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SWSCAV: Real-time traffic management using connected autonomous vehicles

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ABSTRACT

Traffic management methods aim to increase the infrastructure's capacity to lower congestion levels. Using vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) connectivity technologies, connected autonomous vehicles (CAVs) have the potential to operate as actuators for traffic control. In this study, a CAV-based alternative approach for traffic management is proposed (SWSCAV), and its performance is compared to that of lane control signals (LCS) and variable speed limits (VSL), which are also traffic management systems. When a shockwave is detected due to an incident, the CAVs on the road slow until they reach the speed of the observed shockwave (SWS), according to this proposed procedure. Thus, the incoming traffic flow towards the incident is slowed, preventing the queue behind from extending. In a simulation of the urban mobility (SUMO) environment, the suggested method is evaluated for 4800 scenarios on a three-lane highway by varying the market penetration rate of CAVs in traffic flow, the control distances, the incident lane, and the duration. The proposed method reduces the incidence of density values of over 38 veh/km/lane and 28 veh/km/lane in the vicinity of the incident region by 12.68 and 8.15 percent, respectively. Even at low CAV market penetration rates, the suggested method reduces traffic density throughout the network and in the location of the incident site by twice as much as the LCS system application.

1. Introduction

Traffic congestion, especially in crowded cities, causes increased travel times, delays, and even safety issues [1]. Traffic incidents are one of the most common sources of congestion because they can reduce road capacity and cause lane closures [2]. An incident in a particular zone can harm a much larger scale throughout the road network. Traffic management helps mitigate traffic congestion and improve traffic conditions.

With traffic management methods, the infrastructure can be used much more efficiently instead of building new infrastructure from the ground up to reduce the congestion levels and risk factors [3]. Traffic data is necessary for traffic management methods to work effectively and efficiently. There are various data collection methods [4]. Travel times can be diminished by using traffic management methods and safety conditions can be improved. Optimization and machine learning methods are currently used in traffic management methods [5–10]. However, the latest technological advancements have grown traffic management methods in a different direction. The trend is to develop innovative strategies, which mainly use vehicles. Autonomous vehicles (AVs) are one of the most significant technological developments in recent years. It is expected that these vehicles will provide substantial benefits to society, such as reducing fatal accidents and driver errors and providing mobility opportunities to non-drivers, such as elderly and disabled travelers [11]. However, there are concerns about the AVs also increasing the number of vehicles by introducing non-drivers to the traffic [12,13]. It is possible to minimize these concerns by equipping AVs with vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) connection technologies. Vehicles that benefit from these connection technologies are called connected autonomous vehicles (CAVs).

Studies that focus on the influence of AVs and CAVs on traffic networks show that connectivity and cooperation are crucial factors for improving traffic conditions, regardless of the availability of automation [14–16]. Also, CAVs have the potential to act as actuators of traffic control by receiving information from a traffic management center or the infrastructure, such as detectors, through V2I communication [17]. However, the efficiency of

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traffic management with CAVs highly depends on the penetration rate of CAVs. Most of the studies suggest that higher CAV market penetration increases efficiency and performance [18–20]. Other studies have determined an optimum market penetration rate [16,19,21,22], which is useful, considering that there will be mixed traffic conditions for a very long period [23]. The speed difference between upstream and downstream, which increases the likelihood of traffic incidents, can be reduced by harmonizing the speed values and optimizing the speed difference with 30% to 50% CAV market penetration rates [24,25]. The potential benefits from the CAVs, (i.e., preventing bottlenecks and increasing the average speed of the vehicles) also increase for higher traffic demands [14,26], which makes traffic management using CAVs more suitable for congested areas.

Studies, which combine traffic management methods with CAVs, are available in the literature. Variable speed limit (VSL) applications are one of the widely used traffic management methods, and their main aim is to harmonize the speeds between upstream and downstream to obtain uniform traffic and reduce shockwaves. VSL mitigates congestion by 7%–12%, especially for bottlenecks, and optimizes the flow for both recurrent and non-recurrent congestion [18]. Using CAVs to apply the speed limits increases VSL's efficiency [18,27]. Another method to apply VSL is by controlling each lane separately via lane control systems (LCS). LCS can reduce travel times and increase average speeds [28] by considering different conditions such as incidents or weather and increase the effectiveness of VSL [29]. The reaction of the vehicles differs among the lanes in terms of time headways and mean speeds [30]. However, the efficiency of LCS highly depends on compliance rates, which might change per design and driver [31]. Therefore, using CAVs to have efficient lane management performs better [28,32].

There are only a few studies that focus on the usage of shockwaves to relieve congestion. A dissertation investigates dynamic speed limits on recurrent freeway bottlenecks and focuses on congestion, propagation, and shockwave movement to upstream locations. It suggests that a minimum of 20% CAV penetration is necessary to obtain satisfying results. Besides, using shockwaves is found more effective than other VSL applications [22]. A study specifies an optimum speed for CAVs in a work zone by controlling shockwave propagation and found that a 13% delay reduction is possible in the existence of over 80% CV penetration [21]. Early shockwave detection can also harmonize the speeds successfully, and there is an optimum upstream location to implement the speed limit, changing in accordance with the shockwave [16]. Yet, no study in the literature investigates dynamic shockwave speeds as CVs' speed to minimize the delay and density of the traffic.

In this study, a new traffic management method that uses CAVs, namely Shockwave Speed Controlled Connected Autonomous Vehicles (SWSCAV) in case of an incident is proposed. By controlling the speeds of the CAVs, lower speed, and density values are obtained. In the methodology of the proposed method, Fused Lasso and Fast Fourier Transform (FFT) algorithms are used, which made processing live traffic data possible. Fused Lasso is used for smoothing and FTT for upsampling of data. Also, the queue formation at the incident location is slowed down by restraining the approaching vehicles. Since there are few studies regarding shockwave usage to mitigate the congestion, this study contributes to the literature by relieving the congestion using shockwaves through SWSCAV that uses CAVs. SWSCAV is tested in the simulation of the urban mobility (SUMO) environment. By changing the CAV market penetration rates, control distances and incident lanes, and durations, SWSCAV is tested in 4800 different scenarios.

2. Theory

2.1. Lane control signals (LCS)

The LCS method was chosen as a reference traffic management method for measuring the performance of the method proposed in this study, as it is a method that is commonly used and provides an improvement in reducing vehicle queues and increasing road safety. LCS are defined as signals placed on highways that allow, temporarily prohibit, or prohibit the use of certain lanes on streets and highways [29]. In this method, there is an electronic signal sign placed at certain distances (such as 1000 m [33]) in each lane that informs drivers about variable speed limits or lane closings. In practice, LCS is installed in pre-existing infrastructure, resulting in a constant control distance. On the LCS signs, a red cross indicates that the lane is closed, a yellow or green cross arrow indicates that the lane will close ahead, and a green arrow downward indicates that the lane is open. The LCS screens placed on the four-lane road are shown in Fig. 1. For example, in Fig. 1, in a scenario where there is maintenance work, police control, or an accident, the LCS closes the lane with an "X" mark and instructs drivers in the right lane to change lanes before arriving at the accident site. For vehicles in other lanes, drivers are informed that the speed limit is changed to 60. In this way, it is aimed to achieve the common benefits of traffic management methods, such as reducing the number and severity of accidents, increasing traffic throughput, energy-saving, and reduction in travel time. In this study, as a reference method, LCS closes the lane where the accident occurred in accident scenarios. 80% obedience rate of the drivers to the signal was used [34], and the readability distance from which a driver can read the message was chosen as 30 m.

2.2. Variable speed limits

A variable speed limit (VSL) is one of the most used traffic management systems due to its significant traffic improvements. VSL system enables dynamically changing speed limits based on the dominating traffic, incident, and weather. The appropriate speeds that the drivers are recommended to travel are shown on displays on overhead or roadside message signs [36]. One aim of the VSL management method is to decrease the speeds of drivers when traffic conditions are not regular, such as in incident and heavy-rain cases, to maintain the safety of the flow. Reduced speeds prevent or delay flow breakdowns in regions where the volume-to-capacity ratio is near 1 [37]. Another goal of the VSL is to reduce vehicle speed variances to homogenize traffic. Reduced speed differences have positive benefits, resulting in safer traffic and greater throughputs. The compliance of the drivers; on the other hand, has a substantial impact on the VSL performance. According to research on the advantages of VSL based on varying degrees of driver compliance, as the compliance rate rises, so do the traffic improvements given by VSL [38].

2.3. The shockwave theory

The boundary of remarkable changes in flow, speed, and density states in the time–space domain is referred to as a shockwave. Six types of shockwave types are backward forming, forward recovery, rear stationary, backward recovery, frontal stationary, and forward forming shockwaves (see Fig. 2). In this study, backward forming and forward recovery shockwaves will be the critical shockwave types.

Let us consider that there is a significant traffic flow change between two consecutive road sections A (upstream) and B (downstream) (Fig. 3). Let q_A, $k_{A,}$ and u_A are the flow, density, and speed characteristics of section A where q_B, k_B, and u_B are the

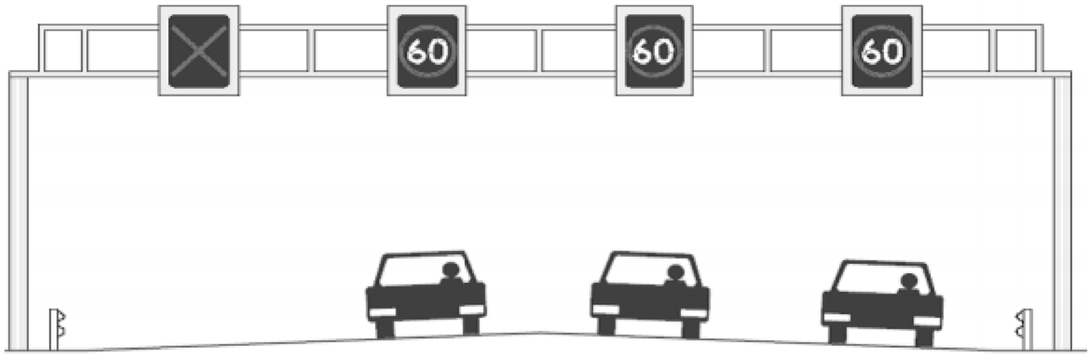


Fig. 1. LCS signs on the four-lane road [35].

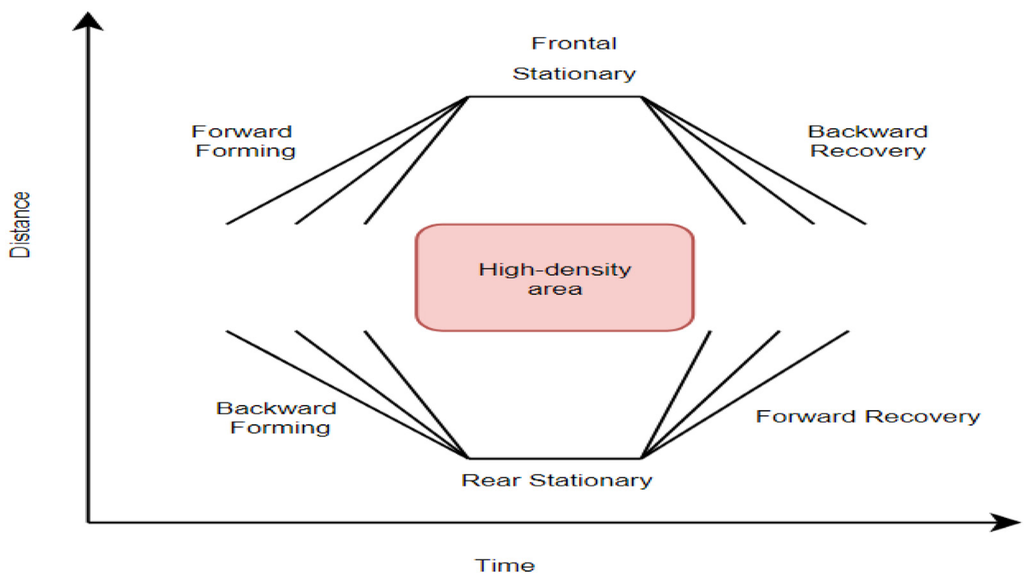


Fig. 2. Shockwave types [39].

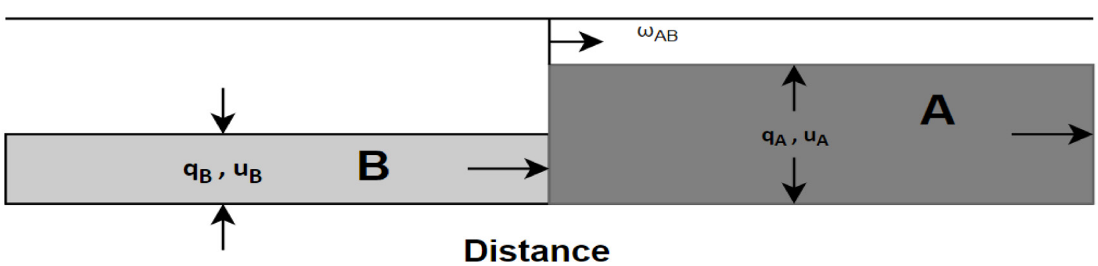


Fig. 3. Shockwave parameters at state A and state B [39].

flow, density, and speed of section B, respectively. Let ω_{AB} is the shockwave speed that lies between flow states A and B. To find shockwave speed; firstly fundamental relationship equations are established for the states A and B:

$$q_A = (u_A - \omega_{AB})k_A \quad (1)$$

$$q_B = (u_B - \omega_{AB})k_B \quad (2)$$

The number of vehicles leaving state B (N_B) should be equal to the number of vehicles entering state A (N_A) since there are no vehicles are inserted, created, or removed. N_A and N_B can be calculated by using:

$$N_A = q_A t = (u_A - \omega_{AB})k_A t \quad (3)$$

$$N_B = q_B t = (u_B - \omega_{AB})k_B t \quad (4)$$

Solving the equation for ω_{AB} will cause:

$$\omega_{AB} = \frac{q_A - q_B}{k_A - k_B} \quad (5)$$

In a case of a shockwave, the shock wave speed will be measured with the data collected by the detectors, and this speed will be given as the target speed for connected autonomous vehicles to decrease their speed.

3. Methodology

3.1. Simulation network

For this study, the open-source SUMO traffic simulator is used because it enables the user to manipulate the simulation with

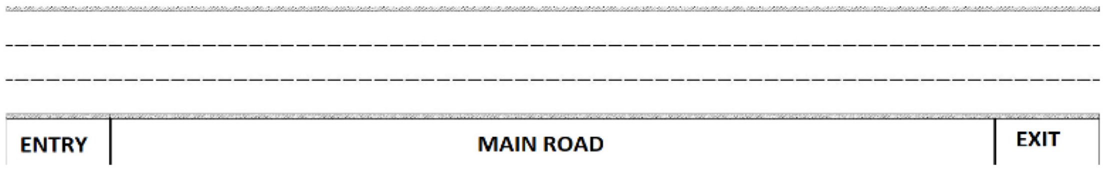


Fig. 4. The simulation road network.

Table 1
Simulation parameters.

Parameter	Value
Simulation period	90 min
Maximum speed (V_{max})	110 km/h
Detector time frequency for data collection	15 s
Distance between detectors	500 m
The total length of the road	10 500 m

the TCP-based client–server architecture (TraCI) on run time. The scenarios are tested on 3 lane highway with a length of 10.5 kilometers which is illustrated in Fig. 4. The simulation network is a tunnel network with three lanes having a width of 3.20 m. The road is composed of "Entry" (250 m), "Main Road" (10 500 m), and "Exit" (250 m) sections. The simulation network size is selected to cover at least the whole shockwave length and control distance throughout any simulation seed.

The vehicles enter the system from the "Entry" section, then follow the "Main Road" and finally leave from the "Exit" section. Table 1 presents the simulation network parameters.

The data is collected and processed every 15 s. In real-life, the frequency of data collection of sensors is adjusted according to the requirements. In the most ideal scenario, CAVs obtain information from sensors at every moment and act accordingly. So, if the detector time frequency is increased, the data delivery frequency will be increased, too. This may reduce the performance of the methodology. As shown in Table 1, the distance between detectors is 500 m because the imaginary sensors between two real sensors are predicted with the Fast Fourier Transform. Then, parameters that distinguish connected autonomous vehicles and driver vehicles were calibrated. In Table 2, the calibrated vehicle and driver parameters used in the SUMO model are given. The main parameters that distinguish connected autonomous vehicles (CAVs) and regular drivers are sigma and speed deviation. Exemption of CAVs from human error has been the main criterion for determining these values. Sigma is defined as the driver's imperfection. It is a Krauss car following model variable that directly affects the awareness of the driver and acceleration of the vehicle. [40]. It is scaled between 0 and 1, where 0 corresponds to perfect driving. In this study, the sigma value was taken as 0.05 for CAVs and 0.4 for regular drivers, as regular drivers are more prone to error in traffic. The speed deviation parameter is the standard deviation of the standardized speed distribution of vehicles. The speed deviation value is taken as 0.1 for CAVs as they move at more homogeneous speeds, and 0.35 for regular drivers because their speed varies more than for CAVs. All other variables are default values of the simulation software for both drive types.

Traffic parameters and thresholds are determined by gradually increasing the demand on the highway section until shockwaves and queues are observed. According to the results, the determined demand is 1500 vehicles per hour per lane. Before proceeding to the method section, it is necessary to identify the traffic congestion limits on the road network. This stage has an essential role in determining when SWSCAV will be activated

Table 2
Simulation variables of LCS scenarios.

Variables	Values
CAV percentage (%)	10, 20, 30, 40, 50, 60, 70, 80
LCS range (m)	500, 750, 1000, 1250, 1500
Compliance rate to close LCS	0.8, 1.0
Compliance rate to far LCS	0.3, 0.7

Table 3
Simulation variables of VSL scenarios.

Variables	Values
CAV percentage (%)	10, 20, 30, 40, 50, 60, 70, 80
VSL range (m)	500, 750, 1000, 1250, 1500
Compliance rate	0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2
Target speed (km/h)	30, 40, 50

Table 4
LCS simulation parameters and definitions.

Parameter	Value	Definition
LCS 1 compliance rate (%)	80	Likelihood of vehicles with driver to adapt to LCS signal close to the incident location
LCS 2 compliance rate (%)	70	Likelihood of vehicles with driver to adapt to LCS signal far from the incident location
Control distance (m)	1000	The distance between LCS 1 and LCS 2.

and how to measure the performance of SWSCAV. The following thresholds have been obtained for the simulation network created as the congestion limits:

(1) The density threshold at which traffic congestion is observed ($K_{congestion}$) is 38 vehicles per kilometer and,
(2) The speed threshold at the congestion location (V_{cr}) is detected as 17 km/h.

The same network with the same parameters and thresholds is set up to measure the performance of other incident management techniques, namely Lane Control System (LCS) and Variable Speed Limits (VSL). Considering the density and speed changes in the critical region, the optimum simulation variables of LCS and VSL implementations are given in Tables 2 and 3 [33].

The variables giving the most effective results for LCS and VSL traffic management methods and their explanations are given in Tables 4 and 5, respectively. The results of LCS and VSL simulations carried out with the parameters that performed most efficiently are compared with the results of SWSCAV.

3.2. SWSCAV: Proposed methodology and its implementation

In SWSCAV, when a shockwave (i.e., due to an incident) is detected, the CAVs a certain distance away from the incident location decelerate until the shockwave speed, resulting in a slowdown of traffic approaching the queue (see Fig. 5). The target speed of the CAVs is selected as the shockwave speed. After the

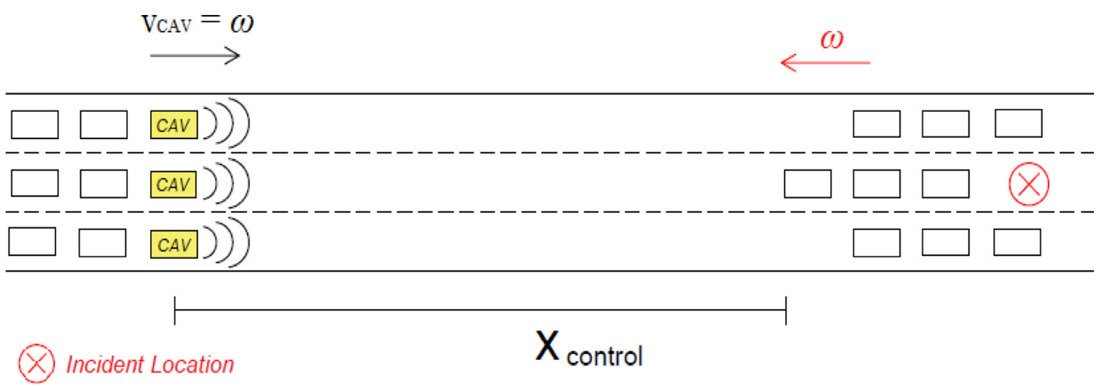


Fig. 5. Sketch of the proposed traffic management method.

Table 5
VSL simulation parameters and definitions.

Parameter	Value	Definition
Compliance rate (%)	50	Likelihood of vehicles with drivers complying with the VSL signal
Control distance (m)	1000	Distance between VSL signal location and incident position
Target speed (km/h)	40	The speed at which vehicles should adjust their speed to

density and flow data are upsampled with FFT, the shockwave boundary is found. The shockwave speed (Eq. (5)) is calculated by using the density and flow data at this boundary. If the speed is slower than 5 km/h and more than the maximum speed, the vehicle ignores the target speed. The distance between the incident location and the point where the CAVs decelerate is called the control distance.

SWSCAV can be defined as controlling the traffic flow with connected autonomous vehicles by using shockwave speed with an incident. The proposed system comprises three parts, as explained in the flowchart (see Fig. 6):

(1) Incident detection by using traffic sensor data or data collected by the sensors of CAVs,
(2) Data preprocessing (i.e., upsampling, smoothing, shockwave calculation) and,
(3) Management of CAVs by controlling their speeds and acceleration.

3.2.1. Preprocess of traffic data

In this study, density values are viewed as periodic signals. During simulations, average occupancy values of detectors placed every 500 m are stored to be transformed into density values. Transformation is given in Eq. (6):

$$k\left(x,t\right)=\frac{1000\times O\left(x,t\right)}{L_v+L_d} \tag{6}$$

where;

1. $k\left(x,t\right)$ is the density value at time instant t and position x.
2. $O\left(x,t\right)$ is the occupancy value recorded by the detector,
3. L_v is the average length of the vehicles,
4. L_d is the range of the detector.

Since the distance between the sensors is very high, speed reductions controlled by SWSCAV may cause the road to underperform by forcing the vehicles to decelerate before they should reduce their speeds. M-times up-sampling with Fast Fourier Transform (FFT) has been applied to data to reduce such inefficiency.

FFT is the algorithm widely used to compute discrete Fourier transforms and perform trigonometric interpolation to up-sample 1-dimensional data. The first step of the FFT is zero-padding, that is:

$$K_{zeropadded}\left[x\right]=\begin{cases}K_t\left[\dfrac{N}{M}\right], & \dfrac{N}{M}\in z\\ O, & else\end{cases}\quad x=1,2,3..N \tag{7}$$

where;

1. $K_{zeropadded}\left[x\right]$ is the xth value of 1-dimensional zero-padded density data,
2. K_t is the dataset composed of $k(x,t)$ values at time t,
3. M is the multiplication factor, which is selected as 10 for this study,
4. N is the desired number of upsampled data obtained by the product of the length of density data and multiplication factor.

The data will be treated as if the detectors are placed at intervals of 50 m instead of 500 m. Then, the signal is completed by changing the zero values as the following method:

$$K_{zeropadded}\left[x\right]=\sum_{n=0}^{N}x_{zeropadded}[n]*e^{\left(-\frac{2*\Pi*i}{N}\right)xn}x=0,1,2,3..N \tag{8}$$

where; $K_{upsampled}[x]$ is the x_{th} value of 1-dimensional, up-sampled density data. The relation between K_t and K upsampled is shown in Fig. 7. The same upsampling procedure is also followed for the flow data to obtain $Q_{zeropadded}$ and $Q_{upsampled}$. To prevent undesirable effects of outliers on shockwave speed calculation and to find out the significant density change points, the Fused Lasso Signal Approximation (FLSA) method is selected to apply to upsampled density and flow data. FLSA is a data smoothing technique used for both spatial and temporal datasets to observe significant pattern changes. The loss function of FLSA is:

$$\hat{\beta}=\arg min\left\{\sum_{i=1}^{N}\left(x_i-\beta_j\right)^2\right\} \tag{9}$$

$$ubject\ to\sum_{i=1}^{N}|\beta_i|\le s_1\ \ and\ \ \sum_{i=2}^{N}|\beta_i-\beta_{i-1}|\le s_2$$

where;

(1) x_i is the one-dimensional data points of x corresponding to successive positions,
(2) β_i and β_{i-1} are the successive data points of β, which is the approximated signal

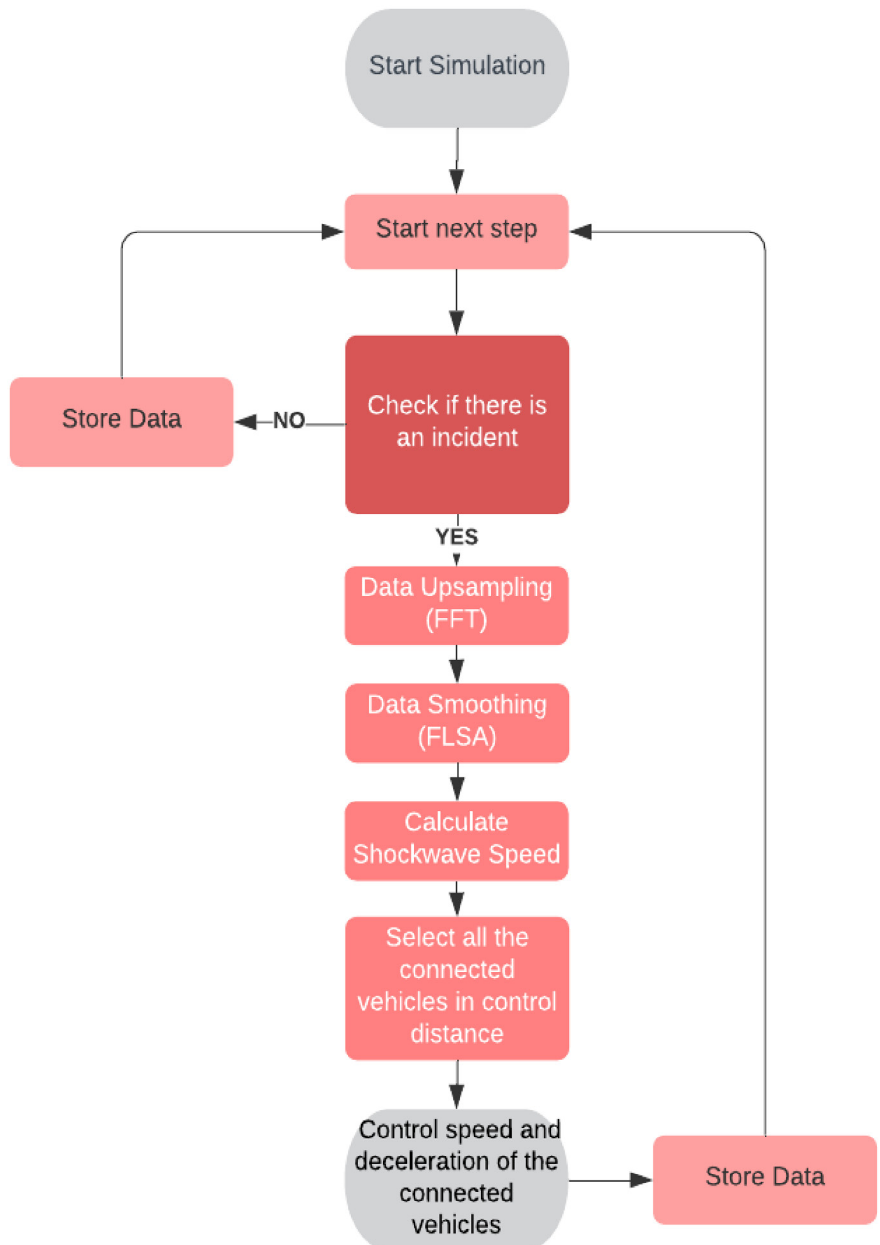


Fig. 6. Flowchart of SWSCAV.

(3) s_1 and s_2 are the parameters that are determined by cross-validation.

The upper constraint controls the sparseness, and the lower constraint controls the absolute differences between coefficients. The products of the FLSA procedure on upsampled data are $K_{approximated}$ and $Q_{approximated}$. In Fig. 8, the blue line represents the upsampled data, and the red line stands for the approximated signal that is flattened. By upsampling data 10 times, the error is minimized, possibly 500 m to 50 m. Therefore, it eliminates any inefficiency caused by the distance of incident location to the sensor.

3.2.2. Real-time traffic management and control: Implementation of SWSCAV

In the incident detection section, besides the densities and critical speed, the shockwave speed at the incident location is also calculated. The place to calculate shockwave speeds is the most left location of the peak domain of the approximated density signal. Shockwave speed (V_{sw}) is calculated as:

$$V_{sw} = \frac{q_s - q_{s-1}}{k_s - k_{s-1}} \tag{10}$$

where;

1. q_s is the instantaneous flow value at location s in the approximated flow signal,
2. q_{s-1} is the instantaneous flow at location $s-1$, which is 50 m behind s,
3. k_s is the instantaneous density at location s,
4. k_{s-1} is the instantaneous density at location $s-1$.

Shockwave speed is limited from V_{cr} to V_{max} to deal with both low and high speeds. Then, all the CAVs between the boundary of the backward shockwave and the spot d_i (control distance) behind the boundary of the backward forming shockwave are selected. For instance, if the backward forming shockwave is detected

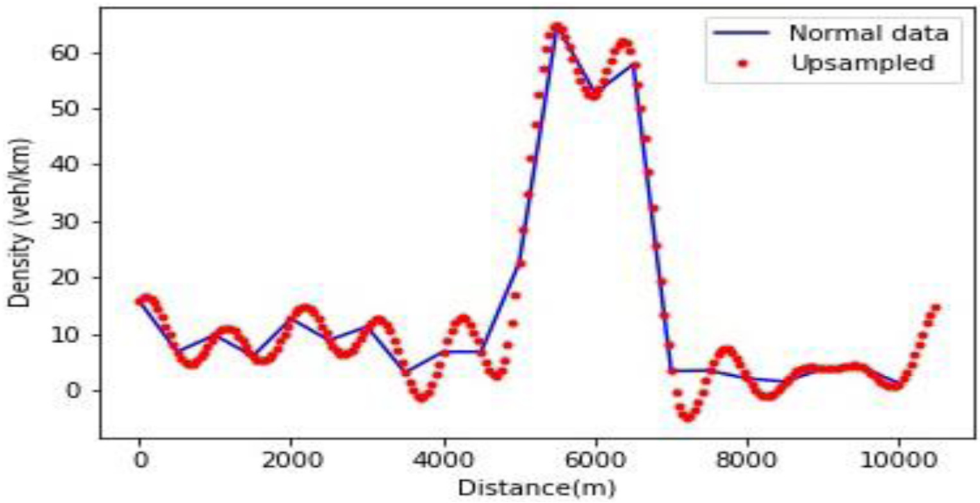


Fig. 7. Upsampled data.

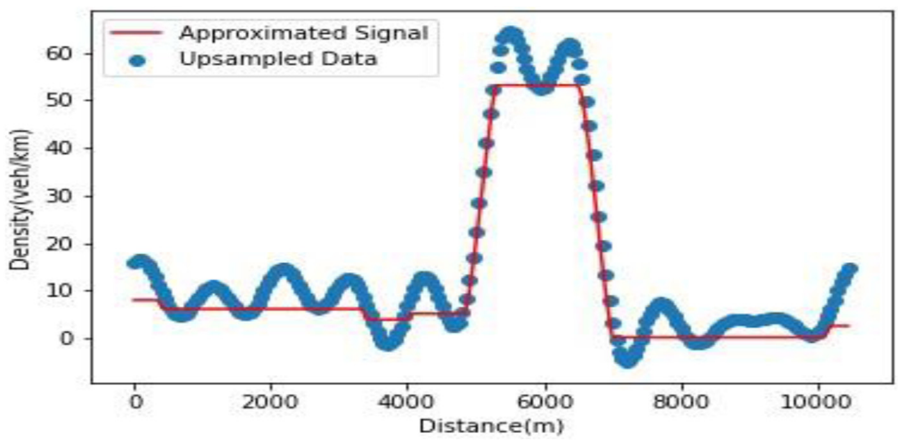


Fig. 8. Upsampled data subjected to FLSA. . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

at the x^{th} meters of the network, CAVs between x^{th} meter and $(x - d_i)^{th}$ meter are selected to be controlled by being dictated to reduce their speeds to V_{sw} in a given time which is called $t_{deceleration}$. The expression of the $t_{deceleration}$ is given as:

$$t_{deceleration} = \frac{V_{current} - V_{target}}{P_{incident} - P_{current}} \tag{11}$$

$V_{current}$ stands for the current speed of the vehicle and V_{target} is the target speed, which is the V_{sw} in this study. $P_{incident}$ is the position of the incident, and $P_{current}$ is the instant position of the vehicle at the time when the command is taken.

4. Simulation analysis and results

The scenarios comprise eight different connected vehicle penetration rates (10%–80%) with five different control distances downstream distances from the incident in which the speed commands are given to CAVs. The control distances chosen are 500, 750, 1000, 1250, and 1500 m. These distances are neither too long nor too short to allow for traffic management. Managing traffic within those control distances does not affect the free flow behind and is suitable for security.

The incidents are separated according to their occurrence lanes, namely right, middle, and left. Besides, different incident durations are taken into account, as given in Table 6. The numbers of scenarios created corresponding to each lane and duration are given in Table 4. For example, for an incident that occurred in the right lane for 10–15 min, the total number of controlled scenarios is 280 (8 × 5 × 7) including different CAV penetration rates and control distances. The same scenarios are also created for uncontrolled CAVs to compare the change. As a result, there are 2400 scenarios in total. Afterward, heatmaps that represent densities based on location at the X-axis and time at the Y-axis are created, as in Fig. 9, which will enable the evaluation of shockwaves visually.

Table 6
The number of scenarios for each lane and duration.

Incident lane (Column A)/ Incident duration (Row 1)	10–15 (min)	15–20 (min)	20–25 (min)	Total
Right	7	5	9	21
Middle	9	6	4	19
Left	9	5	6	20
Total	25	16	19	60

For each scenario, 60 different scenario seeds (different incident scenarios in terms of duration, location, and lane) and 15 repetitions for each scenario seed are performed. There are two sources of randomness: simulation seed and scenario seed. Scenario seed is regarding the incident location, lane, and duration.

The simulation seed is the randomness of the simulation (vehicles' speed distribution, system entry time, and their decision during simulation). The numbers are selected to have at least 5 combinations of each scenario.

4.1. Simulation network

First, some performance criteria are specified to test the heatmaps objectively and accurately (see Table 5). The comparison of performance criteria is made by using the difference between the situations for scenarios where traffic is managed or there are autonomous vehicles in traffic (Controlled) and scenarios, where there is no CAV in the network and traffic composition, is not managed (Uncontrolled Value) CAV cases. The percentage change between the two cases is calculated to see the effect of the speed control based on shockwave speeds. The total duration of each simulation is arranged as 90 min, and data collected in the first 15 min of warmup and the last 15 min of closing periods are subtracted from the raw data.

The percentage changes are calculated:

$$\%\ Change = \frac{V_{Controlled} - V_{Uncontrolled}}{V_{Uncontrolled}} \tag{12}$$

where,

(1) % Change is the percentage change between two cases for a performance measure
(2) $V_{Controlled}$ is the numerical value of the performance measure for the controlled cases.
(3) $V_{Uncontrolled}$ is the numerical value of the performance measure for the uncontrolled cases

The first performance criteria are density thresholds (veh/km) of the whole simulation that are selected as 38 and 28 based on the breaking points on the heatmaps. "K" stands for the traffic density. "The rows "K > 38 (%)" and "K > 28 (%)" stand for the density values higher than the thresholds in the critical region, and "Overall Avg. K" stands for the average density value of the overall simulation heatmap. Another measure is considered as the speed values which are given in "Overall Avg. Speeds", showing the average speed of the entire simulation. The areas that are affected by the incident created a shockwave. In this study, observing the density change in the regions where the shockwave is generated and affected by the shockwave is more important than observing the average density change in the path. Therefore, shockwave duration "Shockwave duration (min)", and shockwave length "Shockwave length (m)" is marked on the heatmap based on the uncontrolled CAV case since the aim is the improvement of the shockwaves. Here, shockwave length represents the distance affected by the incident. For each scenario, the critical region restricted by the shockwave length and duration is marked as shown in Fig. 9 with a red rectangular. The purpose of defining a local system is to exclude areas with free traffic flow where the incident has very little/no impact. The incident affects only the critical region. Then, each criterion applies to the overall system and the red rectangular area, namely density thresholds ("In CR K > 38 (%)" and "In CR K > 28 (%)") and "average speed (8)".

The traffic congestion recovery obtained by the method is according to the change in its density or speed value since the aim is to reduce density and to uniform the speeds. The uncontrolled and controlled values for densities are obtained by dividing the areas where the densities are higher than the threshold in the total area. Therefore, they represent the percentage of traffic density above the threshold. In the critical region, the proportions are much higher than the overall simulation.

In Table 7, one scenario is selected randomly among 2400 scenarios. Because of the control method, the densities higher than 38 and 28 are decreased by 12.68% and 8.15%, respectively. Yet, the overall average density of the system increased by 0.15%, meaning that the recovery of the shockwave formation is obtained by spreading the density to the entire system. Another reason for the increase in average density is the demand for starvation just after the incident area in an uncontrolled case. However, after the shockwave speed directions are given to CAVs, demand starvation disappears, and traffic becomes more uniform, resulting in higher density values in overall traffic. The improvements in the critical regions are even better than the overall simulation. 13.17% and 10.80% decrease in both of the thresholds obtained, and the increase in the average speed of the critical region is more than the overall average speed, which shows more stable traffic with fewer speed differences. Similar results were also obtained for other scenarios.

Table 7
Performance criteria.

Features	Uncontrolled	Controlled	% Change
K > 38 (%)	2,80	2,44	12,68
K > 28 (%)	3,18	2,92	8,15
Overall Avg. K	9,87	9,88	−0,15
Overall Avg. speeds	78,63	78,21	0,53
Shockwave duration (min)	22,75	22,75	22,75
Shockwave length (m)	2000	2000	2000
In CR K > 38 (%)	44,57	38,70	13,17
In CR K > 28 (%)	48,91	43,91	10,22
In CR Avg. speeds	38.73170671	36.76962846	5.065819245

All the analyses are made based on the critical region, and a 38 veh/km threshold is taken into account to test the shockwave. 3D surface plots are created for all CAV penetration rates to observe different effects of the CAV percentages during the incident. As shown in Fig. 10, low CAV penetration rates (10%–50%) are more useful for left lane incidents. As for the middle and right lane incidents, higher penetration rates (60–70%–80%) decrease the densities better. Besides, as the incident duration increases, the difference among different penetration rates becomes more ambiguous and tangled. So, even if the intervention is made, the proposed traffic management method becomes ineffective as the incident duration increase.

Table 8 presents the improvement amounts for different CAV ratios for short, medium, and long duration incidents based on different density levels' mean and standard deviation in the critical region. The relationship between the mean and standard deviation of the change in congested regions in the critical region is a measure of the effectiveness of SWSCAV. If the standard deviation is decreasing compared to the mean, the density of the critical region equalizes, meaning that the system works efficiently. For the short and medium duration cases, the most apparent improvements are for 40% and higher penetration rates, whereas for long-duration cases penetration rates are higher than 50% work efficiently. Considering the distribution of standard deviations according to penetration rates, it is observed that lower penetration rates operate with lower stability. The overall situation, according to the penetration rates, is explained in Table 9, and we get the best results for 70% and 80% penetration rates.

Another critical variable in this study is the lane where the incident occurs. In particular, incidents that occurred in the middle lane raise traffic congestion by affecting both other lanes of the road to a certain extent by interrupting the flow of traffic. Therefore, different accident scenarios are considered depending on their lanes as right, middle, and left. Table 10 reports the scenarios that form shockwaves meaning how many scenarios CAV needed control to improve the traffic congestion out of 105, 95, and 100 cases, respectively. When the ratio of the scenarios with shock waves to all scenarios is analyzed, it is observed that

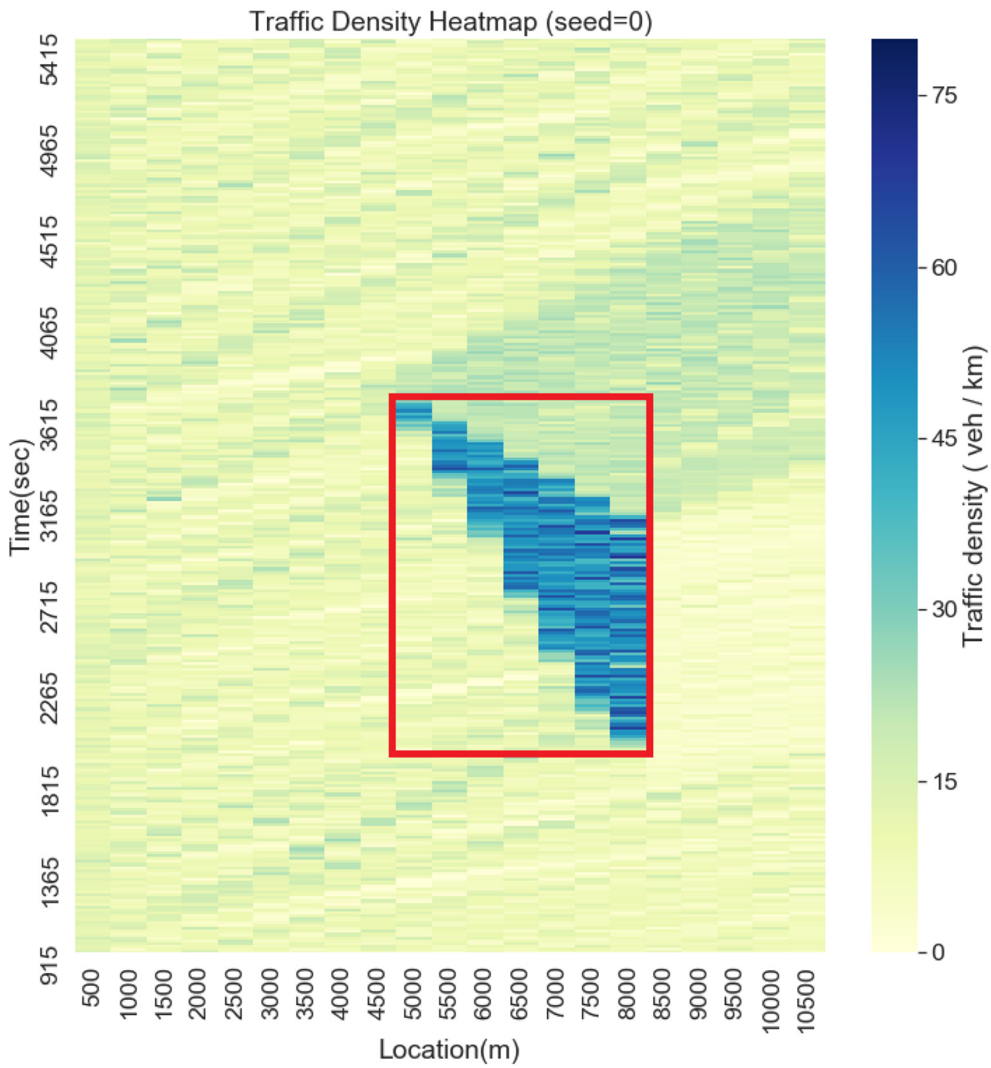


Fig. 9. Density heatmap and critical region.

Table 8
Improvements for different durations.

Scenario	CAV	10_15 K > 38 Mean	10_15 K > 38 Std Dev	Short duration # of scenarıos	15_20 K > 38 Mean	15_20 K > 38 Std Dev	Moderate duration # of scenarıos	20_25 K > 38 Mean	20_25 K > 38 Std Dev	Long duration # of scenarıos
0	10%	−32,31	39,85	85,00	−24,31	29,81	65,00	−3,08	46,97	90,00
1	20%	−39,80	32,18	85,00	−34,29	33,68	65,00	−24,67	31,92	90,00
2	30%	−43,81	30,53	85,00	−28,61	26,63	65,00	−30,37	35,14	90,00
3	40%	−51,70	28,82	85,00	−45,90	23,13	65,00	−27,71	35,81	90,00
4	50%	−54,74	25,19	85,00	−47,31	21,17	65,00	−42,21	41,62	90,00
5	60%	−52,55	27,83	85,00	−49,42	24,03	65,00	−49,79	28,54	90,00
6	70%	−55,73	29,05	85,00	−53,83	30,76	65,00	−42,63	29,22	90,00
7	80%	−54,06	24,49	85,00	−52,99	17,03	65,00	−37,76	23,62	90,00

Table 9
Improvements for different penetration rates.

Scenario	Features	10%	20%	30%	40%	50%	60%	70%	80%
0	K > 38 Mean	2,04	−4,45	−1,93	−9,00	−5,97	−14,77	−16,31	−16,14
1	K > 38 Std Dev	32,81	22,64	20,59	26,80	32,48	12,02	20,79	14,80
2	K > 28 Mean	2,19	−2,62	2,31	−9,59	−8,23	−16,15	−2,95	−18,61
3	K > 28 Std Dev	33,81	17,35	23,94	19,55	29,08	10,30	26,02	15,67
4	Scenario number	161,00	109,00	93,00	79,00	48,00	51,00	61,00	49,00

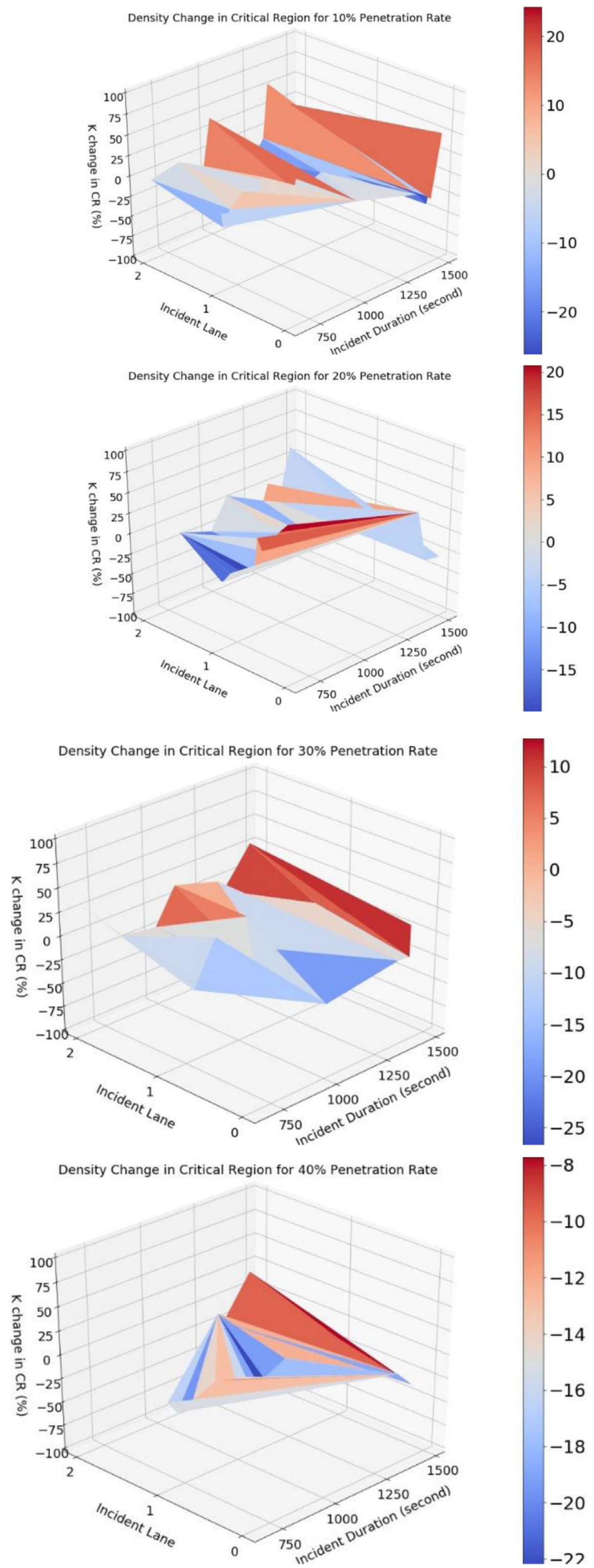


Fig. 10. 3D surface plots for 1000 m of control distance.

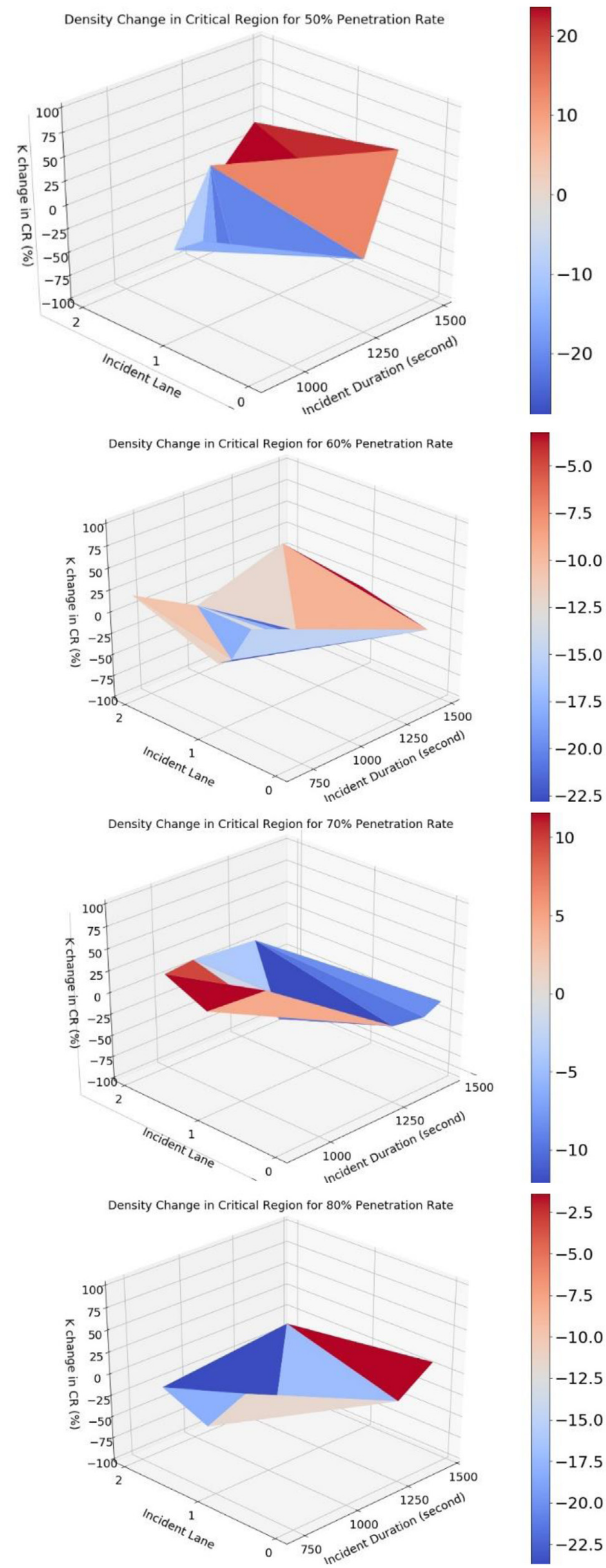


Fig. 10. (*continued*).

less intervention is required for incidents in the right lane. The higher rate of change in right lane incidents can also be explained by this fact. Since it will be easier to solve and control the congestion, which is already at a low level, a larger percentage change is observed proportionally. Most of the middle lane incidents required CAV intervention. In middle and left lane accidents, as the percentage of connected autonomous vehicles increases, it is observed that congested areas in the critical region decrease. However, the 30% penetration rate showed an unexpectedly high improvement in both the middle and left lanes.

Table 10
Improvements for different lanes.

Scenario	CAV	Right K > 38 Mean	Right K > 38 Std Dev	Right # of shockwave scenarios	Middle K > 38 Mean	Middle K > 38 Std Dev	Middle # of shockwave scenarios	Left K > 38 Mean	Left K > 38 Std Dev	Left # of shockwave scenarios
0	10%	−12,98	60,85	60,00	−14,03	18,82	95,00	−29,31	43,77	85,00
1	20%	−45,74	38,29	60,00	−24,32	20,90	95,00	−32,67	37,18	85,00
2	30%	−44,42	30,36	60,00	−32,08	26,09	95,00	−30,64	37,58	85,00
3	40%	−46,57	48,68	60,00	−32,74	17,47	95,00	−46,68	27,98	85,00
4	50%	−65,20	46,50	60,00	−37,27	13,07	95,00	−47,93	29,01	85,00
5	60%	−70,81	25,50	60,00	−38,15	17,44	95,00	−50,45	28,62	85,00
6	70%	−50,62	37,14	60,00	−38,10	25,47	95,00	−48,42	30,10	85,00
7	80%	−45,08	31,65	60,00	−43,79	15,47	95,00	−53,80	23,43	85,00

Table 11
Improvements for different control distances.

CV	500 m K > 38 Mean	500 m K > 38 Std Dev	500 m # of cases	750 m K > 38 Mean	750 m K > 38 Std Dev	750 m # of cases	1000 m K > 38 Mean	1000 m K > 38 Std Dev	1000 m # of cases	1250 m K > 38 Mean	1250 m K > 38 Std Dev	1250 m # of cases	1500 m K > 38 Mean	1500 m K > 38 Std Dev	1500 m # of cases
10%	−15,83	46,43	48,00	−16,87	43,65	48,00	−19,22	41,92	48,00	−21,90	39,41	48,00	−22,08	40,80	48,00
20%	−29,39	36,15	48,00	−30,49	33,28	48,00	−33,55	30,82	48,00	−36,13	30,58	48,00	−34,70	31,70	48,00
30%	−28,97	36,12	48,00	−32,33	33,76	48,00	−34,04	31,43	48,00	−37,35	27,98	48,00	−40,59	30,17	48,00
40%	−36,61	33,41	48,00	−39,92	31,62	48,00	−43,11	33,47	48,00	−40,62	30,61	48,00	−45,40	31,64	48,00
50%	−43,97	36,30	48,00	−45,62	33,50	48,00	−48,08	31,63	48,00	−50,29	27,54	48,00	−52,18	30,44	48,00
60%	−47,10	27,96	48,00	−49,35	26,47	48,00	−49,92	28,52	48,00	−51,85	28,17	48,00	−55,12	24,44	48,00
70%	−40,31	34,79	48,00	−42,66	31,91	48,00	−47,35	29,85	48,00	−46,24	28,21	48,00	−47,87	29,10	48,00
80%	−44,26	24,72	48,00	−43,97	24,52	48,00	−48,16	23,48	48,00	−49,78	22,53	48,00	−52,12	22,41	48,00

Last but not least, another effective parameter in this study is the control distance. Each accident scenario was managed with the help of CAVs at different control distances. These control distances are determined as 500, 750, 1000, 1250, and 1500 m back from the upstream shock wave boundary. The relationship between control distances and penetration rates is given in Table 11. Except for the 10% penetration rate, each penetration rate provided noticeable improvement at each control distance. Also, as the control distance increased, the number of congested areas naturally decreased in the critical region. However, this may result in the formation of new congestion points outside the critical zone or the road being used underutilized.

The line charts which are given in Fig. 11 support the results obtained from the 3D plot and tables. As seen, the 50, 60, 70, and 80% CAV penetration rates give lower density values with an incident, meaning that higher CAV penetration can stabilize the traffic. The change in the speed values of the traffic is less drastic for the 50, 60, 70, and 80% penetration rates, as shown in Fig. 11(b). The speeds do not increase in the incident area considerably; yet, more uniform speed changes create homogeneous traffic with fewer delays as decreasing speed limits do. Another significant result is that the recovery after the incident is much faster for higher CAV rates, meaning that the negative effect of the incident on the entire network will be less compared to lower penetration rates.

4.1.1. Heatmaps

Fig. 12(a) provides the heatmap for an uncontrolled CAV scenario, and Fig. 12(b) is the controlled version of the same scenario. As seen, the densities in the existence of control are more distributed over time and location with less clustering. In both of the heatmaps, there is a backward forming shockwave followed by a frontal stationary shockwave that is the incident. After the blockage, because the incident is over, a backward recovery shockwave occurs. One of the most apparent results from the heatmaps is that the backward forming shockwave is less sharp and more dispersed for the scenario with directed CAVs, which decreases the area of higher densities. Also, forward forming and forward recovery shockwaves coming right after the incident are more evenly spread over a longer time and location results in more uniform traffic. Meaning that the intervention to the CAVs resulted in less waiting time in the traffic, and less stop-and-go-motion, resulting in fewer emissions.

4.1.2. Heatmaps comparison with LCS and VSL

LCS and VSL are traffic management methods used to increase traffic safety and road performance in the event of an accident. However, the performance of both directly depends on how well the drivers comply with these signals. Therefore, the reliability and efficiency of these methods may vary greatly depending on time and location. In this study, the best results for LCS and VSL were studied with the fit rates. This study offers a method by using CAVs to relieve the incident congestion. LCS is modeled in the same simulation environment to compare with SWSCAV scenarios.

Table 12 presents the comparison of traffic management methods at a 50% penetration rate and 1000 m control distance. In the "Only CAV" column, there are CAVs in the system, but they are not managed. Before analyzing this table, it should be remembered that the LCS and VSL methods were simulated with variables that gave the best results. According to Table 10, SWSCAV has achieved a lower traffic density ratio than other methods in the critical region by increasing the speed of the vehicles by approximately 11 km/h. Although the VSL method gives the best result in terms of average speed performance, its density reduction rate is the lowest compared to the others. LCS is in the middle in terms of average speed and density. In addition, even the presence of autonomous vehicles in the system without being managed has enabled the traffic to be further relieved in the event of an incident.

5. Conclusion

In this study, a new real-time traffic management system based on CAVs, SWSCAV, is developed to enhance traffic conditions in the event of an incident. SWSCAV is evaluated in the Simulation of Urban Mobility (SUMO) environment in a three-lane, 10.5 km long tunnel road network with loop detectors every 500 m under 4800 scenarios. Changing the incident lane and duration, CAV penetration rates, and downstream control distances from the incident yields these scenarios.

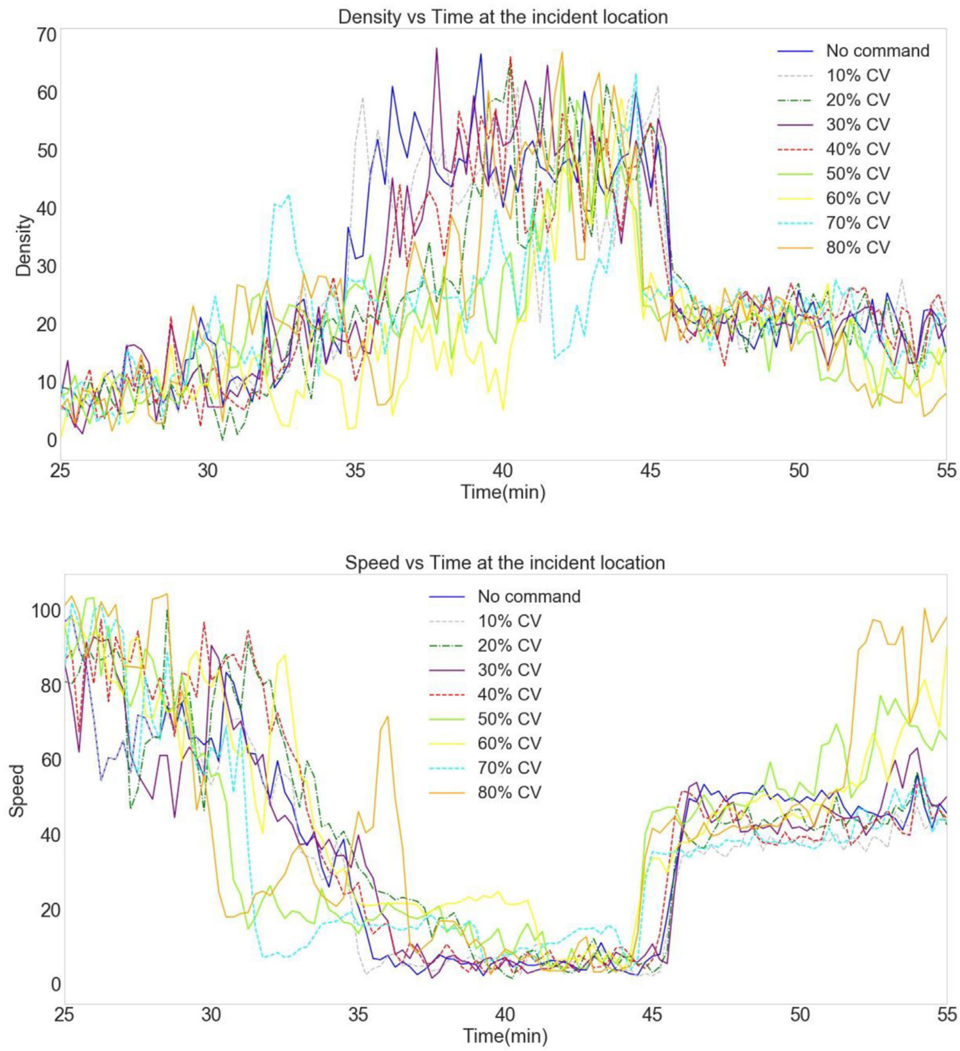


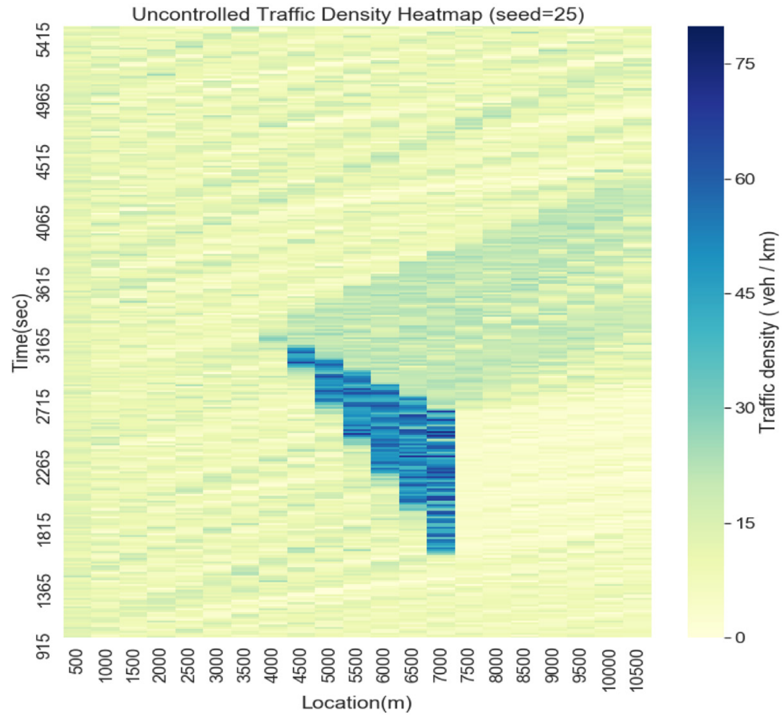
Fig. 11. (a) Density (veh/km) vs. Time at the incident location (b) Speed (km/h) vs. time at the incident location.

Table 12
Comparison of SWSCAV with LCS and VSL traffic management methods for seed = 0.

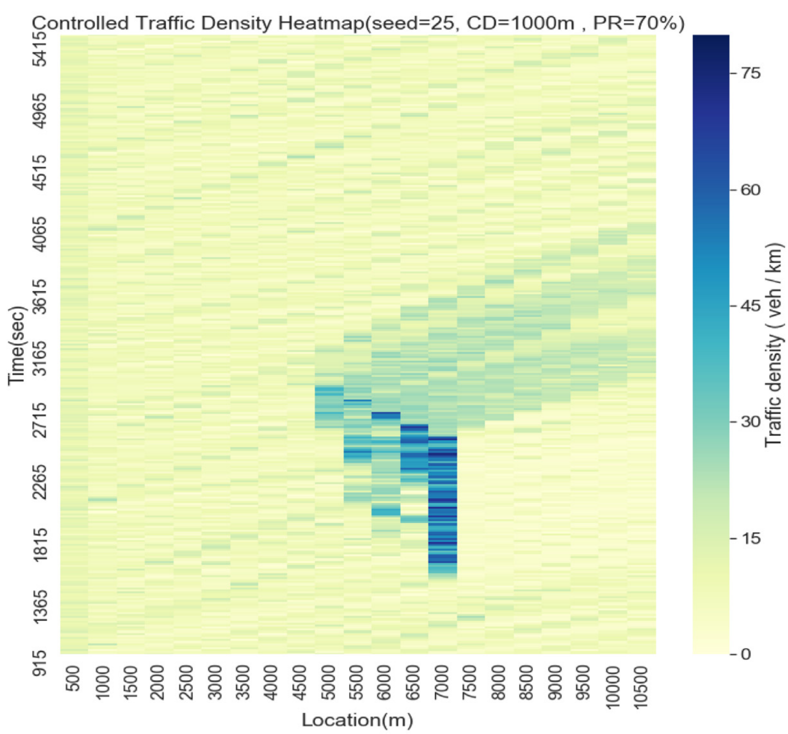
Features	Base	Only Cav	LCS	VSL	Controlled	Only Cav % change	LCS % change	VSL % change	Controlled % change
K > 38 (%)	3,81	2,72	2,73	2,75	2,47	−28,62	−28,26	−27,68	−35,06
K > 28 (%)	4,24	3,01	3,43	3,13	3,15	−28,91	−18,99	−26,05	−25,72
Overall Avg. K	12,19	10,07	10,56	10,20	10,19	−17,43	−13,37	−16,32	−16,44
Overall Avg. speeds (km/h)	64,68	78,95	76,72	78,88	78,37	22,05	18,60	21,94	21,15
Shockwave duration (min)	27,25	27,25	27,25	27,25	27,25	27,25	27,25	27,25	27,25
Shockwave length (m)	3000,00	3000,00	3000,00	3000,00	3000,00	3000,00	3000,00	3000,00	3000,00
In CR K > 38 (%)	35,71	25,19	25,32	25,45	22,86	−29,45	−29,09	−28,73	−36,00
In CR K > 28 (%)	39,48	27,66	31,43	28,70	28,83	−29,93	−20,39	−27,30	−26,97
In CR Avg. speeds (km/h)	38,59	53,13	50,69	52,50	49,36	37,69	31,36	36,06	27,91

An accident was simulated by halting a random vehicle in the simulation at a particular time in a randomized lane and period, and using the density and flow data provided by the sensors, the shockwave speed at the incident zone is determined, and the results are transferred to the CAVs through V2I communication. Fast Fourier Up-sampling is performed on the data acquired from the sensors to overcome missing information caused by the lengthy distance between two subsequent sensors, given that the density and flow data exhibit periodic signal behavior. CAVs that arrive downstream of the incident progressively slow until they reach the estimated shockwave speed. It keeps the established queue around the incident zone from growing longer and maintains the network effect as limited as possible. SWSCAV is also compared with other traffic management methods, namely Lane Control Systems (LCS), which controls the lanes separately based on the incident lane by arranging the speeds, and VSL, which controls the speed of drivers based on the incident location, yet they both highly depend on the compliance rate of the drivers.

For incidents that occur in the left lane, the results indicate that 10% to 50% CAV penetration is sufficient to improve traffic conditions. Concerning incidents in the middle and right lanes, higher penetration rates (60 to 70 percent) are necessary to reduce traffic density. It must be emphasized that, as the duration of an incident extends, traffic conditions become increasingly unrecoverable. The speed measurements in the incident's immediate vicinity do not rise. They become more similar to the rest of the



(a)



(b)

Fig. 12. (a) Heatmap with uncontrolled CAVs, (b) Heatmap with controlled CAVs (CD = Control Distance, PR = Penetration Rate).

traffic. The speed of recovery after an incident increase as CAV rates increase.

Even at low CAV penetration rates, SWSCAV performs better than LCS and VSL in terms of density reduction. Furthermore, it achieves about the same average speed improvement as the LCS, while having a performance of around 3 km/h lower than the VSL. SWSCAV has a more evenly distributed speed distribution and shorter queues. SWSCAV can also be thought of as an extremely dynamic and perfect variant of VSL. As a result, using this technique to VSL can help it perform better. The integration should be tested for both VSL and LCS to determine whether the effect is improved.

For a long time, there will be a mix of traffic on the roads until all cars are automated. CAVs are simulated as fully self-driving automobiles for this research. Without exception, the CAVs are following SWSCAV's instructions. Only eight alternative CAV penetration rates and five different control distances are considered in this investigation. According to the characteristics of a roadway, the best control distance for CAVs may be less or longer than it is in theory.

To fully reap the benefits of these cars, they must be properly introduced to traffic; otherwise, the additional load they will contribute to traffic may cause further issues. SWSCAV's findings suggest that by appropriately utilizing traffic data and utilizing the connection and autonomy of these cars, more effective traffic control can be achieved than before. Furthermore, SWSCAV does not necessitate the construction of new facilities or major expenditures, as it may make use of existing infrastructure.

There are several ways to improve the existing technique of traffic management, which now relies on shock wave speed, by employing more dynamic or pre-defined constant speeds instead of the shock wave speed. It is also possible to use dynamic deceleration and control distances, based on the incident characteristics (e.g., the road geometry, the type of incident, the time of day, etc.) to assure safety in urban traffic.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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