Analyzing Traffic Flow Changes and Incident Management in Long Highway Tunnels using Aimsun Simulation

YI-SHENG HUANG[1,*], YI-SHUN WENG[2], SHI-XIONG DONG[1], WEI-CHIH WANG[1]
[1]Department of Electrical Engineering,
National Ilan University,
26000,
TAIWAN

[2]Department of Electronic Engineering,
Army Academy,
320316,
TAIWAN

[*]*Corresponding Author*

Abstract: - This study simulates the correlation between traffic flow changes and incident handling times in a long tunnel, aiming to identify strategies to alleviate congestion. Using Aimsun simulation software, various traffic scenarios are modeled to evaluate congestion through indicators such as flow, total travel time, delay time, speed, mean queue, and density. The focus of the study is to observe changes in traffic flow and speed in tunnels during traffic accidents in order to establish parameters for determining road traffic congestion. Simulation results show that changes in these parameters during event processing can effectively indicate the degree of traffic congestion.

Key-Words: - Traffic jam, traffic control, traffic flow, traffic safety, tunnel traffic, congestion.

Received: April 9, 2024. Revised: September 4, 2024. Accepted: October 5, 2024. Published: November 1, 2024.

1 Introduction

Traffic congestion can be classified into recurrent and non-recurrent types. Recurrent congestion is a predictable occurrence that can be mitigated through measures such as building new roads and promoting ridesharing programs. Non-recurrent congestion, primarily caused by traffic accidents like vehicle disablements and flat tires, significantly impacts mobility in the United States, [1]. There is a symbiotic relationship between both types of congestion and traffic accidents, creating a vicious cycle that threatens mobility and safety, [2]. Strategic analysis methods are essential to enhance transportation system efficiency, with Intelligent Transportation Systems (ITS) playing a crucial role. ITS technologies address various congestion issues, including traffic accident detection [3], response logistics [4], communication [5] and utilization of ITS simulators to analyze freeway traffic [6]. Car accidents in urban areas can cause significant traffic jams, spreading across the network. Traffic jams arise from temporary obstructions, permanent capacity constraints, or stochastic demand fluctuations, [7]. This study focuses on congestion from grid network accidents, [8]. The main methods for traffic congestion prediction both domestically and internationally include neural network prediction [9], and deep learning prediction, [10]. The [11], proposed spatial and temporal features to predict short-term traffic flow. Traditional traffic control methods for Traffic Incident Management (TIM) on highways include lane control [12], variable speed limits [13], and ramp metering [14]. In urban areas, incident-based traffic congestion is primarily managed through traffic flow diversion by traffic police, which is labor-intensive, inflexible, and costly. Intelligent Transportation Systems (ITS), such as Advanced Traveler Information Systems (ATIS) [15], can enhance network efficiency by recommending alternative routes [16]. Real-time traffic information is delivered to drivers via in-car devices [17] and roadside devices, aiding in routing decisions, [18]. However, these devices have some limitations. Moreover, two traffic light strategies have been proposed for single-intersection control and network-wide control, such as minimizing the queue lengths described by an optimal traffic light switching scheme model and applying network-wide traffic control in large-scale, **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**, [19]. It is worth mentioning that a graphical analysis method unique to kinematic waves is used to depict the spatiotemporal trajectory of traffic waves near bottleneck sections. They found that when the traffic flow upstream of the bottleneck section is less than the capacity of the bottleneck section, traffic waves can smoothly propagate downstream of the bottleneck section without any backward propagation, [21]. However, within the bottleneck area, the propagation speed of traffic waves is slower than that upstream and downstream of the bottleneck. Conversely, when the traffic flow upstream of the bottleneck exceeds the capacity of the bottleneck section, traffic waves will propagate backward. When this backward-propagating traffic wave intersects with the next forward-propagating traffic wave, a backward-propagating shockwave is generated. As far as we know, the concept of motion waves has been successfully applied in traffic flow theory. Motion waves have the ability to describe traffic propagation changes on roads, such as traffic density, flow or speed. This is because they only focus on the movement of the traffic flow itself and do not consider the interaction between individual vehicles. Shock waves, on the other hand, are motion waves caused by local changes such as traffic accidents or traffic bottlenecks. Therefore, shock waves can be used to immediately trigger state behavior that result in sudden changes in traffic flow.

In this study, we address the issue of traffic congestion in long tunnel environments. By employing simulation methods, we aim to identify how the propagation of shockwaves causes vehicle queues, resulting in severe traffic congestion, particularly during peak hours.

2 Fundamental Concept

Kinematic waves are a fundamental concept in traffic flow theory, describing the movement of traffic as a wave-like phenomenon where changes in traffic density propagate through the traffic stream. Unlike dynamic waves, which consider the interactions between vehicles, kinematic waves focus solely on the movement of the traffic stream itself. These waves arise from the relationship between traffic density, flow, and speed, with changes in one parameter influencing the others.

For convenience, Figure 1, i.e., taken from [21], demonstrates the use of the flow-concentration curve to predict conditions near a shockwave. The shockwave is depicted as a heavy line on the space-time diagram on the right. Ahead of the shockwave, the traffic flow is denser, and the waves (represented by plain lines) are drawn parallel to the tangent to the flow-concentration curve at point A. Behind the shockwave, the concentration is lower and the waves travel faster; these waves are drawn parallel to the tangent to the curve at point B. The shockwave, which is formed by the convergence of these waves, travels at an intermediate speed and is represented by a line parallel to the chord AB. The mean vehicle paths (not shown) would be parallel to the radius vectors OB (behind the shockwave) and OA (ahead of it).

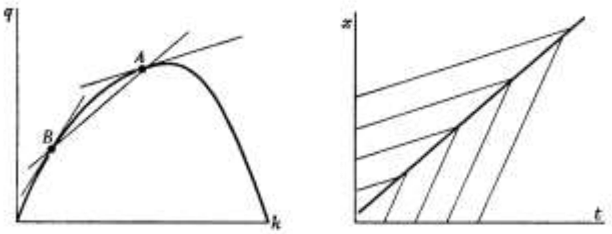

Fig. 1: Forming a shockwave, [21]

This study is mainly to observe the traffic operation conditions in the tunnel. Therefore, understanding the theory of motion waves is crucial for the modeling work and management technology of observing the traffic flow. As mentioned before, motion waves can provide insights into traffic congestion, shock waves and congestion dynamics. and other phenomena. The Lighthill-Whitham-Richards (LWR) model, [21] presents a theory of traffic flow on congested roads. This model provides significant foundational knowledge on traffic dynamics and congestion phenomena. In advance, it is an important concept is that motion waves, which can describe the propagation changes of instantaneous traffic flow density and traffic flow velocity along the road along the road. These motion wave models mainly provide parametric basis that is crucial for understanding traffic dynamics and congestion.

As we all know, the main contribution of the LWR model is to represent the traffic flow as a continuum, and the traffic flow will be regarded as a fluid with density and velocity fields that vary with time and space. It is based on the conservation laws of fluid dynamics, in short, where vehicle conservation corresponds to density and flow conservation is equated to velocity.

The LWR traffic flow model is a combination of partial differential equations. These partial differential equations can specifically describe changes in the density of traffic flow and the speed of traffic flow.

Overall, this study is based on the theoretical foundation of the LWR model to analyze and predict traffic congestion behavior on long tunnel roads.

3 Description of Road Facilities in the Xueshan Tunnel

The research focus on the Xueshan Tunnel, the longest tunnel in Taiwan, located on National Highway No. 5. The tunnel highway is currently the longest tunnel in Taiwan, i.e., Figure 2, connecting Taipei via New Taipei to Yilan County with a total length of 12.942 kilometers, reducing the driving time from two hours to half an hour.

Fig. 2: Location of the Xueshan Tunnel.

The tunnel is with two lanes in each direction, providing sufficient space to guarantee the smooth and safe movement of vehicles. In order to ensure the purpose of the safety of all drivers and maintain smooth traffic flow, the tunnel has established a comprehensive set of driving safety rules. Therefore, the regulations that must be followed when driving a vehicle through the Xueshan Tunnel.

Here are the regulations that must be followed when driving through the Xueshan Tunnel:

1. Vehicles must not exceed the speed limit of 90 km/h: The maximum speed limit is strictly enforced to ensure safe driving and prevent accidents within the tunnel, where visibility and maneuverability are more limited than on open roads.
2. The minimum speed limit is 70 km/h: To maintain a steady flow of traffic and avoid disruptions that could lead to bottlenecks or accidents, vehicles are required to travel at a minimum speed of 70 km/h, except in congested conditions.
3. Under normal conditions, vehicles must maintain a separation distance of 50 meters: This rule helps prevent rear-end collisions by ensuring that there is enough space for vehicles to stop safely in case of sudden braking or other emergencies.
4. Even in congested traffic, when driving at 10 km/h, a separation distance of 10 meters must still be maintained: Even at low speeds, maintaining a safe distance between vehicles is crucial to avoiding minor collisions and ensuring that traffic remains orderly.
5. Lane changes are prohibited across double solid lines: Double solid lines are a clear indication that lane changes are unsafe due to the structure of the tunnel or traffic conditions. Violating this rule could lead to accidents or disrupt the flow of traffic.
6. Parking is strictly prohibited in the tunnel: Stopping or parking in the tunnel can create dangerous situations by obstructing traffic and increasing the risk of collisions, especially given the confined space and limited visibility. In case of emergencies, drivers should pull over to designated emergency areas rather than stopping in the main tunnel lanes.

By following these regulations rules, one can ensure a safer and more efficient travel experience in the Xueshan Tunnel, while also helping to minimize the risks of accidents and traffic delays.

In addition, the Xueshan Tunnel traffic control system is equipped with:

1. Lane Control Signal (LCS): The LCS displays a green arrow (→) or red × icon to indicate whether the lane is currently open, closed, or requires attention due to an accident or maintenance work ahead.
2. Camera Monitor System: The tunnel is equipped with a network of Closed-Circuit Television (CCTV) cameras that provide real-time video feeds to the control center. The cameras monitor traffic conditions continuously throughout the day and can be used for immediate traffic management as well as for post-accident reviews to improve future safety measures.
3. Broadcast Speaker System: The tunnel is equipped with a loudspeaker system that allows administrators to broadcast directly to motorists inside the tunnel. In addition to broadcasting emergency traffic alerts, the system can also issue general traffic updates, such as lane closures or maintenance work, to ensure drivers are aware of changing road conditions.
4. Variable Message Signs (VMS): VMS systems are used to display important traffic information, warnings, and advisory messages to drivers. They are important tools for managing traffic flow and ensuring safety, especially in dynamic or rapidly changing situations such as congestion or accidents.

These traffic control system facilities help keep traffic flowing while minimizing the risks associated with accidents, vehicle breakdowns, and other incidents.

4 Simulation Results

In current traffic research, using simulation software to evaluate traffic management strategies has become a highly effective method. Simulation software not only allows for real-time adjustment of road information with visual animation effects but also provides detailed network data and feedback in the form of databases. Among these, Aimsun software is particularly valuable, offering simulations for various scales, including traffic microsimulation models and traffic mesoscopic simulation models.

According to the commissioned research report reviewing the driving safety regulations for the Xueshan Tunnel, when the traffic flow in the tunnel is maintained between 2,000 and 2,200 vehicles per hour, the speeds in both the northbound and southbound directions can stay above 80 kilometers per hour. However, if the traffic flow exceeds 2,200 vehicles per hour, a significant drop in speed occurs. The southbound traffic only experiences a speed reduction on Saturday mornings due to increased traffic flow, while the northbound traffic shows more noticeable speed fluctuations. Congestion begins on Saturday afternoons and reaches its peak on Sunday afternoons. This work aims to use simulations to identify where shockwave effects occur and develop strategies to alleviate congestion in the Xueshan Tunnel. The simulated road environment is constructed directly from Google Maps data (i.e., shown in Figure 3). Aimsun's road monitoring information is based on the existing road facilities, with the Xueshan Tunnel's two-lane road width of 3.5 meters being used for planning. To simulate the shockwave effects under various traffic flows, the simulation models five different traffic volumes within the Xueshan Tunnel: 500 vehicles/hour, 1000 vehicles/hour, 1500 vehicles/hour, 2000 vehicles/hour, and 2500 vehicles/hour. These different traffic volumes can accommodate traffic analysis for the Xueshan Tunnel at any time of day.

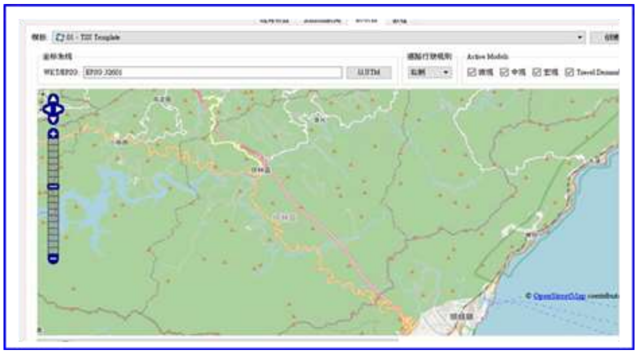

Fig. 3: The simulated road environment is constructed directly from Google Maps data

To facilitate the observation of traffic state changes caused by the formation of shockwaves, this study simulates an incident by adding a traffic signal to the road network, representing an accident site located 2157.05 meters from the tunnel entrance in the northbound lane. The traffic signal remains red to simulate the accident duration. For analysis, the simulation includes traffic events of 5, 10, 15, 20, 25, 30, 35, and 40 minutes (i.e., the duration the signal remains red), causing congestion that begins to spread. We then observe and compare the vehicle speed and vehicle count at distances of 250, 500, 1000, and 2000 meters downstream from the accident site.

Case I: First, under the condition of a traffic flow of 500 vehicles per hour and a driving speed set at 90 km/h, simulations were conducted for eight different accident durations (i.e., from the start of the accident to its clearance). The accident durations were set at 5, 10, 15, 20, 25, 30, 35, and 40 minutes. The simulation data obtained are shown in Figure 4, which represents the average driving speed.

In Figure 4, we can clearly observe the relative curves of average driving speed upstream of the accident site for accident durations ranging from 5 to 40 minutes. During the initial 5 to 10 minutes of the accident duration, the average driving speed generally remains close to normal.

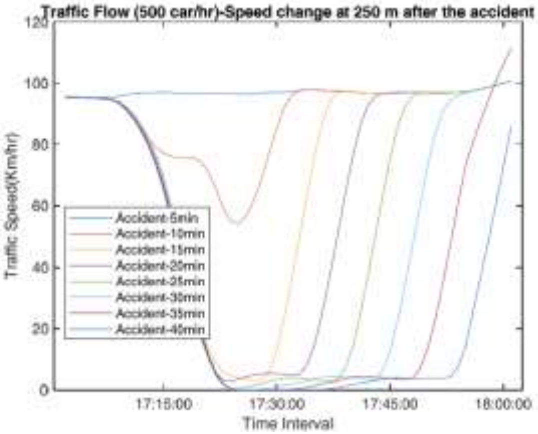

Fig. 4: The average driving speed in the eight different accident durations

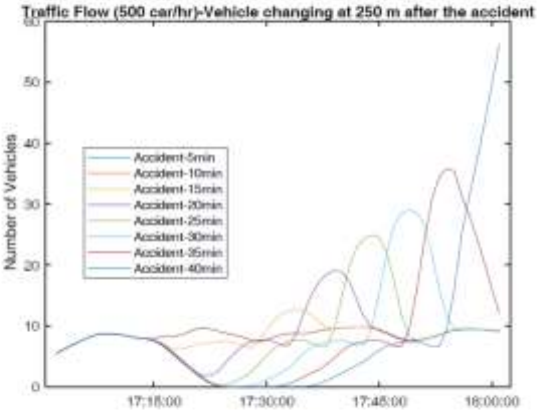

Fig. 5: The number of vehicles passing through the zone in the eight different accident durations

However, as the accident duration extends from 15 to 40 minutes, the congestion time for traffic flow increases from approximately 7 minutes to 30 minutes. Moving forward, in Figure 5, we illustrate the number of vehicles passing through 250 meters downstream of the accident site for a traffic flow of 500 vehicles per hour and accident durations ranging from 5 to 40 minutes. It can be observed that during the first 5 to 10 minutes of the accident duration, there is little variation in the number of vehicles passing through. However, as the accident duration extends from 15 to 20 minutes, the number of vehicles passing through gradually decreases. Beyond 15 to 40 minutes of accident duration, some vehicles are observed to come to a stop for approximately 20 seconds to around 12 minutes.

Case II: Under the same assumptions as Case I, this simulation only changes the traffic flow from 500 vehicles per hour to 1000 vehicles per hour. The resulting simulation data is summarized in Figure 6.

In Figure 6, it is evident that the driving speed of all vehicles decreases to 5 km/h. Additionally, as the accident duration extends and the clearance time increases, not only do driving speeds decrease further, but the duration of slow driving also lengthens. Until the accident duration reaches 15 minutes, some vehicles are observed to come to a stop for approximately 2 to 15 minutes. At 500 meters upstream of the accident site, the situation is generally similar to that observed at 250 meters upstream. At 10000 meters upstream of the accident site, apart from a slight decrease in driving speed within the first 5 minutes of the accident, the driving speed returns to normal. However, after the accident duration reaches 10 minutes, some vehicles are observed to come to a stop. This observation is reflected in the curve of vehicle passage shown in the graph, indicating the occurrence of congestion.

Case III: Under the same assumptions as Case II, this simulation only changes the traffic flow from 1000 vehicles per hour to 1500 vehicles per hour.

When the traffic flow increases from 1000 to 1500 vehicles per hour, the simulation results remain similar. This indicates that the shockwave effect continues to propagate upstream without dissipating. Therefore, to save space, the details of these simulation outcomes are omitted.

Case IV: Under the same assumptions as Case III, this simulation only changes the traffic flow from 1500 vehicles per hour to 2000 vehicles per hour. The resulting simulation data is summarized in Figure 7.

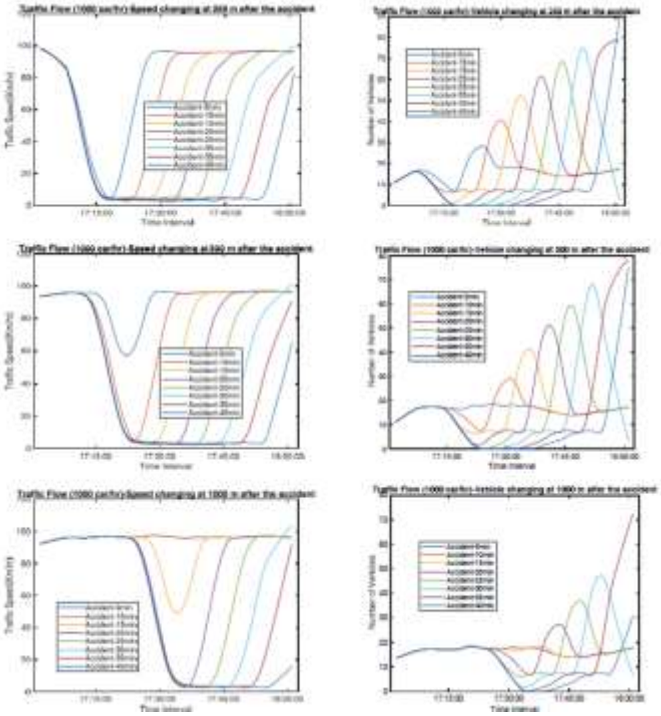

Fig. 6: Case II: the average driving speed and the number of vehicles passing through the zone in the eight different accident durations

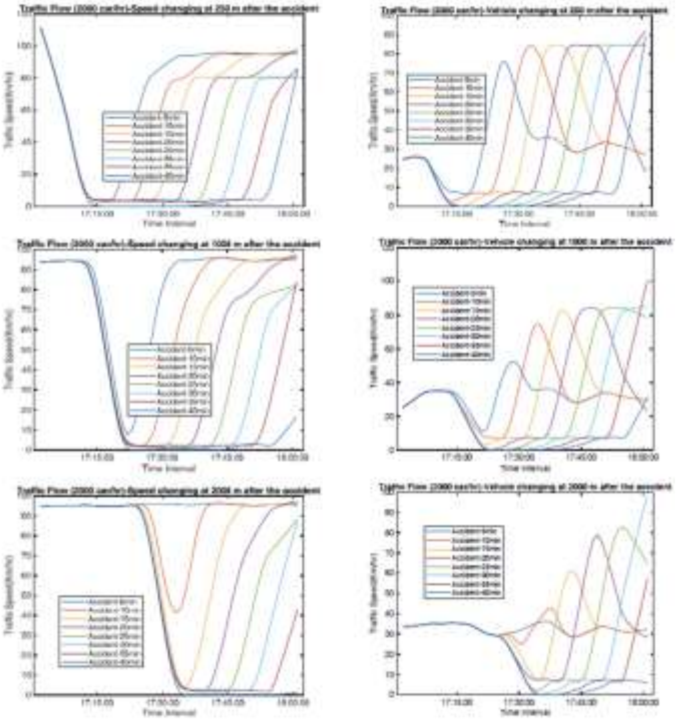

Fig. 7: Case IV: the average driving speed and the number of vehicles passing through the zone in the eight different accident durations

In Figure 7, the simulation results are essentially similar. At 500 meters upstream of the accident site, the conditions are largely unchanged compared to 250 meters upstream. The simulation indicates that the shockwave effect continues to propagate 500 meters upstream without dissipating.

This study primarily simulates accidents within the Xueshan Tunnel under varying traffic volumes to observe the impact of shockwave effects on traffic flow. The findings based on different traffic volumes are as follows:

1. Low Traffic Volume (500-1000 vehicles per hour): When the traffic flow is low, the shockwave effect occurs within approximately 1000 meters upstream of the accident site and does not extend further upstream.
2. Medium Traffic Volume (1000-1500 vehicles per hour): With medium traffic flow, the shockwave effect is observed within 500 meters upstream of the accident site and continues to propagate further upstream, but it dissipates quickly.
3. High Traffic Volume (2000-2500 vehicles per hour): At high traffic volumes, the shockwave effect occurs within 2500 meters upstream of the accident site and continues to propagate further upstream without dissipating quickly.

The preliminary simulation results indicate that by using two primary parameters—traffic volume and the duration from the occurrence to the clearance of an accident—the location of shockwave effects can be predicted. Utilizing variable speed limit signs upstream of the shockwave can help in adjusting vehicle speeds, facilitating quicker dissipation of the shock wave effect, and thereby alleviating congestion in the Xueshan Tunnel.

5 Conclusion

The main focus of this article is on the existing facilities on the Xueshan Long Tunnel Road. Taking different traffic flows into consideration, the Aimsun simulation software tool is used to collect relevant traffic data to analyze the impact of shock waves on the traffic flow in different tunnels.

The main purpose of the research is to understand the key effects of shock waves on the propagation of traffic flow through the formation and propagation of shock waves caused by various traffic flows of different sizes.

First, an Aimsun simulation road model was established based on the existing tunnel facilities. The model incorporates factors such as the number of lanes, traffic flow, vehicle types, driving speeds, and traffic control measures in the tunnel. By inputting these parameters, we hope to simulate real traffic conditions and improve the reliability and accuracy of the simulation results.

Secondly, we added traffic accident scenarios to different traffic flows to facilitate the observation of the impact of traffic accidents on traffic in the tunnel. The characteristics of shock waves caused by traffic accidents were analyzed in detail in different traffic flows including peak and non-peak hours.

Furthermore, the simulation results were used to observe how traffic queues are formed in the tunnel, how shock waves propagate from the accident site upstream, and the impact of these shock waves on the overall traffic flow.

Research results show that when a traffic accident occurs in a tunnel, varying degrees of traffic congestion and shock waves are produced regardless of the size of the traffic flow. High traffic volumes, especially during peak hours, can exacerbate these phenomena and lead to longer delays. Conversely, during off-peak hours, although the shock wave still exists, the impact is relatively small and traffic flow can return to normal faster.

Finally, we propose several mitigation strategies, such as dynamic traffic management strategies and the use of alternative routes, to reduce the negative impact of tunnel closures on traffic flow.

In summary, this study uses Aimsun simulation software to conduct a detailed analysis of the impact of long tunnels on different traffic flows based on the existing facilities on Xueshan Long Tunnel Road, providing valuable data and suggestions for future traffic management decisions.

Acknowledgment:

This work is partially supported by the National Science Council of Taiwan, under Grant NSTC 113-2622-8-A49-011-SB2 and NSTC 112-2221-E-197-025.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the authors used ChatGPT, to check for grammar errors. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References:

[1] Peter T. Martin, *Traffic Incident Management State of the Art Review, MPC-10-229B*, Civil and Environmental Engineering University of Utah, Sep. 2011.

[2] Neudorff, L., J. Randall, *Freeway Management and Operations Handbook, Report FHWA-OP-04- 003*, U.S. Department of Transportation, FHWA, September 2003

[3] B. M. Williams, and A. Guin, “Traffic management center use of incident detection algorithms: findings of a nationwide survey,” *IEEE Trans. Intell. Transp. Syst.*, vol. 8, Jun. 2007, pp. 351-358.

[4] K. G. Zografos, K. N. Androutsopoulos, and G. M. Vasilakis, “A real-time decision support system for roadway network incident response logistics,” Transp. Res. Part C, vol. 10, Feb. 2002, pp. 1–18.

[5] R. N. Mussa, and J. E. Upchurch, “Monitoring urban freeway incidents by wireless communications,” *Transp. Res. Rec.*, vol. 2001, Jan. 2007, pp.153–160.

[6] L. Figueiredo, J. A. Tenreiro Machado, and J. R. Ferreira, “Dynamical analysis of freeway traffic”, *IEEE Trans. Intell. Transp. Syst.*, vol. 5, Dec. 2004, pp.259–266.

[7] C. Wright, and P. Roberg, “The conceptual structure of traffic jams,” *Transp. Policy*, vol. 5, Jan. 1998, pp. 23–35.

[8] L. Qi, M. C. Zhou, and W. Luan, “A dynamic road incident information delivery strategy to reduce urban traffic congestion,” *IEEE/CAA Journal of Automatica Sinica*, vol.5, Sep. 2018, pp. 934–945.

[9] Li, Z., Liu, F., Yang, W., Peng, S., Zhou, J., “A Survey of Convolutional Neural Networks: Analysis, Applications, and Prospects,” *IEEE Transactions on Neural Networks and Learning Systems*, vol. 33, Dec. 2022, pp. 6999–7019.

[10] Fang, W., Zhuo, W., Yan, J., Song, Y., Jiang, D., Zhou, T., “Attention meets long short-term memory: A deep learning network for traffic flow forecasting,” *Phys. A: Stat. Mech. Its Appl.*, vol. 587, Feb. 2022, 126485.

[11] W. Zhang and Y. Yu, “Short-term Traffic Flow Prediction Based on Spatio-temporal Analysis and CNN Deep Learning,” *Transportmetrica A: Transport Science*, vol. 15, July 2019, pp.1-45.

[12] M. Jha, D. Cuneo, and M. Ben-Akiva, “Evaluation of freeway lane control for incident management,” *J. Transp. Eng.*, vol. 125, Dec. 1999, pp. 495−501.

[13] P. W. Lin, K. P. Kang, and G. L. Chang, “Exploring the effectiveness of variable speed limit controls on highway work-zone operations,” *J. Intell. Transp. Syst.*, vol. 8, 2004, pp. 155−168.

[14] J. B. Sheu and M. S. Chang, “Stochastic optimal-control approach to automatic incident-responsive coordinated ramp control,” *IEEE Trans. Intell. Transp. Syst.*, vol. 8, Jun. 2007, pp. 359−367.

[15] F.-Y. Wang, N.-N. Zheng, D. P. Cao, C. M. Martinez, L. Li, and T. Liu, “Parallel driving in CPSS: a unified approach for transport automation and vehicle intelligence,” *IEEE/CAA J. of Autom. Sinica*, vol. 4, Oct. 2017, pp. 577−587.

[16] G. Xiong, F. H. Zhu, X. W. Liu, X. S. Dong, W. L. Huang, S. H. Chen, and K. Zhao, “Cyber-physical-social system in intelligent transportation,” *IEEE/CAA J. of Autom. Sinica*, vol. 2, Jul. 2015, pp. 320− 333.

[17] F.-Y. Wang, “Parallel control and management for intelligent transportation systems: concepts, architectures, and applications,” *IEEE Trans. Intell. Transp. Syst.*, vol. 11, Sep. 2010, pp. 630−638.

[18] M. Papageorgiou, C. Diakaki, V. Dinopoulou, A. Kotsialos, and Y. B. Wang, “Review of road traffic control strategies,” *Proc. IEEE*, vol. 91, Dec. 2003, pp. 2043−2067.

[19] Y. S. Huang, Y. S. Weng, and M. C. Zhou, “Modular Design of Urban Traffic-Light Control Systems Based on Synchronized Timed Petri Nets,” *IEEE Trans. Intelligent Transportation System*, 15(2):530-539, 2014.

[20] J. Luo, Y. S. Huang, and Y. S. Weng, “Design of Variable Traffic Light Control Systems for Preventing Two-Way Grid Network Traffic Jams Using Timed Petri Nets,” *IEEE Trans. Intelligent Transportation System*, vol. 21(7) , 2020.

[21] M. J. Lighthill and G. B. Whitham, “On kinematic waves. II. A theory of traffic flow on long crowded roads,” *Proc. R. Soc. Lond. A, Math. Phys. Sci.*, vol. 229, May 1955, pp. 317–345.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Yi-Sheng Huang and Yi-Shun Weng organized and analyzed the simulation results and optimization process.
- Shi-Xiong Dong and Wei-Chih Wang conducted the simulation using Aimsun.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

This work is partially supported by the National Science Council of Taiwan.

Conflict of Interest

The authors have no conflicts of interest to declare.

Creative Commons Attribution License 4.0 (Attribution 4.0 International, CC BY 4.0)