Proceedings of the 2024 Winter Simulation Conference
H. Lam, E. Azar, D. Batur, S. Gao, W. Xie, S. R. Hunter, and M. D. Rossetti, eds.

ENHANCING DRIVER BEHAVIOR MODELS IN RESPONSE TO EMERGENCY VEHICLES

Gopikrishnan Nair Suresh Kumar[1], Michael Hunter[1], and Angshuman Guin[1]

[1]School of Civil and Environmental Eng., Georgia Institute of Technology, Georgia, GA, USA

ABSTRACT

Emergency Vehicle Preemption (EVP) is a traffic operation strategy intended to minimize the travel times of Emergency Vehicles (ERVs) in a network. The ripple effects of a disruptive event such as the entry of an ERV are usually seen over a broad area of the traffic network, under medium to heavy traffic conditions. As traffic densities continue to grow, incorporating a robust preemption system is vital in ensuring prompt emergency responses. Preemption systems are often evaluated under naive scenarios in a simulation environment, without consideration of the interactions between ERVs and non-ERVs. This research intends to develop ERV and non-ERV driver models to enable realistic simulation of such interactions. The findings show large differences in the simulated performance metrics reported on standard simulation platforms with and without the incorporation of realistic driver behavior.

1 INTRODUCTION

As cities continue to evolve, the congestion on the roads has also seen a meteoric rise. The Global Traffic Scorecard published by INRIX estimates that the average driver in the United States loses 51 hours in congestion annually (INRIX 2018). The resulting impacts on the network compounded by the constraints of the existing infrastructure have led to the development of real-time traffic operation management methods for congestion mitigation. Emergency Vehicle Preemption (EVP) is one such strategy that has both operational and safety benefits. Preemption refers to an active change in the signal cycle at a signalized intersection with a goal of allowing an emergency vehicle that is approaching the intersection to traverse the intersection with the least amount of travel time delay.

Emergency response vehicles (ERVs) such as fire engines and ambulances are not subject to the standard rules and regulations on the road. When responding to an emergency, these vehicles, e.g., have the freedom to travel at higher speeds, traverse red lights at intersections, or use shoulder lanes to bypass stopped traffic. These maneuvers are undertaken to shorten the delays they may face due to the congestion, but such actions always come at the risk of endangering other road users. Thus, the benefits of EVP are twofold: reduced response times and increased safety. A timely signal change to green on the intersection approach relevant to the ERV could clear out queues on that intersection approach, thereby reducing travel times for the ERV as well as facilitating a safe path for the ERV across the intersection (FHWA 2006) by avoiding ERV maneuvers such as crossing the center-line or traversing the intersection on red.

Studies on preemption strategies typically try to find an optimum time to interrupt the signal cycle. There are relatively few studies that delve into different methods of actuation that would minimize the impact on general traffic while improving ERV travel times (Shaaban et al. 2019; Obrusník et al. 2020). The various algorithm alternatives are commonly modeled on a microscopic simulation platform and are compared with appropriate metrics. The simulated approach of the ERV is generally similar, with a preempt call being placed to the signal controller either dynamically or from a fixed detector. The resulting effects of the ERV on the network can be quite diverse in nature. It is to be expected that the presence of an ERV will invoke some level of response from the vehicles in its vicinity. Vehicles may attempt to pullover, creating a path for the ERV to pass through. This path of least resistance would contribute to alleviating the

ERV delay to some extent. This paper presents an attempt to model these interactions and quantify their impacts so that effects of preemption can be accurately reported.

2 BACKGROUND

In general, most transportation microscopic simulation models comprise of a number of vehicle classes with different driving characteristics. However, for studying EVP, vehicle class driving behaviors may need to change drastically. When an ERV is introduced into the network, it is necessary to model two distinct driving behaviors: the ERV driver behavior and the non-ERV driver behavior. The non-ERV vehicles will respond to the presence of an ERV by trying to "pullover" so as not to hinder the ERV's movement. Depending on the current position of the vehicle, they may try and pull over to the shoulder lane or to the neighboring right lane. These interactions can significantly alter ERV and non-ERV performance, with changes in the delay experienced by both vehicle types. Evidence in this regard could be seen in the survey conducted in Germany (Weinert and Düring 2015) to evaluate the risks that may arise from non-ERV responses to the presence of emergency vehicles. Two hundred and fifty-two drivers of various emergency services responded that the non-ERV interactions are critical in such situations and their actions can affect necessary ERV behavior. In follow-up studies, Weinert et al. (2019) utilized survey and video data to establish that people have vastly varying reaction times in response to ERVs. More recently, Cortes and Stefoni (2023) attempted to simulate a realistic behavior model using video data.

Several simulation platforms have been utilized to model the interactions between ERVs and the general traffic. Zhang et al. (2009) employed the CORSIM™ platform to model the driving behaviors of non-ERVs in conjunction with ERV movement logic. Weinert et al. (2019) leveraged the open-source SUMO® platform for their analysis. Additionally, Cortés and Stefoni (2023) conducted their study using the PARAMICS simulation platform. A majority of the studies employ some version of a Vehicle-to-Infrastructure (V2X) or Vehicle-to-Vehicle (V2V) communication system (Buchenscheit et al. 2009; Savolainen et al. 2010; Lidestam et al. 2020). This greatly affects how drivers may react as the increased awareness may result in more ideal responses.

This study models the behaviors on PTV-VISSIM® and takes advantage of its External Driver Models (EDM) component (PTV 2021) to control non-ERV vehicle movement during ERV response. To maintain a more baseline comparison, no V2V or V2X communications are assumed for the non-ERV traffic in the current study. As the focus of this study is on the development of preemption strategies without any assumptions of V2V communications, this study simply assumes that the signal controllers can communicate with each other and are aware of the location of the emergency vehicle and its response status, which is generally feasible with current field deployed technologies.

While traffic signal preemption systems offer significant advantages, there are challenges associated with their implementation. While long preemption hold times can ensure minimal delays for ERVs, it is necessary to identify the minimal hold time required for minimal ERV delays, to ensure that the non-ERVs are not unnecessarily penalized. The current study develops the driving behavior models required to facilitate development of realistic simulation models of ERV scenarios that will provide a more accurate rendition of the cost function that needs to be optimized for optimal preemption. This study focuses on the methodology for the implementation of non-ERV driving behavior in response to ERVs based on interviews with ERV operators. The behaviors are not specifically calibrated to a given area, rather the study utilized generally accepted default driving behaviors where appropriate and considers varying non-ERV response levels in the presence of an ERV.

3 STUDY AREA

The driver behavior model development is tested on a simulation of a section of the Peachtree Industrial Boulevard (PIB) located in Norcross, Georgia. The corridor is 6.2 miles in length with signal preemption implemented at eight of the mainline intersections. This provides a sufficiently large simulation with diverse intersection and lane geometries for the EVP and non-EVP driver behavior model development. The simulation was developed on the PTV VISSIM® 2021 platform (PTV 2021) and is pictured in Figure 1 alongside a satellite view. The input volumes and signal plans reflect typical field conditions over a 24-hour period on a weekday (Guin et al. 2023). However, there were no field data distinguishing operations with and without emergency vehicle preemption. Hence, field-specific calibration is not possible.

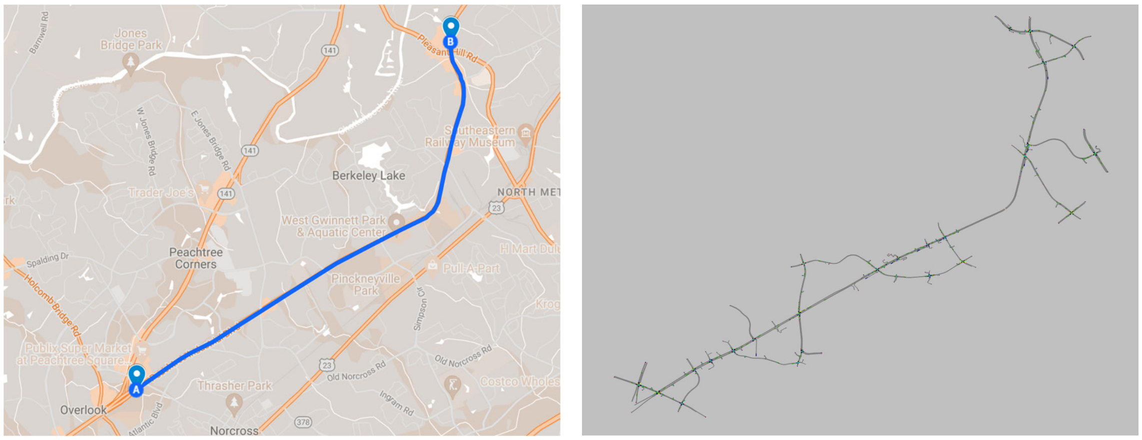

Figure 1. A satellite view of the study area in the Peachtree Industrial Boulevard (left) and the modeled network (right) in VISSIM®.

4 MODEL DEVELOPMENT INPUTS

4.1 Focus Group

Observing and generalizing driver behaviors on roads in the proximity of an ERV can be quite difficult. These events are rather uncommon, and the behavior can be very dependent on road conditions. To approximate such a complex class of behaviors, this study gathered inputs from firefighters and ERV operators to establish reasonable estimates and assumptions about the behavior of ERVs and interactions between ERVs and non-ERVs. A focus group was established and a series of curated questions targeting different areas of ERV and non-ERV behavior were formed and posed to the group. Important distinctions were made to assess non-ERV behavior and ERV behavior separately. The key to modelling driver behavior models is to understand what a realistic response is, rather than an expected one. The discussion with the focus group was primarily intended to assess uncertainties related to driver behavior that can be used to tune the driver behavior model in the simulation to reflect the complex interactions between the ERV and non-ERVs. The following parameters were the focus of the discussion:

- *Response Uncertainty:* How often does an ERV driver observe drivers being reluctant to pullover.
- *Response Distance:* The distance at which non-ERV drivers start to respond to the presence of an ERV.
- *Emergency Vehicle Lane Usage:* The standard operating procedures and the preferred choice of lanes for ERV drivers while responding to an emergency.
- *Level of Compliance:* Percentage or likelihood of non-ERVs to change lanes or make a path for the ERV.
- *Intersection Behavior:* The ERVs maneuver through an intersection can be complex and include the paths used and the standard operating rules to negotiate an intersection, especially when approaching a red signal.
- *Lane Change Delay:* The average time taken for a non-ERV to complete a lane change and potential factors influencing lane changes.

The focus group noted that the level of compliance amongst the non-ERV drivers was generally high. Given enough space and time, most drivers eventually change lanes if it is required to allow the ERV to pass. The ERV drivers reported that non-ERVs would begin their response up to five to ten car lengths downstream. This observation served as the basis for the model to establish an area of impact of an ERVs presence. However, while the compliance rate is high, the time taken to comply may differ. The ERV operators are trained to not apply pressure to vehicles and induce panic among the drivers. The ERV drivers adhere to the maximum speed limits allowed on the road and occupy the leftmost lane wherever possible. Their routing choices attempt to minimize deviations from free-flow speed. Despite the standard protocols that are put in place, the responses of the vehicles and the ERV drivers are also heavily dependent on the physical configurations of the corridor. Under dense traffic conditions, the ERV drivers may exclusively use the shoulder lane to move through the corridor.

4.2 Compliance Delay

The major finding from the focus group discussion was that the compliance seen on roads is indeed close to 100 %. However, compliance is not always instantaneous. There are variable levels of delays experienced before the drivers comply. While it is not possible for the ERV driver to know for sure the reason for delayed response, in certain cases the non-ERV drivers are simply stuck in place with nowhere to go unless the vehicle in front of them or on the next lane makes space available for them to pull over. Since there could be numerous reasons for the delay in compliance, the expectation that all road users will conform to an "ideal pullover behavior" is impractical and was not reported by the ERV drivers.

To make the non-ERV behavior model a closer representation of the real world, a degree of randomness was introduced. An assumption was made to correlate behavioral variation with vehicle speed and, consequently, the current traffic density in the corridor. The study assumed that vehicles are more hesitant and likely to delay pullovers under denser traffic conditions. A speed cutoff of 5 km/h was used for vehicles that delay a lane change in the current circumstances, while vehicles traveling faster than 5 km/h are assumed to seek to pull over as soon as possible, i.e., a non-ERV will not change lanes into another non-ERV. With these assumptions, the level of compliance remains at 100 %, while the time to pull over becomes a vehicle-dependent factor. These assumptions could be readily altered based on field data.

For modelling purposes, for vehicles under 5 km/h, an exponential distribution curve was created to represent pullover delays, assuming a mean of 2.5 seconds and a maximum limit of 15 seconds. However, this distribution disregards any minimum perception-reaction time. To address this, a minimum cutoff (floor) equal to the recommended brake-reaction time (AASHTO 2018) of 2.5 seconds was applied to obtain a modified distribution for the pullover delays (Figure 2). Thus, vehicles take a minimum of 2.5 seconds and a maximum of 15 seconds to initiate a pullover once the conditions are met. The upper cutoff threshold (15 seconds in this example) is subject to calibration for the field conditions specific to future application of the model.

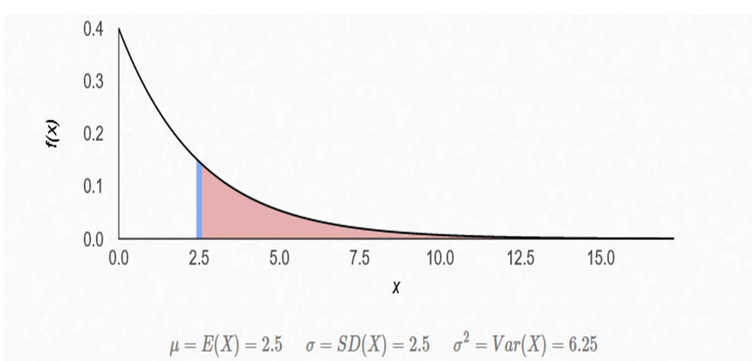

Figure 2. The compliance delay distribution,

5 SIMULATION ENVIRONMENT

5.1 Design Considerations

The behavior models are designed to be transferable with customizable features. The key functional requirements were identified prior to modeling, and these served as guides for the model development.

- *Generalized Framework:* The ERV driver model needs to provide the capability and flexibility to augment existing PTV-VISSIM® model scenarios. The use of the ERV driver model should not be limited by the physical configuration of the system or network used in the testbed simulation scenario. The ERV driver models must be able to navigate diverse types of roads and interact with different traffic flow conditions. Moreover, the behavior should be defined by constraints and parameters whose values are modifiable based on observed data from the field.
- *Primary Maneuver:* Non-ERV pullover behaviors are the most commonly observed maneuvers in scenarios involving an ERV. Although an ERV may execute extreme maneuvers such as crossing over the centerline and traveling in the opposing lane, these are relatively rare maneuvers. The ERV and non-ERV behavior models need to support the primary maneuver at a minimum.
- *Efficient Implementation:* The addition of ERV and non-ERV driver models should not be heavily detrimental to simulation performance. As PTV-VISSIM® offers a few different ways to approach driver behavior modeling with varying levels of control and vastly different runtime performances, it is important to identify and implement an efficient approach.

5.2 Simulation Components

5.2.1 Simulation Platform

After consideration of several alternatives, PTV-VISSIM® was selected for development. The presence of an active and collaborative user community as well as the maturity of the platform were seen as significant benefits. VISSIM®'s detailed documentations and seamless implementations of network- and vehicle-related Application Programming Interfaces (APIs) also made it more approachable.

5.2.2 External Driver Model

External Driver Models (EDMs) serve as supplementary components designed to extend the functionalities of PTV-VISSIM®, providing users with increased control over fine-tuning vehicle-specific behavior. EDMs provide a more nuanced level of control to the microscopic interactions that can be induced in the model. As these can be defined separately for each class of vehicles, two EDMs were created for handling the ERV and non-ERV vehicles, respectively. The implementation of these EDMs involves the utilization of C++ for model development, which is integrated into PTV-VISSIM® as Dynamically Linked Libraries (DLLs). To illustrate the connection and data exchange between PTV-VISSIM® and the EDMs, a visual representation is presented in Figure 3.

The External driver model function provides a way to replace the internal default driver behavior in PTV-VISSIM®. At every timestep, VISSIM executes the EDM code for each specified vehicle class. VISSIM sends information regarding the vehicle and the neighboring environment to the DLL. The implementation in this study uses this information to perform checks related to distances between vehicles and the vehicle's location to determine if any vehicle maneuver response is necessary (discussed in Section 6). If the conditions satisfy the user-defined thresholds, the EDM selects an appropriate maneuver and sends the signal to VISSIM to execute it. Once VISSIM receives the signal, it follows the instructions as long as it does not violate the network design boundaries. The model in this study is primarily capable of sending instructions for lane changes and acceleration corrections. If the conditions are not met, the EDM does not send back any signal to execute an action and can simply pass along any data that the user may deem useful.

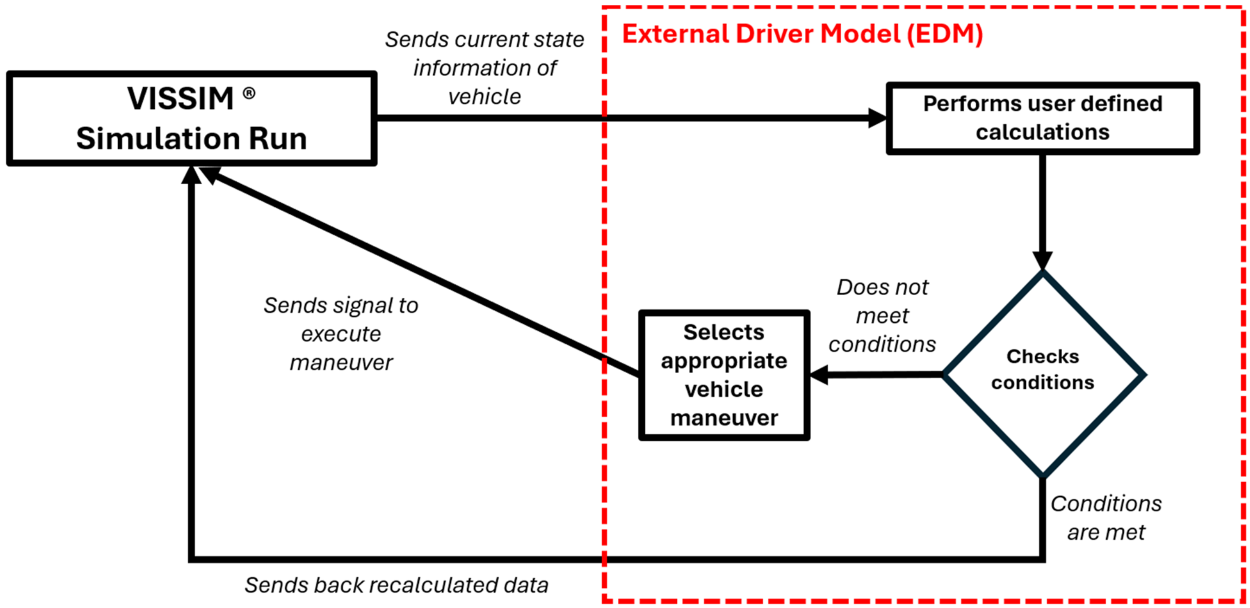

Figure 3. The driver model architecture within VISSIM.

5.2.3 COM

The Component Object Module (COM) allows interaction with and modification of VISSIM objects during runtime using scripts. Network inputs such as volumes, turn counts, or signals can be dynamically imported at will. The scripts for the model were developed in Python 3.

6 MODEL FEATURES

In the modelling process, several assumptions were made to facilitate implementation, accompanied by overarching guidelines for clarity and coherence. These assumptions are enumerated below, with accompanying guidance wherever feasible:

- *Area of Effect:* Each affected vehicle class is assumed to perceive its surroundings within a limited area, encompassing two vehicles ahead and behind, as well as two lanes on either side. The range can be increased by introducing new indices and increasing perception (Figure 5).
- *Distances*: The initiation of pullover behavior is contingent on the proximity of vehicles to the ERV. Upon detecting an ERV within 150 feet, vehicles are directed to execute a lane change to the right. Conversely, the action of rejoining the lane is executed only when a minimum distance of 330 feet is observed (Figure 4).
- *Speeds*: The ERV models adhere to a customized desired speed distribution, generally not exceeding 10 kph over the speed limit. The desired speeds are user-dependent, allowing a custom speed distribution to be incorporated into the model for flexibility.
- *Shoulder Lane Behavior*: In instances where a shoulder lane exists in the model, vehicles pulling over from the right-most lane are expected to come to a complete stop.
- *Separate EDMs*: To accommodate the differences in expected behaviors of general vehicles (non-ERVs) and ERVs, a decision was made to model them separately. Thus, two distinct vehicle-type-specific EDMs were created and set to operate in parallel at every timestep.

In summary, these assumptions establish a solid foundation for the modeling process. Flexibility in parameter adjustment and adherence to the specified conditions enhance the model's accuracy in simulating pullover behaviors and the interactions of ERVs with other vehicles on the road.

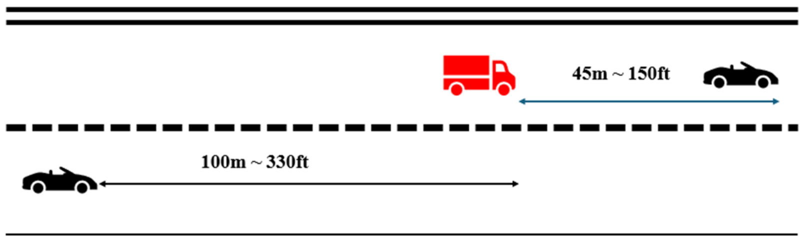

Figure 4. The minimum distance limits for pulling over and remerging.

V(2, 2)	V(1, 2)		V(-1, 2)	V(-2, 2)
V(2, 1)	V(1, 1)		V(-1, 1)	V(-2, 1)
V(2,-1)	V(1,-1)		V(-1, -1)	V(-2,-1)
V(2,-2)	V(1,-2)		V(-1,-2)	V(-2,-2)

Figure 5. The observable boundary for each vehicle and relative coordinates; V (x,y) = Neighboring vehicles (x =relative lane number, y = relative upstream/downstream position).

6.1 Pullover Model Algorithm

The algorithm is designed around the primary constraint that each vehicle can see two lanes to its left and right. Each of the neighboring vehicles is then assigned separate global variables, which are used to store their position, speed, and unique vehicle identifier. Prior to each simulation run, the random seed and the compliance delay curve parameters are also defined. The distribution is described by the average time prior to initiation of pullover request and the cutoff limits for the pullover delay. At every timestep, each vehicle checks its surroundings for the presence of an upstream ERV (1). If the conditions are met, the EDM sends a signal to PTV-VISSIM® for initiating a lane change maneuver to the right (4,2). If the vehicle is already in the right-most lane, the vehicle will pull over to the shoulder lane and come to a complete stop (5). Vehicles in other lanes will move down one lane to the right and keep moving as allowed by the traffic conditions on the road segment. The time taken to initiate the move is determined by sampling from the compliance distribution (3). The vehicle waits until this time elapses before it begins the lane change. Once the lane change is completed, each vehicle waits until the ERV has passed and a minimum distance has been achieved between the vehicle and the ERV, before attempting a merge back to its original lane (6). This condition is also checked by vehicles which have not performed a lane change but within range and in the neighboring lane of an ERV, should they seek to change lanes to achieve a higher speed.

The model is governed by the equations described below. At each timestep of the simulation run, several vehicle-specific variables are initialized. These include variables for their IDs, types, lane numbers, and speeds. Relative position variables are also assigned to neighboring vehicles, as specified in Figure 5, allowing them to perceive each other's presence. Finally, the compliance delay conditions in Figure 2 are also specified.

- Vehicle ID = V_i; Vehicle Speeds = S_i; Vehicle Lane numbers = L_i, Vehicle Types = T_i
- Distances between vehicle and ERV = $X_{i\text{-}ERV}$ (meters)
- Neighboring vehicle IDs relative to focus vehicle = $V_{j,k}$
- $G(\sigma,\mu)$ = Delay Distribution; R = Random draw from the delay distribution

$$ProximityCheck(x) = \begin{cases} \mathbf{1}, \ if \ \mathrm{T}_{0,\mathrm{k}} = \mathrm{T}_{\mathrm{ERV}} \ \ and \ \ 0 \leq \ |\mathrm{X}_{\mathrm{i-ERV}}| \leq \ 45, \ \mathrm{k} \in [-2,-1] \\ \mathbf{0}, \ \text{otherwise} \end{cases} \tag{1}$$

$$ActiveLaneChange\ (x, y) \ = \begin{cases} \textbf{Executes lane change to left after 'y' Delay}, \ if \ x = \ 1 \\ \textbf{Executes lane change to right after 'y' Delay}, \ if \ x = -1 \\ \textbf{Does not execute lane changes}, \ if \ x = \ 0 \ (Default\ Value) \end{cases} \tag{2}$$

$$ComplianceDelay(x) = \begin{cases} \left(\boldsymbol{R} \sim \boldsymbol{G}(\boldsymbol{\sigma}, \boldsymbol{\mu})\right), \ \ if \ \mathrm{S_i} \leq 5 \ \mathrm{km/h} \\ \mathbf{0}, \ \text{otherwise} \end{cases} \tag{3}$$

$$LaneChangeSignal(x) = \begin{cases} \boldsymbol{ShoulderLane}(\boldsymbol{x}), \ \ if \ \mathrm{ProximityCheck(x)} \ = \ 1 \ and \ \mathrm{Li} \ = \ 1 \\ \boldsymbol{ActiveLaneChange}(-\mathbf{1}), \ \ if \ \mathrm{ProximityCheck(x)} \ = \ 1 \ and \ \mathrm{Li} \ != \ 1 \\ \mathbf{0}, \ \text{otherwise} \end{cases} \tag{4}$$

$$ShoulderLane(x) = \{[\boldsymbol{ComplianceDelay}(\boldsymbol{x}), \boldsymbol{ActiveLaneChange}(-\mathbf{1}), \boldsymbol{S_i} = \mathbf{0}\ ]\} \tag{5}$$

$$Remerge\ Allow(x) = \begin{cases} \mathbf{0}, \ if \ \mathrm{T}_{1,\mathrm{k}} = \mathrm{T}_{\mathrm{ERV}} \ and \ \ 0 \leq \ |\mathrm{X}_{\mathrm{i-ERV}}| \leq \ 100, \qquad k \in [-2,2] \\ \mathbf{1}, \ \text{otherwise} \end{cases} \tag{6}$$

7 RESULTS

7.1 Simulation Runs

Two variations of the simulation model were created for the different default preemption exit strategies available in PTV-VISSIM®'s Ring Barrier Controller (RBC) traffic signal controller, namely, Normal exit and In-Step exit. More details about the development of the preemption strategies are available in the study by Roy (2023). A total of 160 simulations runs were conducted on each of the developed models. The only controlled varying factor between each run was the entry time of the ERV (32 variations) into the network and the random seed for replicate runs (5 per entry time). The runs used approximately one hour for warm-up before any ERV was introduced.

7.2 No Pullover Versus Idealized Pullover

This study made a key assumption regarding the compliance delay and its probability distribution curve. In an ideal world with highly cooperative road traffic, drivers would instantly pull over as soon as the initial perception conditions are met. As the model aims to be a realistic reflection of the interactions on the roads, it is important to quantify the difference between an ideal scenario and a practical scenario. A comparison between these two scenarios is performed with simulation runs using a realistic assumptions model and an idealized pullover model. The idealized pullover model executes an algorithm which directs the drivers to instantly execute the lane change, which implies that there is no delay in the initial signal sent to trigger the lane change and when the maneuver is executed. The realistic model assumes a random time value drawn from the delay distribution for the initiation of the lane change, with a lower bound of 2.5 seconds.

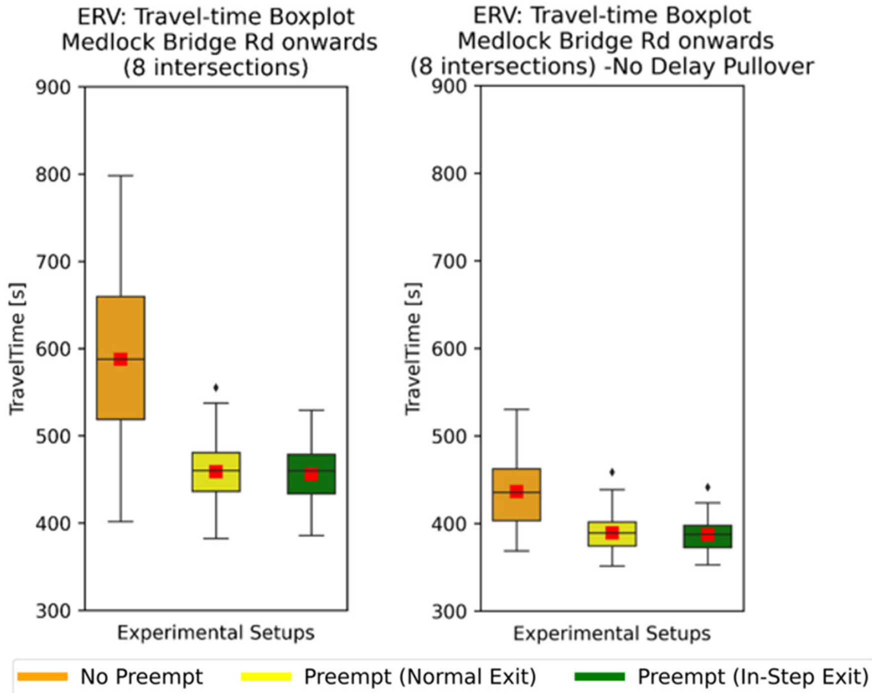

Figure 6. A travel time comparison of the ideal pullover (right) and no pullover case (left).

However, first considered is the ideal pullover versus no pullover (i.e., the default naïve driver behavior in most simulations). The base case scenarios of no-preempt cases were compared to the two preemption cases with differing exit criteria. The ERV travel times across the corridor are used as the primary performance metric. The box plots in Figure 6 show that the difference is significant. In the no-preempt scenarios, a 170 second difference can be seen in travel times when all vehicles cooperate instantly. This accounts for a 28.9 % improvement over the realistic assumption. Without the pullover behavior (the simulation model default), the use of preemption resulted in a 140 second improvement in overall travel times. This improvement diminished to just 45 seconds in the scenario when the vehicles used the ideal pullover.

7.3 No Pullover Versus Realistic Pullover

Next, the realistic implementation of pullover behavior was tested on the preemption models. The ERV travel times aggregated over 160 runs for each scenario are shown in Figure 7. Box plots for the non-ERV travel times have been created for discrete periods of time of length equal to one cycle length and compared for the two scenarios in Figure 8.

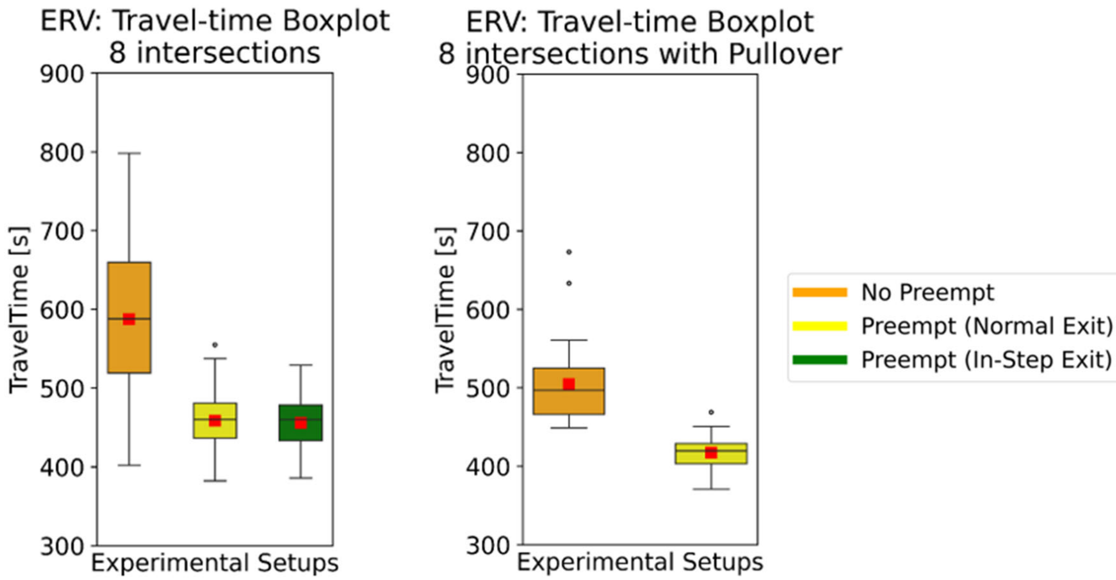

Figure 7. A comparison of aggregated travel times of an ERV with (right) and without (left) pullover.

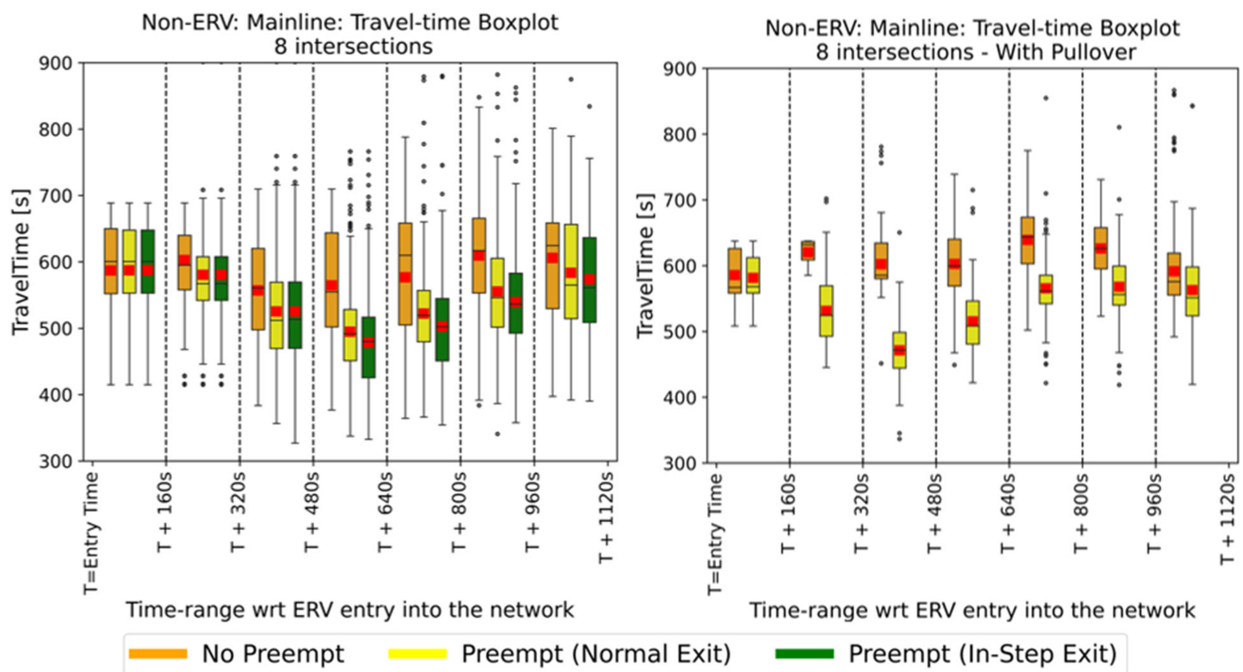

Figure 8. The observed changes to travel times of non-ERV vehicles with (right) and without (left) pullover.

The results illustrated in Figure 7 demonstrate significant ERV travel time improvements across various scenarios following the implementation of the realistic pullover behavior as well. The reductions are slightly less compared to the idealized pullover cases. Between the two no-preemption cases, there is an average reduction of approximately 80 seconds (compared to 170 seconds in the idealized case comparison), while in the preemption scenario, the reduction is around 40 seconds (compared to 45 seconds in the idealized case comparison). Notably, the impact of pullover behavior is more pronounced in scenarios lacking preemption. The inclusion of pullover capabilities not only contributes to ERV delay reduction but also influences the effectiveness of preemption. With pullover enabled, the length of the queue requiring preemption decreases, resulting in a diminished impact of preemption on delay reduction. Furthermore, Figure 8 illustrates that with pullover behavior, there is notably higher disruption for non-ERVs in scenarios without preemption, but with preemption, this disruption diminishes significantly. However, in both cases, with and without pullover, the preemption's impact on non-ERV vehicles tends to dissipate around the 7th signal cycle from the ERV's entry.

7.4 Effect of Minimum Cutoff

In the delay function shown in Figure 2, a value of 2.5 seconds has been used as the minimum time a vehicle may take to start the pullover procedure. This value was chosen to represent the reaction time requirements that are bypassed in the idealized representation. This threshold needs to be calibrated for actual field conditions for use in future research. To explore if the effects of such an assumption are significant as theorized, a set of runs were performed with a model without a 2.5 seconds floor in the delay function. The comparisons provided in Figure 9 show an overall difference of 10–15 seconds in ERV travel times when comparing identical strategy runs with and without the 2.5 seconds floor in the delay function. The delay function with the 2.5 seconds floor, results in a slightly larger travel time for the ERV. The non-ERV travel times are expected to be influenced by the aftereffects of the pullover maneuver itself, and not by the time taken prior to execution, and did not show any difference in response to the two functions.

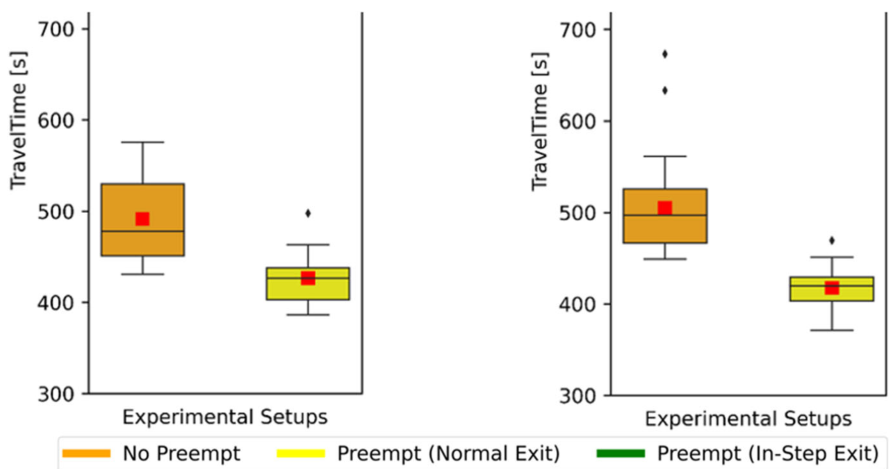

Figure 9. The effect on ERV travel times by introducing a minimum cutoff to the pullover functions. (Left: Without cutoff; Right: With cutoff).

8 CONCLUSION

The findings from this study provide strong evidence that pullover behavior that is typically a mandate in real world traffic has a significant influence on ERV travel times. The perceived benefits of both the pullover models and the preemption strategies are subject to a large variation when modeled simultaneously. While the ideal pullover scenario results in the most significant improvement in travel times, it also attributes a lower value of improvement due to the preemption strategies. This scenario envisions complete compliance and instantaneous traffic flow, creating a corridor with minimal impediments for ERVs. In practice, achieving such a behavior would be rare, and exploring strategies without incorporating a level of realistic pullover behavior into a model would yield flawed results.

While this study had to make several assumptions regarding the values of the parameters used in the model due to the lack of empirical data, the study provides the foundations of the pullover model. The resulting theoretical model can be transferred to any network once the parameters have been calibrated with local data. The developed codes and guides have been made available on GitHub (https://github.com/gtigatech/EVP-EDM). Furthermore, future research should explore more complex scenarios, such as crossovers and intersection negotiations, to enhance behavior models and provide insights into the effectiveness of preemption strategies for emergency response scenarios in different roadway and intersection geometries. By addressing these complexities, researchers can better isolate the actual impact of EVP and develop better response strategies.

REFERENCES

AASHTO. 2018. "A Policy on Geometric Design of Highways and Streets". American Association of State Highway Transportation Officials.

FHWA. 2006. "Traffic Signal Preemption for Emergency Vehicles – A Cross-Cutting Study". US Federal Highway Administration, Report FHWA-JPO-05-010;NTIS-PB2006107709.

Buchenscheit, A., F. Schaub, F. Kargl, M. Weber. 2009. "A VANET-based Emergency Vehicle Warning System". In *2009 IEEE Vehicular Networking Conference, VNC 2009*. Available at https://doi.org/10.1109/VNC.2009.5416384.

Cortés, C.E. and B. Stefoni. 2023. "Trajectory Simulation of Emergency Vehicles and Interactions with Surrounding Traffic". *Journal of Advanced Transportation*. Available at: https://doi.org/10.1155/2023/5995950.

Guin, A., S. Roy, D. Kwesiga, G.N.S. Kumar, and M. Hunter. 2023. "Strategy Analysis and Evaluation for Emergency Vehicle Preemption and Transit Signal Priority with Connected Vehicles using Software in the Loop Simulation". (No. FHWA-GA-23-2203).

INRIX. 2018. "INRIX Global Traffic Scorecard". *INRIX Research*, February. Available at: https://media.bizj.us/view/img/10360454/inrix2016trafficscorecarden.pdf.

Lidestam, B., B. Thorslund, H. Selander, D. Näsman, and J. Dahlman. 2020. "In-Car Warnings of Emergency Vehicles Approaching: Effects on Car Drivers' Propensity to Give Way". *Frontiers in Sustainable Cities* 2:19. Available at: https://doi.org/10.3389/frsc.2020.00019.

Obrusník, V., I. Herman, and Z. Hurák. 2020. "Queue Discharge-based Emergency Vehicle Traffic Signal Preemption". In: *IFAC-PapersOnLine*. Available at: https://doi.org/10.1016/j.ifacol.2020.12.1998.

PTV. 2021. "PTV VISSIM Manual". PTV AG Germany.

Roy, S. 2023. "Emergency Vehicle Preemption Strategies Using Machine Learning to Optimize Traffic Operations". Ph.D Dissertation. Georgia Institute of Technology.

Savolainen, P.T., T.K. Datta, I. Ghosh, and T. Gates. 2010. "Effects of Dynamically Activated Emergency Vehicle Warning Sign on Driver Behavior at Urban Intersections". *Transportation Research Record* 2149:77–83. Available at: https://doi.org/10.3141/2149-09.

Shaaban, K.; M.A. Khan, R. Hamila, M. Ghanim. 2019. "A Strategy for Emergency Vehicle Preemption and Route Selection". *Arabian Journal for Science and Engineering*, 44:8905–8913. Available at: https://doi.org/10.1007/s13369-019-03913-8.

Weinert, F. and M. Düring. 2015. "Development and Assessment of Cooperative V2X Applications for Emergency Vehicles in an Urban Environment Enabled by Behavioral Models". In *Lecture Notes in Mobility*. Available at: https://doi.org/10.1007/978-3-319-15024-6_8.

Weinert, F., M. During, and K. Bogenberger. 2019. "Influence of Emergency Vehicle Preemption on Travelling Time and Traffic Safety in Urban Environments Enabled by Innovative Behavioral Models and V2X Communication – Simulation and Case Study". In: *2019 IEEE Intelligent Transportation Systems Conference, ITSC 2019*. Available at: https://doi.org/10.1109/ITSC.2019.8916890.

Zhang, L., J. Gou, K. Liu, G. McHale, R. Ghaman, and L. Ling. 2009. "Simulation Modeling and Application with Emergency Vehicle Presence in CORSIM". In: *IEEE Vehicular Technology Conference*. Available at: https://doi.org/10.1109/VETECF.2009.5378787.

AUTHOR BIOGRAPHIES

GOPIKRISHNAN NAIR SURESH KUMAR is a Ph.D student in the School of Civil and Environmental Engineering at the Georgia Institute of Technology. His research interests are primarily in the area of connected vehicles and their implementation within simulation models. His email address is gkumar74@gatech.edu.

MICHAEL HUNTER is a professor in the School of Civil and Environmental Engineering at Georgia Institute of Technology. His primary teaching and research interests are in transportation operations and design, specializing in adaptive signal control, traffic simulation, freeway geometric design, and arterial corridor operations.His email is michael.hunter@ce.gatech.edu**.**

ANGSHUMAN GUIN is a Principal Research Engineer in the School of Civil and Environmental Engineering at the Georgia Institute of Technology. His research interests are in freeway operations, connected and autonomous vehicles, intelligent transportation systems, traffic simulation, and Smart Cities. His email is angshuman.guin@ce.gatech.edu**.**