Quantifying the impact of driver compliance on the effectiveness of variable speed limits and lane control systems

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***Abstract*— *Variable speed limits* (VSL) and *lane control systems* (LCS) are commonly applied *active traffic management* (ATM) strategies to improve traffic mobility and safety. These systems can be used for recurring congestion or for non-recurrent incident response settings. Regardless of the setting, it is naturally assumed that for such systems to be effective, the driver compliance rate must be reasonably high. In this work, we investigate the impact of a wide range of driver compliance rates on safety and mobility performance measures during incidents. We consider a microsimulation setup in which rule-based VSL and LCS systems are deployed, and we vary the number of complying drivers that adhere to the variable speed limits in response to an incident. Our main finding is that VSL and LCS systems can achieve a substantial benefit in key safety performance measures without reducing mobility measures significantly, even when the driver VSL compliance rates are as low as 5% in sufficiently dense traffic. This result can be explained by examining the impact of a small number of complying drivers on the surrounding traffic.**

I. INTRODUCTION

Continued population growth is placing increasing demands on transportation infrastructure to perform efficiently and safely. Incidents occurring on critical freeway infrastructure reduce the capacity of the freeway, generate non-recurrent congestion, and increase the risk of secondary incidents. In the US, traffic incidents are estimated to be responsible for 25% of all traffic congestion [1]. Active traffic management strategies are needed on freeways to respond to incidents and reduce the resulting negative impact on safety and mobility.

One of the most promising strategies in *active traffic management* (ATM) are *variable speed limit* (VSL) systems, which have been widely investigated and deployed [2], [3]. By dynamically changing speed limit values, VSL systems are able to smooth the speed of traffic to avoid sudden slowdowns, thus improving traffic safety. In [4], the authors calculated the real-time crash likelihood to evaluate the safety benefit of VSL and found that VSL can improve traffic safety in medium-to-high speed regimes, but no benefit was obtained in low speed regimes. Another micro-simulation study [5] showed that VSL can improve safety substantially when speed limits posted are set at or similar to the actual average speed of the vehicles. As for empirical studies, the work in [6] conducted a before-after analysis of crashes and demonstrated that the number of injury crashes decreased by 18% after the deployment of VSL on a motorway in Belgium. The authors in [7] similarly found that crash risk can be significantly reduced by employing VSL control strategies.

Although the safety benefits of VSL have been confirmed both from simulation and field data, the conclusions from different papers regarding the benefits of VSL in terms of mobility (e.g., travel time and throughput) do not always align. For example, Lin et al. (2004) [8] found that VSL systems can improve bottleneck throughput through simulation, and Hoogendoorn et al. (2013) [9] by using field data from the Netherlands showed that VSL systems can reduce travel time. In contrast, the empirical study conducted in [10] found no evidence that VSL improves traffic mobility.

Lane control systems (LCS) are another widely used tool for ATM that indicates the status of the downstream lanes to drivers. Compared to VSL systems, few studies have evaluated the effectiveness of LCS for mobility and safety. The work [11] evaluated the effectiveness of LCS through simulation experiments, and found that LCS could lead to efficient lane changing but with an increase in travel time if not configured properly.

Zhang and Ioannou (2015) [12] proposed the use of LCS to mitigate the negative impact of VSL systems on travel time. It found that lane changing occurring near the bottleneck is one of the main reasons for not achieving a travel time improvement with VSL control. However, it did not analyze the effectiveness of VSL and LCS under different driver compliance rates, which we address in our work. Guo et al. (2020) in [13] developed a combination of VSL and LCS control strategy under a connected and automated vehicles environment and obtained a considerable reduction of travel time. To tackle the problems of low VSL compliance rate and spatially static speed limit control zones, Gregurić et al. (2022) in [14] applied deep reinforcement

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learning to propose novel VSL strategies in the context of connected vehicles. Yuan et al. (2021) [15] evaluated the effectiveness of VSL and LCS with modeling uncertainty considerations. The same authors evaluated the impact of the distance between VSL sign and the bottleneck in [16]. In a work closely related to ours, a study conducted simulation experiments to understand the effectiveness of VSL under different levels of driver compliance in terms of traffic mobility and safety [17]. As compliance rate increases, they found that safety increases but travel time also increases. However the system considered did not include an LCS system, which can also add positive benefits to mobility performance measures as well as potentially offset the reduction in mobility caused by VSL.

Our work is motivated by a $90M project in the Nashville, TN area to upgrade physical infrastructure and deploy an integrated smart traffic management system on the I-24 corridor southeast of downtown Nashville. The first ATM systems on the corridor will be LCS and VSL designed to improve safety along the 28-mile section as well as to improve reliability of mobility measures. Based on numerous stakeholder requirements, the system will initially be launched with a rule-based LCS and VSL system. Later, the rules will be allowed to be adjusted via an artificial intelligence (AI) algorithm that learns over time the effectiveness of small adjustments to the rules based on data collected from the traffic sensors on the corridor.

The main contribution of this paper is to present for the first time a thorough study on the combination of VSL and LCS control strategies under non-recurrent congestion and for different levels driver compliance with the VSL systems. The results we obtain and the conclusions we derive can help inform the implementation of strategies in places where drivers compliance differ, e.g., the US vs Europe. Moreover, the results we find on the relationship between the number of strict compliant drivers and effective compliance rate is relevant in the context of connected and automated vehicles for speed control in highways, since those technologies open up opportunities to increase the number of compliant vehicles.

The remainder of the article is organized as follows. Section II introduces the VSL and LCS control algorithms as well as the evaluation metrics employed in this study. Section III presents the network under study and the parameter settings for the micro simulation representing a portion of the I-24 Smart Corridor. The results and respective discussions are included in Section IV. Finally, Section V presents the conclusions.

II. DESCRIPTION OF THE CONTROL SYSTEMS

A. *Non-recurrent bottleneck traffic control*

During the past few decades, the field of active traffic management has developed numerous control approaches to manage recurring traffic jams. In contrast, the field of active traffic management under traffic jams caused by non-recurring incidents is underdeveloped. Standard control strategies for non-recurrent bottlenecks include *variable speed limits* (VSL), ramp metering, route guidance, and *lane control systems* (LCS). VSL can be designed to control the inflow of the bottleneck to mitigate the effect of capacity drop such that traffic mobility improves. It has also been shown in other studies [18] that VSL can smooth the traffic speed and reduce speed variability, which improves traffic safety. Ramp metering is used to control ramp flow according to highway traffic conditions. Several studies [19], [20] investigate the combination of VSL and ramp metering, with most concluding that VSL and ramp metering combined outperform each strategy when used individually. Route guidance provides recommendations of alternative routes for divers, thus improving traffic mobility and reducing the probability of secondary collision when an incident has taken place. Other studies [12], [21] demonstrate that the capacity drop phenomenon is due to the lane-changing behavior occurring close to the bottleneck. To avoid this, LCS can be applied to inform drivers about the status of individual lanes downstream so that they can make lane-changing decisions before arriving to the congested area. However, few studies have evaluated the effectiveness of LCS as well as the combination of VSL and LCS.

In general, there are two approaches to VSL control: rule-based reactive response and proactive measures. Rule-based VSL is usually determined by traffic characteristics, e.g., the traffic speed, flow, and occupancy [3]. Under this class of approaches, VSL is only active after congestion formation leading to less efficient performance in terms of mobility. Proactive VSL control, on the other hand, usually considers a traffic prediction model to compare and select the optimal speed limits to post before congestion propagates. However, estimating the dynamic behavior of traffic is challenging because of the uncertainty in the traffic demand and driver behavior. Therefore, rule-based VSL systems are often selected [2]. As for LCS control, many strategies deployed in real scenarios are also rule-based [21].

B. *VSL and LCS traffic management algorithms*

In this work we consider rule-based algorithms for VSL and LCS systems. The rule-based algorithms are designed for deployment in US traffic management systems that are targeted to improve safety while recognizing that driver compliance is not generally high, even when the limits are regulatory. In this section we briefly summarize the rule-based algorithms that are scheduled for deployment in Fall 2022 by the Tennessee Department of Transportation on the I-24 SMART Corridor in Nashville, TN.

The VSL system is designed to display a speed limit that is as close to the actual traffic speed at the slowest point along the roadway, rounded up to the nearest 5 mph. For example, if a portion of the roadway has traffic traveling at 31 mph, the posted speed at that location will be 35 mph. To avoid large variations in the posted speeds along the roadway, the speed limit on gantries upstream of the slowest point are sequentially increased by a small increment (i.e. 5 or 10 mph) if possible (if the traffic upstream is traveling sufficiently fast), or fixed at the same speed otherwise. The posted speed limits on all gantries must be selected from the set of speed limits between 35 mph and 65 mph in multiples of 5 mph. At any instant in time, the speed limits of adjacent gantries must not have a speed reduction in the direction of travel by more than 10 mph. To minimize the difference between posted speed limits upstream of the slowest point and the observed speeds at those locations, while adhering to the speed reduction constraint, the limits are often increased in 10 mph increments in the upstream direction.

In practical implementations such as the planned deployment on I-24, sensors are located near each gantry to allow reliable matching of the posted speed limit to the observed speed at the slowest point. Additional rules govern how the slowest speed on the roadway triggers activation of the algorithm, and further refinements are used in complex settings in which multiple slow points on the roadway occur simultaneously.

The goal of the LCS system is to inform drivers of downstream lane closures. The system displays one of three symbols above the lanes of travel on an overhead gantry to indicate the status of the lane. The symbols and their use are determined by the Federal Highway Administration's *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD). Per MUTCD, a steady downward green arrow indicates the lane is available for use, while a red "X" indicates the lane is closed. A yellow "X" indicates the lane is closed ahead and the user is to vacate the lane. These symbols are implemented in a set of logical rules that are applied on three gantries upstream of a crash. If one or more lanes are obstructed (e.g., due to a crash) the gantry immediately upstream of the crash displays a red "X" above the closed lane(s), and green downward arrows above all other lanes. The next gantry upstream displays a yellow "X" above the lanes corresponding to a red "X" on the downstream gantry, and green downward arrows above all other lanes. The third gantry upstream of the incident repeats the symbols displayed on the second gantry. The 4th and 5th gantries upstream will display the speed limit as determined by the VSL algorithm. Additionally, the gantry downstream of the incident will show all green arrows to indicate all lanes are open. These rules work well for roadways that maintain a fixed number of lanes through the corridor and when the gantries are evenly and densely spaced (e.g., such as every 0.5 miles).

C. Performance metrics

The following performance metrics are used to evaluate the effectiveness of the control strategies under the set of scenarios defined in the next section. We select different metrics as mobility and safety indicators. Some of the measures are only available at the microscopic level, and consequently can only be evaluated in micro-simulation. These measures are useful to better understand the consequences of the deployed systems. Other measures can be readily computed from sensor data, such as inductive loops or radar units that measure aggregate traffic information on the freeway.

We consider the following mobility measures:

- *Total time spent:* Let the number of vehicles on the roadway at discrete time k be denoted N_k, and ΔT represents a discrete time step. The *total time spent* (TTS) is computed as:

$$TTS = \Delta T \sum_{k=1}^{K} N_k. \tag{1}$$

- *Bottleneck throughput:* The bottleneck throughput measures the average throughput of vehicles passing the incident. Let k_{start} denote the start time of the incident, and k_{end} denote the first time at which the incident is no longer present.

$$Q_{\text{bottleneck}} = \frac{1}{k_{\text{end}} - k_{\text{start}}} \sum_{k=k_{\text{start}}}^{k_{\text{end}}-1} Q_k, \tag{2}$$

  where Q_k is the bottleneck throughput at time k.
- *Average travel time:* The average travel time $\bar{\tau}$ of all vehicles that have finished their trip during the simulation.
- *Total stopped time:* Let S_i denote the number of (near) stops experienced by vehicle i as it travels the route. A stop is initiated for a vehicle when the vehicle velocity drops below 4 mph, and the stop terminates when the vehicle velocity exceeds 7 mph. The total stopped time is simply the total duration of stopped time summed across all vehicles in the simulation.

The following surrogate safety measures are introduced:

- *Total number of stops*: The total number of stops simply counts the number of (near) stop events that occur per vehicle, and sum across all of the vehicles. A stop event is defined identically as in the total stopped time mobility measure.
- *Coefficient of variation in speed*:
  Let the speed of traffic at sensor location j at timestep k in lane l be denoted v_{jkl}. Let $\bar{v}_{jkl}$ denote the upstream average speed in lane l, averaged over the J sensors upstream of sensor j at time k. Similarly, let σ_{jkl} denote the standard deviation of the speed in lane l computed over the J sensors upstream of j at time k. The number of sensors J is fixed as a parameter, i.e., we compute over the $J = 3$ upstream sensors. We define the one-sided coefficient of variation of the sensor at j at timestep k and lane l as:

$$CV_{jkl} = \begin{cases} \frac{\sigma_{jkl}}{\bar{v}_{jkl}} & \text{if } v_{jkl} \geq \bar{v}_{jkl} \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

  The intuition for (3) is that if the speed in lane l at sensor j at time k is lower than the upstream average speed, then drivers will encounter slower traffic at j, and the variation of the speed profile is important. On the other hand, if the speed is increasing at j relative to the upstream average, then the spatial variation of the speed profile is not important.
  To aggregate the one-sided coefficient of variation, we first average across the lanes to get a lane-averaged

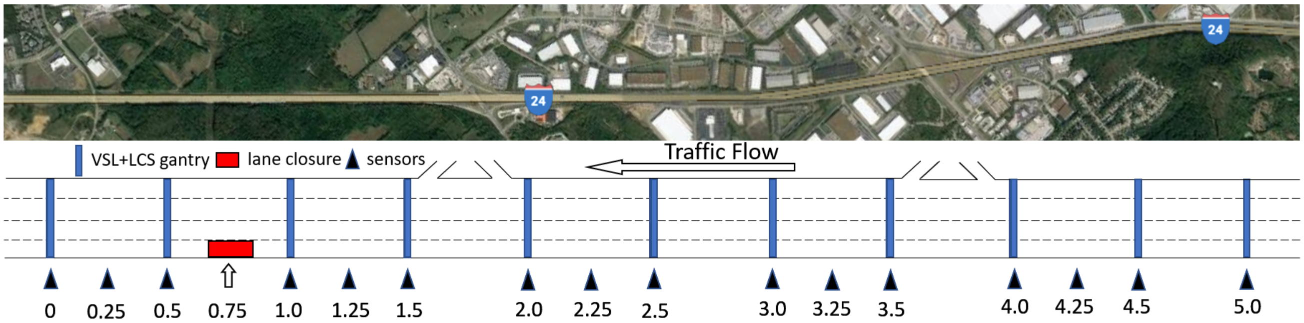

Fig. 1. Simulation stretch from I-24 map and the mile marker of sensors, gantries and lane closure.

CV, denoted CV_{jk}. To produce a single measure of the coefficient of variation over time and space, the lane averaged CV_{jk} can be summed over all sensor locations j and all timesteps k. To further emphasize the importance of large lane averaged CV_{jk} in the sum, we use a thresholded summation as our measure:

$$CV = \sum_j \sum_k (CV_{jk})_{>0.2} \tag{4}$$

where $(x)_{>0.2}$ returns the value x if $x > 0.2$, and 0 otherwise.

III. SYSTEM MODELING

In this section, we briefly introduce the experimental scenario modeled in the simulator. TransModeler is used as our stochastic micro-simulator primarily because of the included comprehensive set of features for simulating incident-based non-recurrent bottlenecks. The second reason is the extensive Python API that allows customization of speed limits and lane use signs, facilitating the implementation of VSL and LCS control strategies.

A. Corridor under study

As preparation work for the I-24 SMART corridor project, this study considers a 5 mile stretch in the westbound direction starting from the intersection of Sam Ridley Pkwy West, Nashville. Two ramps present along this stretch are included in the developed model for the stretch. The simulation starts at 7:50 AM and ends at 10:00 AM including a 10-min warm period to prevent loading effects. Traffic inflow is set to 1800 vehicles per lane per hour and remains constant over the entire simulation period. The on-ramp inflow from upstream to downstream is set as 0.6% and 0.5% of the total traffic flow, respectively.

Most studies evaluating the effectiveness of VSL strategies only consider a small number of devices, which may have resulted in VSL systems not being used to their fullest potential. For this reason, the I-24 SMART corridor will set up gantry structures at 0.5-mile intervals, each containing VSL and LCS signs, colocated with a roadside RDS unit. The posted speed applies to all lanes and is enforceable. In this study, speed limit signs and lane use signs in the traffic management tool of TransModeler are used to represent VSL and LCS, where the speed limit sign is effective for all lanes but lane use sign is lane-based. The sensors in the road editor are used to represent the RDS stations measuring traffic characteristics every 30s.

B. Simulated incidents

This paper considers incidents causing the leftmost lane closure since this is one of the most common incident types along the corridor under study. Usually, most crash-caused incidents have police and emergency vehicles attending on-site so there is a certain clear space for the incident lane upstream. Therefore, our incident parameter has a length of 300 ft to consider the aforementioned situation. The incident starts from 8:20 AM and lasts for 20 minutes, which is also a typical duration for incidents in the corridor. Finally, we locate the incident 0.75 miles upstream from the end of the network in order to understand the downstream effects. The network details are shown in Figure 1.

C. Compliance rate

In TransModeler, we set a VSL compliance rate that determines the proportion of vehicles that will not, even when given the opportunity, exceed the speed limit for a road segment (except for the period of time required to slow down on a new road segment or when speed limits change). All vehicles attempt to travel at their maximum allowable speed and other factors affecting compliance rate are removed from the TransModeler simulation. We define six VSL compliance rate scenarios — 2.5%, 5%, 25%, 50%, 75% and 100% compliance — and test the effectiveness and traffic impacts of VSL across 25 simulation runs of each rate. The low compliance rates of 2.5% and 5% are tested to investigate the impact of very few compliant drivers on overall traffic, which is a common obstacle in ATM deployments.

A separate compliance rate is available for LCS, which we set at 90% for all simulations using LCS, since we expect this to be generally high on the corridor of study.

IV. NUMERICAL SIMULATIONS AND RESULTS

In this section, we present a performance comparison of VSL and LCS for mainstream traffic control under different drivers compliance rates and investigate the roles that VSL and LCS play in terms of improving mobility and safety.

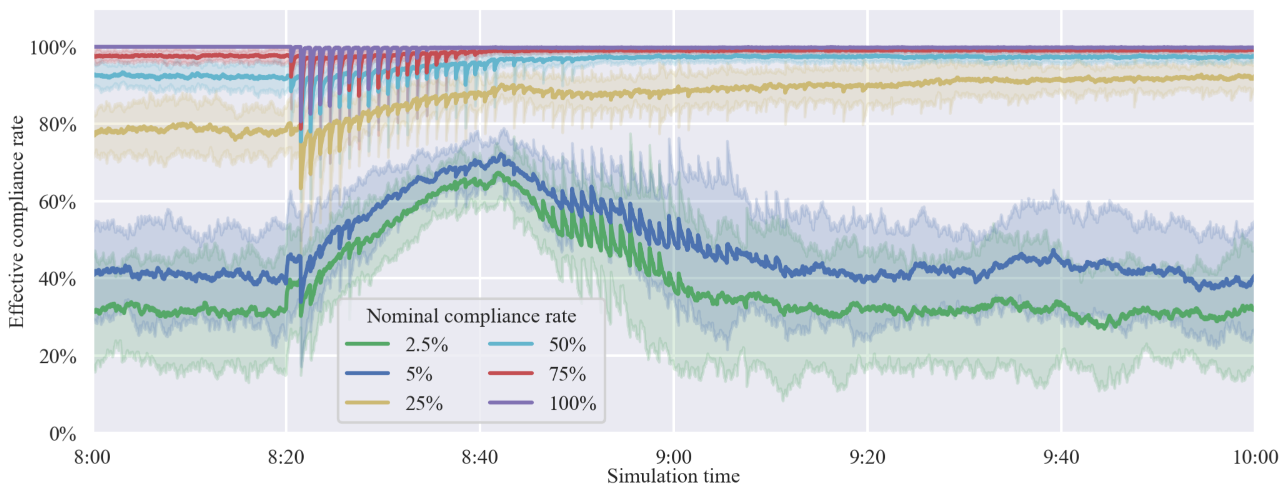

Fig. 2. Effective compliance rate over time of combination control scenarios with VSL compliance rate of 2.5%, 5%, 25%, 50%, 75% and 100%. *Note: the shaded area represents the interval within two standard deviation from the mean effective compliance rate of 25 simulations; sudden drops in effective compliance can be attributed to vehicles changing speed on a new road segment or when VSL signs updates.*

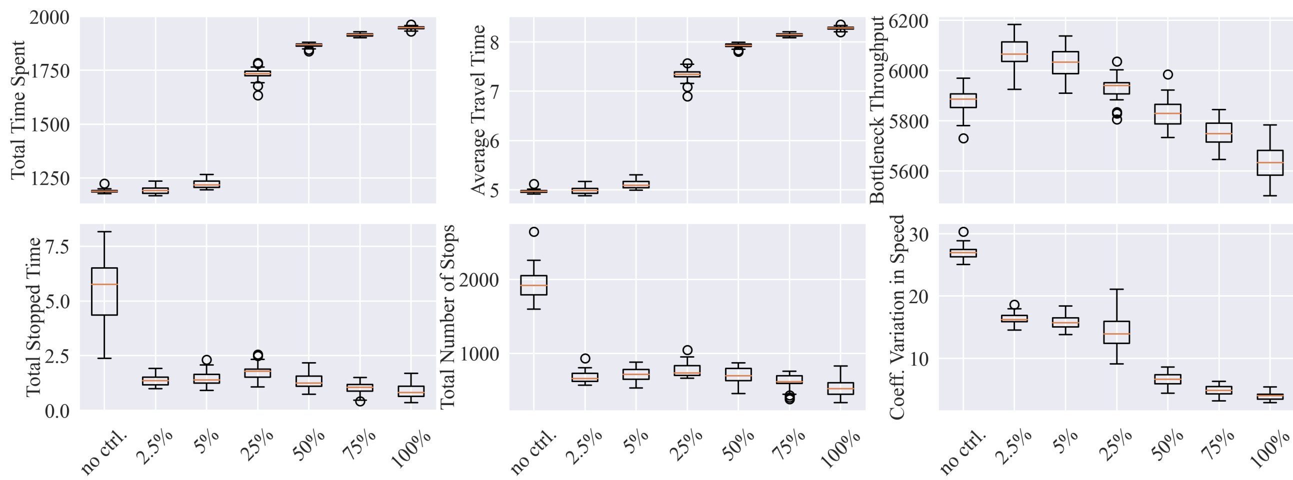

Fig. 3. Traffic measures under no control baseline scenario and LCS+VSL control scenarios with speed compliance rates of 2.5%, 5%, 25%, 50%, 75% and 100%.

A. *Effective speed compliance rate*

The compliance rates defined for TransModeler simulations directly affect only the prescribed proportion of vehicles (i.e., 10% compliance rate sets the maximum speed of 1 in 10 vehicles at the posted speed limit). However, the presence of compliant vehicles within the traffic stream limits the ability of non-compliant vehicles to exceed the posted speed. Therefore, we define the *effective compliance rate* to be the observed proportion of vehicles that are traveling at or below the posted speed limit, plus 2% tolerance. Simulations results, shown in Figure 2, demonstrate that effective compliance rate is far higher than the nominal compliance rate. A very low nominal compliance rates of 2.5% results in at least 30% effective compliance rate, a 12x increase; and 5% nominal compliance result in at least 40% effective compliance rate. During the simulated incident (at 8:20 in Figure 2), effective compliance rate increases further. These results highlight the power of a few drivers (1 in 40 or 1 in 20) to have an outsize impact on the overall traffic stream and help realize the benefits of ATM strategies.

Depending on the overall objective of traffic managers, this situation shown for low compliance rates could be preferred. Alternatively, further improvements in safety measures (speed variation and number of stops) can be realized if compliance rates increase and traffic managers are willing to trade off detrimental impacts to mobility measures.

B. *Impact of control on mobility and safety*

Traffic mobility and safety measures are calculated for the 25 stochastic simulations of combined VSL and LCS under each one of the six compliance rates plus the baseline scenario of no control. Figure 3 shows the distribution of each of the six measures over 25 stochastic simulations under these scenarios. We see multiple distinct trends amongst the

TABLE I

THE MEAN (AND STD) OF TRAFFIC MEASURES UNDER NO CONTROL, VSL ONLY, LCS ONLY, AND LCS+VSL (SPEED COMPLIANCE OF 5%).

Scenario	TTS (veh · hr)	Bottleneck Throughput (veh/hr)	Avg. Travel Time (min)	Total Stopped Time (hr)	Total Num. Stops	Coef. Variation in Speed
no control	**1099.32** (8.74)	5878.44 (54.96)	4.97 (0.04)	5.52 (1.59)	1943.20 (234.03)	27.02 (1.07)
VSL	1270.10 (20.76)	5794.68 (56.97)	5.32 (0.09)	5.75 (2.04)	1879.64 (166.14)	19.41 (1.56)
LCS	1148.84 (5.68)	**6225.60** (47.97)	**4.80** (0.03)	1.48 (0.25)	735.76 (68.43)	23.52 (0.82)
LCS+VSL	1221.8 (21.58)	6035.40 (61.35)	5.11 (0.09)	**1.47** (0.35)	**717.56** (93.77)	**15.83** (1.17)

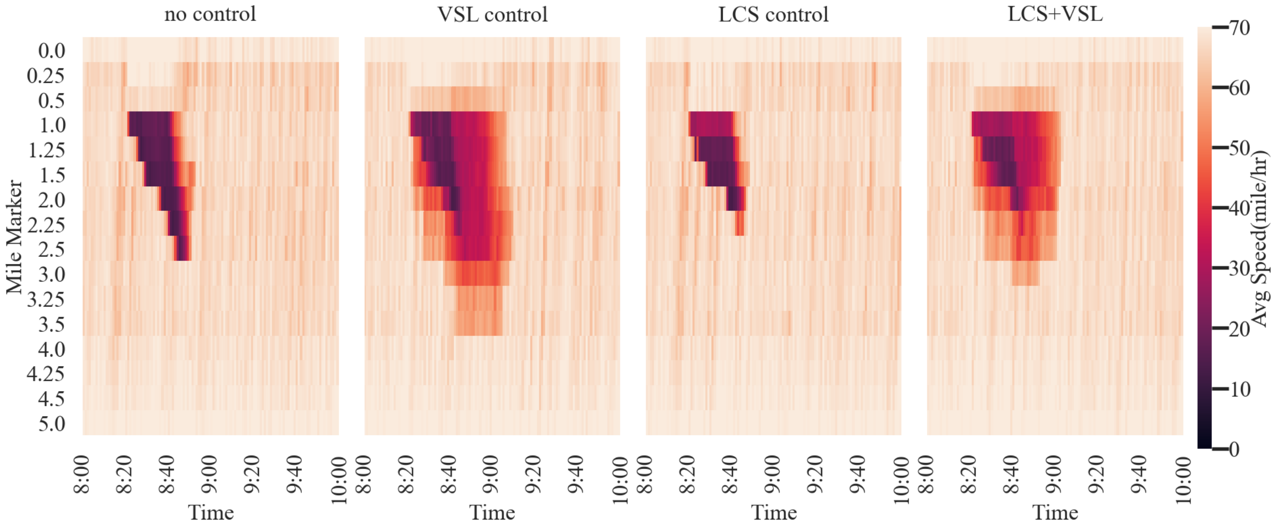

Fig. 4. Time-space diagram of average speed under no control, VSL control only, LCS control only and LCS+VSL control.

response measures: travel time measures show a negative impact at compliance rates of 25% and higher; time and number of stops are improved from baseline at all (non-zero) compliance rates; bottleneck throughput is slightly higher for low compliance rates and decreases below baseline thereafter; and coefficient of variation in speed improves significantly as compliance rate increases.

These results are somewhat mixed. High compliance rates are good for safety measure proxies: stopped time, number of stops, and speed variation, but negatively impact mobility measures: travel time and bottleneck throughput. Low compliance rates are a compromise choice between no control and high compliance – compliance rates of 2.5% and 5% lead to a demonstrable improvement in time and number of stops, speed variation, and bottleneck throughput, while having little to no negative impact on total and average travel time.

C. *Contribution analysis for VSL and LCS*

We now analyze the independent contribution of VSL and LCS that drives the balance and tradeoff of mobility and safety measures discussed previously.

Additional simulations were conducted for scenarios with VSL only and LCS only, and compared with the combined LCS+VSL control and the no control baseline. Compliance rate for VSL is fixed at 5%, which results in a favorable mobility/safety tradeoff as mentioned earlier. Summary results are given in Table I. Indeed, the combined LCS+VSL strategy produces better results in time and number of stops and speed variation, compared to VSL or LCS alone. The results indicate that gains realized in time and number of stops are due mostly to LCS, while reduced speed variation is achieved mostly by VSL. LCS alone is able to slightly reduce average travel time, but LCS+VSL leads to only a small increase over baseline; all control leads to small increases in total travel time. Bottleneck throughput increases under both LCS alone and LCS+VSL.

Overall, we see that VSL and LCS both contribute substantially to gains in safety under joint control, while again leading to only modest compromises in travel time mobility measures.

To further understand the traffic dynamics under these control strategies, we generate the time-space diagrams of average speed recorded by sensors for the no control baseline, VSL only, LCS only, and the combination of LCS+VSL. These diagrams are shown in Figure 4, where the vertical axis represents the length of the roadway (upstream direction is increasing mile markers) and the horizontal axis shows the progression of traffic across time; darker colors indicate lower speeds or stopped traffic. We see that VSL has the effect of smoothing traffic speeds upstream of the incident, which prevents the occurrence of hard breaking events. Recall from Table I that VSL was most responsible for improvements in speed variability. As a consequence, VSL extends the congestion both temporally and spatially. In contrast, LCS control reduces the length of congestion but maintains a hard speed transition. The LCS+VSL combination blends these two effects: it reduces speed variability heading into congestion but incurs less spatial and temporal propagation of lower speeds compared to VSL alone.

V. CONCLUSIONS

This paper implements a micro-simulation to evaluate the effectiveness of VSL and LCS systems under different driver compliance rates during non-recurrent congestion. In general, traffic safety is positively correlated with compliance rate while mobility is negatively related. With a little impact on travel time, the combination of VSL and LCS can improve traffic safety significantly even in low compliance rate scenarios. It is shown that a small number of compliant vehicles can lead to a much higher effective compliance rate. Also, an independent contribution of VSL and LCS analysis demonstrates that using the rule based VSL alone can improve traffic safety but deteriorate mobility. With the help of LCS, the combination control can improve safety without dramatically reducing mobility.

It is worthwhile to note that the results we obtained highly depend on the simulator itself and we may or may not observe the same effectiveness from the real world after deploying VSL and LCS on I-24. The time-dependent nominal compliance rate and constantly-changing driver's behavior, which play an important role in the effectiveness of VSL and LCS system, is hard to be accurately simulated, especially when new traffic control devices are introduced to the corridor. In addition, it is necessary to get a new appraisal of the performance metrics when switching from simulation to the real world because of potential challenges in data collection. In our future work, we intend to evaluate the real world performance of the system when deployed on the I-24 Smart Corridor.

REFERENCES

[1] C. Systematics, "Traffic congestion and reliability: Trends and advanced strategies for congestion mitigation," tech. rep., United States. Federal Highway Administration, 2005.

[2] X.-Y. Lu and S. E. Shladover, "Review of variable speed limits and advisories: Theory, algorithms, and practice," *Transportation Research Record*, vol. 2423, no. 1, pp. 15–23, 2014.

[3] B. Khondaker and L. Kattan, "Variable speed limit: an overview," *Transportation Letters*, vol. 7, no. 5, pp. 264–278, 2015.

[4] M. Abdel-Aty, J. Dilmore, and A. Dhindsa, "Evaluation of variable speed limits for real-time freeway safety improvement," *Accident Analysis & Prevention*, vol. 38, no. 2, pp. 335–345, 2006.

[5] C. Lee, B. Hellinga, and F. Saccomanno, "Evaluation of variable speed limits to improve traffic safety," *Transportation Research Part C: Emerging Technologies*, vol. 14, no. 3, pp. 213–228, 2006.

[6] E. De Pauw, S. Daniels, L. Franckx, and I. Mayeres, "Safety effects of dynamic speed limits on motorways," *Accident Analysis & Prevention*, vol. 114, pp. 83–89, 2018.

[7] Z. Cheng, J. Lu, and Y. Li, "Freeway crash risks evaluation by variable speed limit strategy using real-world traffic flow data," *Accident Analysis & Prevention*, vol. 119, pp. 176–187, 2018.

[8] P.-W. Lin, K.-P. Kang, and G.-L. Chang, "Exploring the effectiveness of variable speed limit controls on highway work-zone operations," in *Intelligent Transportation Systems*, vol. 8, pp. 155–168, Taylor & Francis, 2004.

[9] S. Hoogendoorn, W. Daamen, R. Hoogendoorn, and J. Goemans, "Assessment of dynamic speed limits on freeway a20 near rotterdam, netherlands," *Transportation Research Record*, vol. 2380, no. 1, pp. 61–71, 2013.

[10] M. Papageorgiou, E. Kosmatopoulos, and I. Papamichail, "Effects of variable speed limits on motorway traffic flow," *Transportation Research Record*, vol. 2047, no. 1, pp. 37–48, 2008.

[11] M. Jha, D. Cuneo, and M. Ben-Akiva, "Evaluation of freeway lane control for incident management," *Journal of Transportation Engineering*, vol. 125, no. 6, pp. 495–501, 1999.

[12] Y. Zhang and P. A. Ioannou, "Combined variable speed limit and lane change control for truck-dominant highway segment," in *2015 IEEE 18th International Conference on Intelligent Transportation Systems*, pp. 1163–1168, IEEE, 2015.

[13] Y. Guo, H. Xu, Y. Zhang, and D. Yao, "Integrated variable speed limits and lane-changing control for freeway lane-drop bottlenecks," *IEEE Access*, vol. 8, pp. 54710–54721, 2020.

[14] M. Gregurić, K. Kušić, and E. Ivanjko, "Impact of deep reinforcement learning on variable speed limit strategies in connected vehicles environments," *Engineering Applications of Artificial Intelligence*, vol. 112, p. 104850, 2022.

[15] T. Yuan, F. Alasiri, Y. Zhang, and P. A. Ioannou, "Evaluation of integrated variable speed limit and lane change control for highway traffic flow," *IFAC-PapersOnLine*, vol. 54, no. 2, pp. 107–113, 2021.

[16] T. Yuan, F. Alasiri, and P. A. Ioannou, "Selection of the speed command distance for improved performance of a rule-based VSL and lane change control," *IEEE Transactions on Intelligent Transportation Systems*, 2022.

[17] B. Hellinga and M. Mandelzys, "Impact of driver compliance on the safety and operational impacts of freeway variable speed limit systems," *Journal of Transportation Engineering*, vol. 137, no. 4, pp. 260–268, 2011.

[18] E. F. Grumert, A. Tapani, and X. Ma, "Characteristics of variable speed limit systems," *European Transport Research Review*, vol. 10, no. 2, pp. 1–12, 2018.

[19] L. Wang, M. Abdel-Aty, and J. Lee, "Implementation of active traffic management strategies for safety on congested expressway weaving segments," *Transportation Research Record*, vol. 2635, no. 1, pp. 28–35, 2017.

[20] R. C. Carlson, D. Manolis, I. Papamichail, and M. Papageorgiou, "Integrated ramp metering and mainstream traffic flow control on freeways using variable speed limits," *Procedia-Social and Behavioral Sciences*, vol. 48, pp. 1578–1588, 2012.

[21] Y. Zhang and P. A. Ioannou, "Combined variable speed limit and lane change control for highway traffic," *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, no. 7, pp. 1812–1823, 2016.