle sends out a message $m_{i,r}^{out}$ (in case it has a speed estimate available), and receives a set of messages $m_{i,r,k}^{in} \in \mathscr{M}_{i,r}^{in}$ from surrounding vehicles k. At the end of each round, the received messages are processed, and new messages to send out are prepared. Each vehicle's message consists of four fields: (A) "timestamp", (B) "section", (C) "value", and (D) "in-degree". Field (A) is populated with the current timestamp, field (B) is populated with the vehicle's current section, field (C) is populated with the vehicle's current estimate $\hat{v}_{i,r}^{ROI}$, and field (D) is populated with the vehicle's in-degree $\mathscr{N}_i$, which represents the number of received messages. These fields are used by the gossip and consensus algorithms during speed estimation.

Speed Estimation & Communication Protocol: Vehicles in the sensing section estimate the speed state of the ROI v^{ROI} using a discrete-time average consensus algorithm. A homogeneous traffic state across all lanes is implicitly assumed [1]. Vehicles in the sensing section determine their estimate of the ROI speed $\hat{v}_{i,r}^{ROI}$ as the weighted average of their own speed and the received estimates from surrounding vehicles in the sensing section as follows:

$$\hat{v}_{i,r}^{ROI} = \frac{1}{\mathscr{N}_i + 1}(v_i + \sum_{m_{i,r,k}^{in} \in \mathscr{M}_{i,r}^{in}} m_{i,r,k}^{in}["value"]) \tag{1}$$

Vehicles in the actuation section communicate their received estimates via a gossip algorithm with each other, and therefore back-propagate information on received estimates from the sensing section. They determine their speed estimates as described in the three following cases. (i) In case the vehicle did not receive any message from surrounding vehicles in the communication round, it will stick to its previous estimate:

$$\hat{v}_{i,r}^{ROI} = \hat{v}_{i,r-1}^{ROI} \tag{2}$$

(ii) In case the vehicle received at least one message from surrounding vehicles of the sensing section, it will consider only those p messages from the sensing section and determine its speed estimate as the average of the received speed estimates:

$$\hat{v}_{i,r}^{ROI} = \frac{1}{p}(\sum_{m_{i,r,k}^{in} \in \mathscr{M}_{i,r}^{in}} m_{i,r,k}^{in}["value"]) \tag{3}$$

(iii) In case the vehicle received messages from surrounding vehicles of the actuation section only, it will determine its estimate as the most recent available estimate from all received messages. If the resulting estimate from any of the cases above exceeds a certain maximum considered estimation age a_{max}, the vehicle forgets previous estimates and does not possess an estimate. Vehicles that just entered the sensing section will reset their speed estimate to their current speed.

Vehicles in the sensing section always have a speed estimate of the ROI (at least determined by their own speed), while vehicles in the actuation section do not always have a speed estimate.

Control Law: We assume a share γ of all connected vehicles is compliant. Each connected and compliant vehicle i follows a Bellman, two-point, bang-bang control law [9, 10], based on its speed estimate $\hat{v}_i^{ROI}$, to control its maximum speed v_i^{max} as follows:

$$v_i^{max} = \begin{cases} \tilde{v}_i^{max} & \text{if} \quad \hat{v}_i^{ROI} \geq v_{thr} \\ \tau \times \tilde{v}_i^{max} & \text{if} \quad \hat{v}_i^{ROI} < v_{thr} \end{cases} \tag{4}$$

If the speed estimate $\hat{v}_i^{ROI}$ drops below a certain threshold speed v_{thr}, vehicles will consider a reduced maximum speed, which is defined by the speed reduction factor $\tau \in [0, 1]$.

[1] In most countries, outer lanes on highways are used for higher speed travelling compared to the middle lanes. However, our approach employs the average speed across all lanes in the ROI, as the highway segment is before a bifurcation. Yet, this assumption does not affect how the approach works.

Microsimulations: The four-lane highway network used to evaluate our model is shown in Fig. 1. As vehicles need to perform their lane changes before the bifurcation, conflicts can occur, slowing down vehicles upstream and causing increasing congestion. The red vehicle for example needs to change lanes, but as other vehicles on that lane, such as the yellow bus, prevent it from lane changing, it must decelerate, which causes congestion on the vehicles upstream in its lane. For higher levels of in-flowing traffic, the average speed and out-flow in the region of interest (sensing section) drops, while the density grows.

We conduct time-discrete micro-simulations of the road network using SUMO [11]. Traffic is spawned randomly by sampling a Bernoulli distribution, and picking a random lane origin-destination combination with a uniform distribution. The fleet composition on the highway is assumed to be mixed traffic consisting of the following four vehicle types: cars (55%, max. speed 200 km/h), delivery vehicles (22%, max. speed 200 km/h), omnibuses (11%, max. speed 85 km/h), and trucks (12%, max. speed 130 km/h). The maximum speed on the highway is assumed to be 100 km/h (which can be violated/exceeded by aggressive driving behavior up to 25 km/h). Traffic simulation experiments are run for 6000s of simulation time, with an additional 1000s warm-up time, and repeated 20 times to determine average and standard deviation for traffic fundamentals (speed, density, flow), communication, and control-related statistics.

3 Results & Discussion

In this section, we discuss dedicated experiments, that were conducted for the design and evaluation of the communication system and controller. Afterwards, the control performance is analyzed, followed by a discussion on convergence guarantees of the consensus algorithm.

Parameter Design Experiments: Fig. 2 describes the decentralized communication system design. Various simulation experiments were conducted, to determine the following parameter combination for the communication infrastructure: every $t_r = 2$s speed estimation, and $a_{max} = 30$s maximum information age. This parameter combination achieves sufficiently high estimation quality, and broad information distribution, while not costing too much DSRC bandwidth, and not demanding too frequent communication from vehicles.

Fig. 3 (top row) describes the decentralized two-point controller design. The speed threshold v_{thr} and speed reduction factor τ are varied, with effects on the participation of vehicles in the actuation section, and with mixed findings on improvements in speed, flow, and density. The higher v_{thr}, the more vehicles participate in reducing their speed. Depending on τ improvements in speed, flow, and density can be achieved. Finally, we consider the following parameter combination for the control law: $v_{thr} = 80$ km/h and $\tau = 0.9$. This parameter combination achieves the largest and most consistent improvements across all three traffic fundamentals.

Control Performance Analysis & Impediments to Communication System:

First, the control performance is evaluated for different, static per-lane in-flows, and different compliance rates γ. in Fig. 3 (bottom row). Significant improvements can be achieved beginning from an in-flow beginning from 720 veh/h. The ROI speed can be increased by 15%, the density can be reduced by 5%, and the out-flow can be increased by 8%. The improvements resemble those of prior works using VSL in a similar context [5]. Even though vehicles in the proposed decentralized method have ROI speed estimates that are sometimes outdated or inaccurate, they achieve comparably similar performance improvements to vehicles with perfect estimates (blue line). The more vehicles comply with the control law (larger γ), the better the control performance. Based on our simulations, at least $\gamma = 25\%$ compliance rate is necessary to achieve significant improvements. This is consistent with prior findings employing a centralized sensing and communication approach [5].

Second, the control performance is analysed in two different, dynamic in-flow scenarios in action, as shown in Fig. 4. When speed drops and density rises without control, one can especially well observe the stabilization introduced by the decentralized, Bellman controller, with its implications on the traffic state. The participation in actuation and estimation quality depends on the scenario. The estimation quality (measured as relative mean absolute error of the ROI speed estimates) is essentially higher before capacity (left scenario) when compared with at capacity (right scenario). Moreover, before capacity, the control causes actuation of vehicles when it is necessary to decongest, while at capacity an almost permanent actuation of compliant vehicles can be observed. The left scenario showcases another challenge of the decentralized approach between 2000s and 2400s. In this interval, the share of vehicles upstream that have an estimate drops significantly, and estimation quality worsens substantially. Vehicles tend to cluster in platoons. If a gap between two groups of vehicles is larger than the maximum communication distance d_c, it acts like an information barrier preventing the flow of information upstream. This causes the communication system, consensus, and gossip algorithm to fail due to the lack of connectivity. Even though the communication and estimation fail during that interval, and therefore no actuation takes place, there are no significant impairments of the traffic state during that time, and the communication system recovers. In addition to that, the two scenarios of Fig. 4 demonstrate the correlation of estimation quality, actuation, and the ROI traffic state. In times of a dropping speed and rising density in the ROI, actuation starts to increase after some delay and stays on a high activity level until the traffic state recovers. When estimates worsen, the effects of control on traffic state improvements are disturbed. What's more, the results of Fig. 4 highlight, that this approach not only improves the speed on average but also homogenizes the traffic over time.

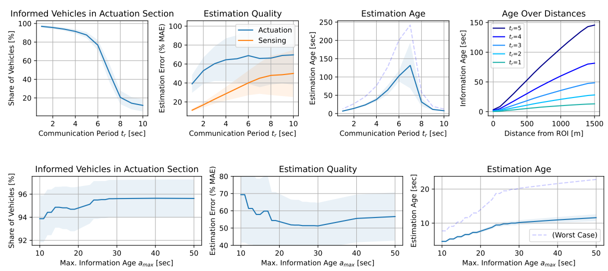

Figure 2: **DSRC Communication Design.** Communication Period Duration t_r, Maximum Estimation Age a_{max}, and their effect on ROI Speed Estimation Quality. Plots generated for per-lane in-flows of 720 veh/h.

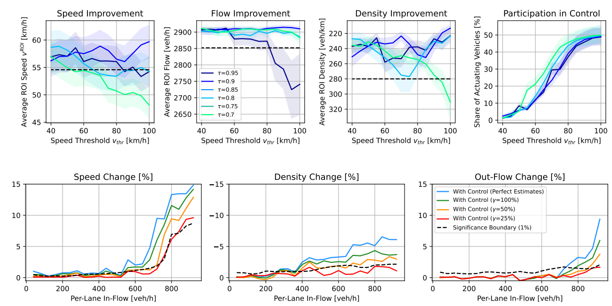

Figure 3: **Two-point Controller Design.** Speed Control Threshold v_{thr}, Speed Control Factor τ, Compliance Ratio γ, and their effect on ROI traffic improvement. Plots in the first row show traffic improvement for per-lane in-flows of 720 veh/h.

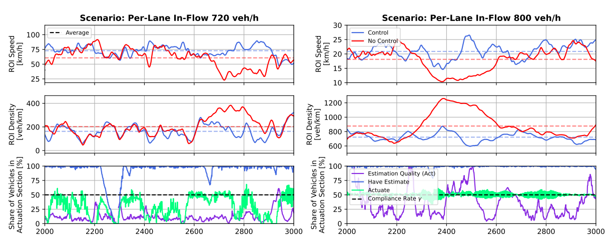

Figure 4: **Controller effect on two congestion scenarios.** Speed, density, and estimation metrics are shown for high (720 veh/h) and very high (800 veh/h) inflows. The controller ($\gamma = 50\%$) can significantly reduce congestion in both cases.

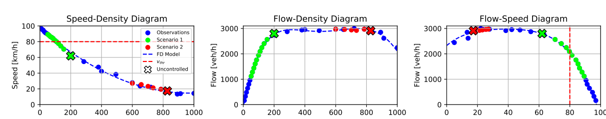

Figure 5: **Fundamental Diagram of Highway Bifurcation & Control**. The presence of the decentralized variable speed limit controller improves traffic conditions significantly.

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