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# Lane-level Traffic Jam Control Using Vehicle-to-Vehicle Communications

Myounggyu Won, *Member, IEEE,* Taejoon Park, *Member, IEEE,* and Sang H. Son, *Fellow, IEEE*

***Abstract*— A traffic jam is one of the most significant social issues of our time. Wasted time and fuel due to traffic congestion causes economic losses not to mention driver's stress. Various kinds of intelligent transportation systems (ITS) techniques have been developed to alleviate traffic jams. Recent research showed that vehicle-to-vehicle communication (V2V) can be used to reduce traffic jams. However, previous ITS-based approaches have not paid full attention to the fact that a traffic jam is a very complicated and dynamic phenomenon often resulting in the heterogeneous intensity of a traffic jam for each lane. In this paper, we propose a lane-level traffic jam control system providing varying driving advisory depending on dynamically measured intensity of a traffic jam per lane. Simulation results demonstrate that our approach has 9% smaller average delay compared with the state-of-the-art approach.**

## I. Introduction

A traffic jam is a serious social problem in many countries. In the U.S., more than 5.5 billion hours have been wasted, which are equivalent to 2.9 billion gallons of fuel costing about $121 billion in 2012 [1]. Situations in European countries are not much different. The vehicle numbers of European nations have sharply increased while the highway capacity has not been commensurate with the growth pace [2]. There have been numerous efforts to alleviate the impact of traffic jams, e.g., building additional highway capacity and rerouting demand for highway travel. However, one of the major causes of traffic jams is often attributed to inefficient use of highways [3], which means that a traffic jam can be reduced if we effectively control the traffic on a congested highway. Fortunately, recent research shows that intelligent transportation systems (ITS) techniques can significantly contribute to the effective usage of a highway resulting in reduced traffic jams [4].

A number of ITS-based approaches have been developed to mitigate the impact of traffic jams [5][6][7]. In particular, connected vehicle (CV) technology has received significant attention due to its potential to address traffic jams. In line of this trend, recently, Knorr *et al.* [8][4] proposed a traffic jam control protocol that effectively alleviates traffic jams with marginal penetration rates. A key idea of their work is to use vehicle to vehicle (V2V) communications to detect a traffic jam, more specifically by computing an average speed of preceding vehicles; upon detecting a traffic jam, based on the three phase traffic theory [9][10], drivers are advised to keep a large headway distance to the preceding vehicle, thereby reducing the impact of "over-deaccleration effect" which is known to worsen a traffic jam.

A particular note is that the state-of-the-art approach relies on the average speed of preceding vehicles [8][4] to determine if a traffic jam exists. However, although a traffic jam can be represented by low average speed, as previous research noted, there exists speed variance between lanes under congestion [11]. In fact, some empirical measurements performed on a highway in Japan [12][13] showed that strong correlation between lanes exist, and the fast lane is often more severely congested than the slow lane, which is referred to as *reverse-lane usage*. Furthermore, the high speed variance between lanes is important because it increases the safety issue on a highway – some research finds that a critical factor that causes the safety problem on a highways is the speed variance rather than the high speed [14].

In this paper, we propose a *fine-grained* approach for reducing a traffic jam aiming at significantly higher performance. Given the observation that notable speed variance exists between lanes, the proposed protocol offers "fine-grained" traffic jam control in the sense that it uses the lane-level average speed of preceding vehicles rather than using the average speed of all preceding vehicles regardless of lanes. Therefore, the proposed protocol is capable of performing a more sophisticated analysis of a traffic jam. Furthermore, a fuzzy inference system is integrated into the proposed control algorithm to cope with the dynamics of a traffic jam and provide various levels of driving advisory depending on the intensity of the traffic jam for each lane. The proposed protocol is rigorously evaluated through simulations, and it is demonstrated that the proposed protocol reduces the average delay by up to 9% in comparison with the state-of-the-art protocol [8][4].

The rest of the paper is organized as follows. In Section II, we review the literature, especially focusing on approaches based on CV technology. We then provide some background knowledge on both the three phase traffic theory and the state-of-the-art solution in Section III. In Section IV, based on the background knowledge, we present the details of our proposed protocol. Section V provides the performance evaluation of the proposed protocol. We then conclude in Section VI.

## II. Related Work

This section reviews previous works focusing on algorithms and protocols developed to reduce traffic jams based on CV technology. Schunemann *et al.* [5] proposed to use CV technology to allow vehicles to share the current local traffic

Myounggyu Won, Taejoon Park, and Sang H. Son are with the Department of Information and Communication, Daegu Gyeongbuk Institute of Science and Technology (DGIST), Daegu, South Korea, e-mail: mgwon@dgist.ac.kr, tjpark@dgist.ac.kr, and son@dgist.ac.kr.

information in order to optimize their routes. They designed an algorithm that provides alternative routes that circumnavigate congested areas. Lakas and Chaqfeh [7] developed a system that effectively detects a traffic jam through vehicle-to-vehicle communications. The information about a traffic jam is disseminated using a flooding-based geocast protocol, and given the information, vehicles compute the best alternative routes using their modified version of Dijkstra algorithm. Narzt *et al.* [6] developed a concept to improve traffic flow based on the pheromone principle of ant colonies, i.e., by modeling vehicles with CV technology as individual insects depositting digital pheromones on the road such that other vehicles make use of the trails to find optimal alternative routes. Unfortunately, these solutions focusing on finding alternative routes do not take into account the secondary traffic congestion on the alternative routes especially when many vehicles are advised to use the alternative routes.

There are more proactive approaches that do not rely on finding alternative routes, i.e., solutions designed to reduce the current traffic jam before it gets worsened by providing effective driving advisory to drivers [15][16][8][4]. Kerner *et al.* [15] proposed an algorithm that advises larger space gap to the preceding vehicle when a traffic breakdown occurs to reduce the traffic jam. In particular, one notable contribution is their test-bed for wireless vehicle communications, which enables the evaluation of their proposed algorithm under the various characteristics of wireless communications between vehicles. Unfortunately, their algorithm is based on an assumption of 100% penetration ratio. Fekete *et al.* [16] proposed a distributed and self-regulated protocol to reduce traffic jams which provides adaptable distributed strategies against traffic jams based on local data clouds formed among vehicles. Their proposed solution guarantees good performance with relatively small penetration rates; however, it still requires more than 60% penetration rates. Knorr and Schreckenberg [8] first proposed an approach that effectively stabilizes traffic flow and reduces a traffic jam with penetration rates of as low as only 5%. In their recent work [4], they also factored in human limitations such as reaction time for adapting driving behavior as well as wireless communication characteristics such as radio propagation, and different mobility models.

## III. Background

### A. Three-Phase Traffic Theory

Traffic flow on a highway can be characterized by space-time transitions between three phases: free flow (F), synchronized flow (S), and moving jam (J) [9][10][17][18]. The F phase has low traffic density, thus allowing vehicles to accelerate/deccelerate arbitrarily. The traffic flow becomes unstable with sufficiently high density and can be easily broken even with small perturbations like sudden stoppage of a vehicle, which usually arises at highway bottlenecks or on/off ramps [9]. Consequently, the F phase is transitioned to S phase when such traffic breakdown occurs and the average vehicle speed is significantly decreased. Within the region of synchronized flow, self-compression (also called as the pinch region), i.e., significantly high local traffic density is observed. In the J phase, the pinch region starts to propagate upstream. Kerner showed that the propagation of a traffic jam can be reduced by providing strong speed adaptation to the vehicles within a synchronized flow [19]. More specifically, drivers are advised to have a larger gap to their preceding vehicles to decrease the probability of further traffic breakdown - if the gap is too small, it is more likely that the following driver performs unnecessarily strong braking maneuver, which causes the chain reaction of braking for the following drivers, resulting in traffic breakdown.

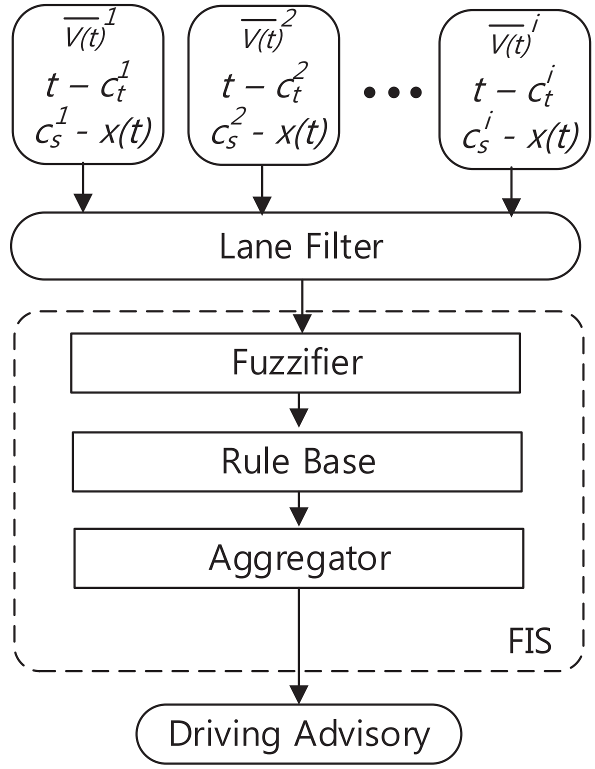
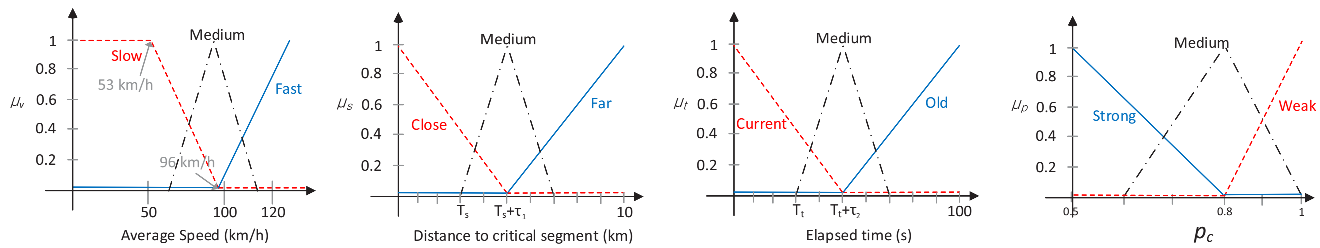



Fig. 1: Overview of proposed solution

### B. Connected Vehicle (CV) Technology

We review the state-of-the-art traffic jam control protocol based on the three-phase traffic theory [4]. In this protocol, a vehicle $i$ periodically broadcasts a beacon message containing its velocity $v_i$, acceleration $a_i$, position $x_i(t)$ at time $t$. Upon receiving beacon messages, vehicle $i$ calculates the average speed $\overline{v}(t)$ of all vehicles ahead. If $\overline{v}(t)$ is smaller than a given threshold $T_v$ more than two consecutive beacon intervals $I$ (i.e., $\overline{v}(t-I) < T_v$ and $\overline{v}(t) < T_v$), the vehicle marks the critical segment by setting $c_t$ as $t$ and $c_s$ as $x_p(t) + \gamma$, where $\gamma$ is the communication range. The information on the critical segment, i.e., $c_t$ and $c_s$ is broadcast through the next scheduled beacon message.

Once a critical segment is determined, vehicles start to adapt their speed if the critical segment is recent and the vehicles are geographically close enough to the critical




(a) A membership function for average speed

(b) A membership function for distance to critical segment

(c) A membership function for elapsed time

(d) A membership function for driving advisory

Fig. 2: Example membership functions designed for general U.S. highways

segment. More specifically, if the following conditions are satisfied:

$$t - c_t < T_t \text{ and } 0 < c_s - x(t) < T_s,$$

where $T_s$ and $T_t$ are the spatial and temporal thresholds, the vehicles are advised to maintain a particular headway distance – note that the thresholds $T_s$ and $T_t$ must be determined depending on highway environments. Knorr *et al.* [4] adopted the Comfortable Driving Model (CDM) [20], which is based on Nagel-Schreckenberg's cellular automation [21], to model the advised driving behavior. In this model, a probability $p$ is introduced to determine the probability of braking.

$$p \leftarrow \begin{cases} p_b & \text{if } l_{n+1} = \text{true AND } t_h < t_s \\ p_0 & \text{if } v_n = 0 \text{ AND NOT} \\ & (l_{n+1} = \text{true AND } t_h < t_s) \\ p_d & \text{otherwise.} \end{cases}$$

where $t_h$ is the time headway; $t_s$ is the interaction horizon; and $l_{n+1}$ is the preceding vehicle's braking status. So $p_b$ is the probability of braking given the preceding vehicle is within the interaction horizon and the preceding vehicle is braking. The probability $p_0$ simulates the *slow-to-start*, i.e., delayed acceleration although there is no obstruction ahead. In other cases, $p_d$ is used as the probability of braking. Knorr *et al.* [4] added $p_c$ to integrate an additional gap $gap_n$ to the preceding vehicle as follows.

$$p \leftarrow \begin{cases} p_b & \text{if } l_{n+1} = \text{true AND } t_h < t_s \\ & \text{AND } gap_n \leq v_n t_r \\ p_c & \text{if } l_{n+1} = \text{true AND } t_h < t_s \\ & \text{AND } gap_n > v_n t_r \\ p_0 & \text{if } v_n = 0 \text{ AND NOT} \\ & (l_{n+1} = \text{true AND } t_h < t_s) \\ p_d & \text{otherwise.} \end{cases}$$

When the additional gap $gap_n$ is smaller than $v_n t_r$, i.e., the distance traveled during the driver's reaction time ($t_r = 1$ in their model), $p_b$ is applied. If the additional gap is greater than the driver's response time, $p_c$ is applied, thereby allowing drivers to brake even if the vehicle maintains longer distance to the preceding vehicle, i.e., creating the "over deacceleration effect".

## IV. Protocol Design

### A. Overview

A vehicle periodically broadcasts a beacon message containing its velocity, acceleration, position, and time similar to [4]. A key idea is to allow vehicles to perform *per-lane traffic analysis*. To achieve this, a beacon message contains an additional field: an index of the lane denoted by $l_i$ that the vehicle currently uses – recent research on vehicular localization supports the idea that a vehicle can find on which lane it is located [22] although current technology requires more work to improve the accuracy. Upon receiving beacon messages at time $t$, using lane indices in the messages, a vehicle can compute the average speed of preceding vehicles for each lane $l_i$, denoted by $\overline{v}(t)^i$. Consequently, if $\overline{v}(t)^i$ is smaller than the threshold $T_v$ more than two consecutive intervals, the upstream front location of the critical segment $c_s^i$ for lane $l_i$, and the timestamp for the critical segment $c_t^i$ for lane $l_i$ are computed and broadcast.

The proposed protocol not only detects a traffic jam separately for each lane, but also provides different driving advisory for the different degree of a traffic jam per lane. A challenge is how to differentiate the intensity of a traffic jam. To address the challenge, we adopt the fuzzy logic. More specifically, we fuzzify the parameters used to determine a traffic jam, i.e., $\overline{v}(t)^i$, $t - c_t^i$, and $c_s^i - x(t)$ into membership functions denoted by $\mu_v^i, \mu_t^i$, and $\mu_s^i$ respectively; and instead of comparing the parameters to the thresholds and making a binary decision, we enable the proposed system to evaluate the dynamics of a traffic jam by inputting the fuzzified parameters into our fuzzy inference system, which outputs appropriate driving advisory for vehicles on each lane. An overview diagram is shown in Figure 1.

### B. Fuzzy Inference System

In this section, through an example, we present the details on how the fuzzy inference system is applied to provide a vehicle with varying driving advisory depending on different intensity of a traffic jam. More specifically, we present an example design of the fuzzy inference system focusing on general U.S. highways.

The design of membership function $\mu_v^i$ is first discussed. We differentiate the average speed into three linguistic terms

TABLE I: An example rule base

| | Avg. Speed | Distance | Time | Driving Advisory |
|---|---|---|---|---|
| Rule 1 | Slow | Close | Current | Strong |
| Rule 2 | Slow | Close | Medium | Strong |
| Rule 3 | Slow | Close | Old | Strong |
| Rule 4 | Slow | Medium | Current | Strong |
| ... | ... | ... | ... | ... |
| Rule 24 | Fast | Medium | Old | Weak |
| Rule 25 | Fast | Far | Current | Weak |
| Rule 26 | Fast | Far | Medium | Weak |
| Rule 27 | Fast | Far | Old | Weak |

– $\{SLOW, MEDIUM, FAST\}$. We refer to [3] to differentiate $FAST$ and $SLOW$ average speed. The report published by U.S. Department of Transportation [23] provides the average speed for the top 25 congested highway locations in U.S. Based on the report, we determine the average speed below which can be always called $SLOW$. We also refer to the speed limit of U.S. [24] to define the average speed over which can be called always $FAST$. Consequently, we get a membership function as depicted in Figure 2a.

Other membership functions are similarly designed. For the design of $\mu_s^i$, three linguistic terms $\{CLOSE, MEDIUM, FAR\}$ are used. To differentiate $CLOSE$ and $FAR$, the threshold $T_s = 3$ km from [4] is adopted, where $\tau_1$ is a system parameter which enables an easy adaptation to various highway environments – refer to the the membership function shown in Figure 2b. Note that threshold $T_s$ is determined based on given traffic environments. The membership function $\mu_t^i$ is designed using three linguistic terms $\{CURRENT, MEDIUM, OLD\}$. The threshold $T_t = 30$s from [4] is adopted to differentiate $CURRENT$ and $OLD$. Similar to the design of $\mu_s^i$, a system parameter $\tau_2$ is employed. Consequently, the membership function is designed as shown in Figure 2c.

Once crisp input values are fuzzified into corresponding fuzzy values using the fuzzifier, the rule-base of FuzzyJam comes into play to determine the level of traffic jam and corresponding driving advisory which is represented using the terms $\{STRONG, MEDIUM, WEAK\}$. An example rule-base is shown in Table I. The fuzzy driving advisory in turn is translated into a corresponding crisp value using the membership function for the driving advisory; as explained in Subsection III-B, the degree of driving advisory is controlled by parameter $p_c$, i.e., smaller $p_c$ means the smaller probability of "overdeacceleration effect", thus representing stronger driving advisory. Figure 2d displays the membership function for the driving advisory. As shown, the membership function selects the suggested value of $p_c$ (i.e., $0.8 \cdot p_b$) by [4] as the boundary value between $STRONG$ and $WEAK$ driving advisory. In addition, for determining the firing strength, we use the commonly used *MIN* method, and for the *aggregation* and defuzzification methods, we use the *MAX* and centroid methods, respectively – due to space constraints, we omit the details of the methods; see [25] for details.

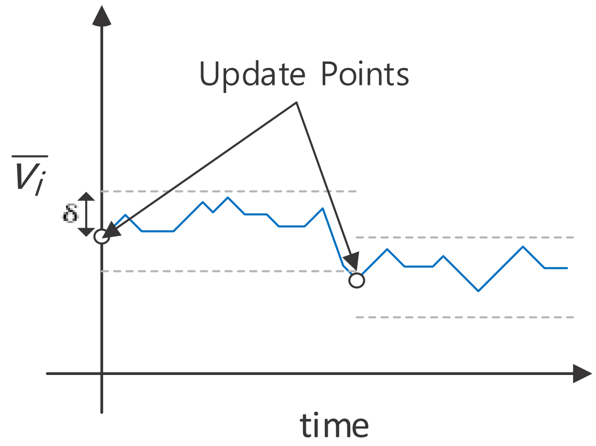



Fig. 3: Illustration of the threshold-based method

### C. Real-time Update

The parameters used to determine the intensity of a traffic jam for each lane, i.e., $\overline{v}(t)^i$, $t - c_t^i$, and $c_s^i - x(t)$ must be updated whenever a new beacon message is received in order to provide an up-to-date driving advisory. However, a challenge is that updating the driving advisory every time a beacon message is received incurs very high computational overhead as shown in Section V. A possible solution is to update the driving advisory periodically, e.g., every 10 seconds. However, this periodic update may miss an important event when the driving advisory must be updated; it may also result in unnecessary update, i.e., updating the driving advisory even though none of $\overline{v}(t)^i$, $t - c_t^i$, or $c_s^i - x(t)$ has been significantly changed.

To address the challenge, in our proposed protocol, a *threshold-based update method* is adopted. More specifically, $\overline{v}(t)^i$, $t - c_t^i$, and $c_s^i - x(t)$ are monitored and compared to the previous *critical values*, i.e., the most recent parameters used for determining the intensity of a traffic jam (e.g., Update Points in Figure 3). When the difference between the current value of a parameter and the critical value is greater than $\delta$ (i.e., defined for each of the parameters), then the parameters are plugged into our fuzzy inference system and new driving advisory is computed. In Section V, we evaluate the impact of $\delta$ (focusing on the parameter $\overline{v}(t)^i$) on the performance of our protocol.

### D. Lane Change

When a vehicle performs a lance change from $l_i$ to $l_j$, the driving advisory for the vehicle must also be immediately changed for the new lane to reduce the impact stemming from using unsuitable driving advisory. In order to achieve this, we allow vehicles to maintain not only the information for the lane that it currently uses, but also the information for other lanes, i.e., keeping $\overline{v}(t)^i$, $c_t^i$, and $c_s^i$ up-to-date for all $l_i$. Consequently, when a vehicle changes the lane from $l_i$ to $l_j$, the vehicle immediately inputs $\overline{v}(t)^j$, $t - c_t^j$, and $c_s^j - x(t)$ into our fuzzy inference system and gets an appropriate driving advisory for $l_j$.

TABLE II: Simulation setup - traffic

| | |
|---|---|
| **Lane** | 2 lanes |
| **Length** | 18Km (12,000 cells) |
| **Vehicle speed (car)** | 34m/s |
| **Vehicle speed (truck)** | 26m/s |
| **Vehicle length (car)** | 4m |
| **Vehicle length (truck)** | 12m |
| **Portion of trucks** | 10% |
| **Operation time** | 6.5 hours |

TABLE III: Simulation setup - network

| | |
|---|---|
| **Pathloss** | Nakagami-m |
| **TX power** | 17dBm |
| **Antenna gain** | 0dBm |
| **Sensitivity threshold** | -90dBm |
| **Reception threshold** | -81dBm |
| **MAC Protocol** | DSRC |
| **Beacon interval** | 240ms+random(0,10)ms |
| **Beacon size** | 500Bytes |

## V. Performance Evaluation

The performance of the proposed protocol was evaluated in comparison with the state-of-the-art traffic jam control based on V2V [4]. JiST/SWANS [26][27] with extension by Ibrahim and Weigle [28] and Kilot [29] was used for our simulations.

### A. Simulation Setup

For our simulations, a two-lane highway segment was used which spans 18Km with a 300-m-long on-ramp located about 1.5Km away from the downstream boundary. In terms of traffic flow, the on-ramp was fed with vehicles at a rate of 450 vehicles/hour/lane, and the traffic for the main road was given as shown in Figure 4. Various parameters for traffic and network for our simulations are summarized in Tables II and III. In particular, for V2V, DSRC [30] was used with realistic Nakagami-m [31] physical layer model. With this simulation setup, a traffic jam is observed at the on-ramp area as shown in Figure 5. In addition, by adopting the realistic two-lane lane change model for different types of vehicles [20], in our simulations, speed variance between lanes are also observed as shown in Figure 6.

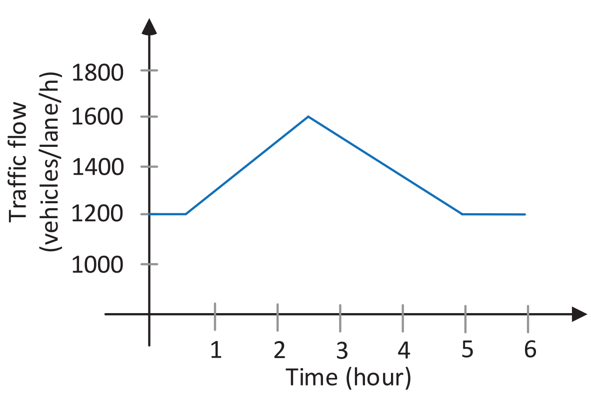



Fig. 4: Traffic flow of main road

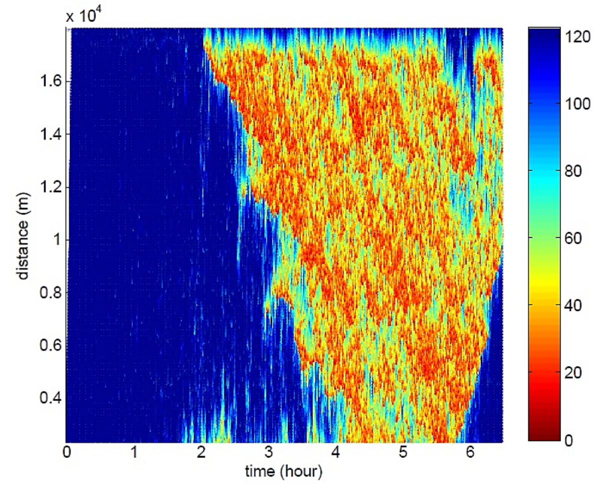



Fig. 5: Spatio temporal representation of the traffic jam (km/h)

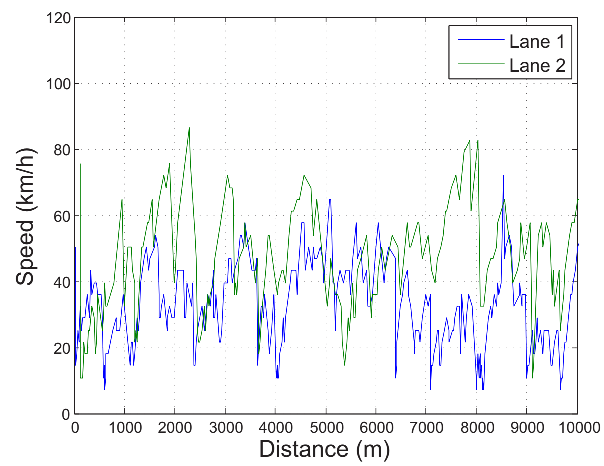



Fig. 6: Speed difference between lanes

### B. Effect of Penetration Ratio

We first measure the average delay by vayring the penetration ratio. The results are shown in Figure 7. Each point represents the average of 30 simulation runs. As the penetration ratio is increased, the average delay of both protocols decrease. This is simply because the traffic jam is further reduced if more cars follow the driving advisory. In particular, the graph shows that even with a small penetration ratio around 5 to 10%, there is still a significant improvement in the average delay for both protocols. It is also notable that the standard deviation of both protocols decrease as more cars are influenced by the protocols. This is because as more cars follow the protocols, the randomness stemming from the dynamics of a traffic jam is more effectively controlled. The most important observation is that our proposed protocol has smaller average delay compared with the state-of-the-art. More specifically, it reduces the average travel time by up to 9% in comparison with the state-of-the-art [8][4].

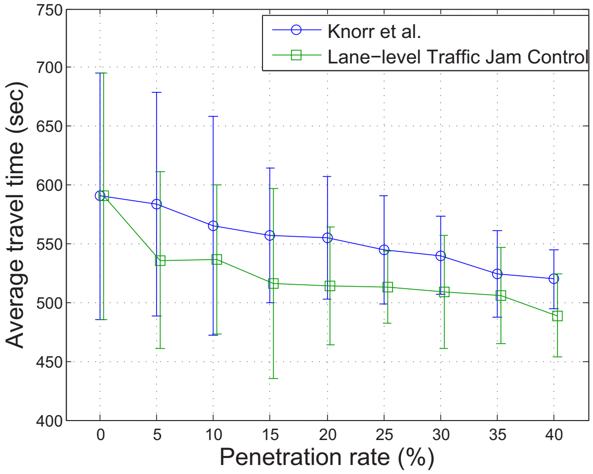



Fig. 7: Effect of penetration rates

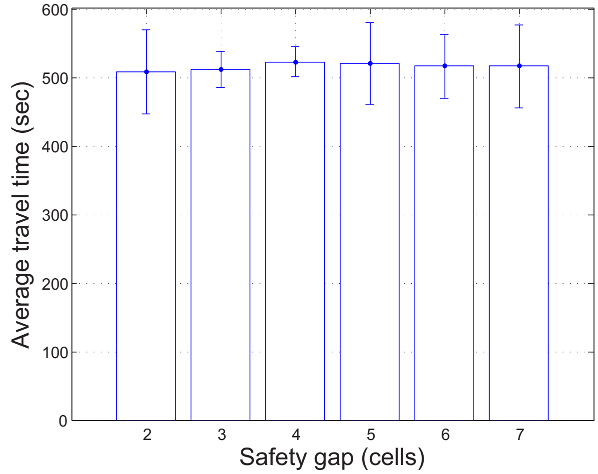



Fig. 9: Effect of lane change

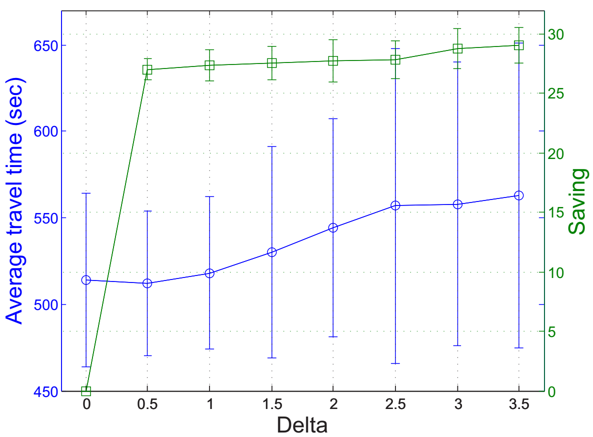



Fig. 8: Effect of $\delta$

## *C. Effect of $\delta$*

In this section, we investigate the effect of $\delta$. For this experiment, a penetration ratio of 20% was used – note that for other penetration ratios, similar results are observed. The results are depicted in Figure 8: as $\delta$ increases the average delay also increases. The reason is because with smaller $\delta$ the protocol does not cope well with the dynamics of the traffic jam. Of particular notice is the significant increase of the standard deviation, which indicates that higher $\delta$ does not effectively control the random behavior of a traffic jam. On the other hand, in terms of computational resource savings in percentage, even with a slightly higher $\delta$, a significant amount of savings was observed. As the graph shows, after the amount of savings peaks up initially, it gradually increases as we get higher $\delta$. This result shows that considering the decreased average delay, selecting small $\delta$ can be sufficiently beneficial.

## *D. Effect of Lane Change*

It is certain that the lane change behavior of vehicles would affect the performance of the proposed protocol. In our simulations, we investigate the effect by changing the lane change ratio of the lane change model [20] used for our simulator. More specifically, we simulate aggressive lane change behavior by adjusting the *safety gap* (in cells) [20] for changing lanes, i.e., larger the gap, more aggressive lane change behavior is exhibited. Figure 9 shows the average travel time for different safety gaps. As shown, no significant difference was observed between any two safety gaps. The results indicate that our mechanism of applying new driving advisory immediately after a lane-change properly suppresses the performance degradation caused by lane changes.

# VI. Conclusion

In this research, we have found that speed variance between lanes is another important factor affecting the performance of traffic jam control algorithms. Based on these findings, we have designed a protocol that enables vehicles to perform per-lane traffic analysis which allows for diversified driving advisory for each lane, thereby achieving significantly higher performance compared with the state-of-the-art traffic jam control protocols. In particular, we adopted the fuzzy inference system to our protocol to represent effectively the dynamic characteristics of a traffic jam and to provide diversified driving advisory.

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