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Traffic Shockwave Analysis at Signalized Intersections

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ABSTRACT

The relationship among flow, density, and speed represents the fundamental and most important properties in traffic flow theory. The purpose of this study is to analyse shockwaves at a signalized intersection. At such an intersection, a green light allows vehicles to move freely at their desired speeds until the signal changes to red, at which point vehicles must stop. During the red phase, vehicles queue up, the flow becomes zero, and the density reaches jam density. When the signal turns green again, the flow increases from zero to a maximum value, referred to as the dissipation state. Experimental data for shockwave analysis were obtained by observing a single-lane closure at a four-legged intersection. Traffic counts were recorded at 15-minute intervals over an hour and then converted to vehicles per hour for flow calculations; similar conversions were applied to speeds and densities. Shockwave speeds during both the accumulation state and the dissipation state were calculated using the average values from peak A.M., off-peak A.M., peak P.M., and off-peak P.M. periods of the data collection days. These calculated wave propagation speeds were compared with directly measured values obtained from the flow–density–speed relationship. Additionally, other parameters such as the maximum queue length and the dissipation time at the end of the red phase were determined, as these are also critical in traffic shockwave analysis.

1. Introduction

Road traffic plays a vital role in sustaining the global economy, yet the limited space available for road expansion continues to present challenges (Diyar, 2017). To maintain the steady flow of traffic under such constraints, intelligent transport systems (ITS) have become increasingly important. These systems rely on the exchange of large volumes of data, enabling communication between infrastructure and drivers, between infrastructure and vehicles, and among vehicles themselves (Abejide and Adedeji, 2024). The goal is to support safe, smooth, and economical traffic operations by enhancing traffic management and mitigating congestion. The study of traffic behaviour and the creation of road infrastructure that supports effective traffic operations are essential components of traffic engineering. Traffic stream parameters must be thoroughly understood to comprehend how traffic behaves at both route segments and intersections (Rompis, 2018). According to Rompis (2018) and Gaddam and Rao (2019), these metrics are typically divided into measurements of quantity, such as density and flow, and measures of quality, such as speed. The lane flow equation, which contrasts the quantitative and qualitative features of traffic streams, captures the link between these characteristics. The intricate blending of driver and vehicle behaviour, both of which are fundamentally irregular, is represented by traffic streams. Nonetheless, bottleneck conditions, which can result from collisions, lane reductions, work zones, or the commencement of red signals at crossings, commonly impede traffic flow (Hale et al., 2016; Khan et al., 2018; Abramova et al., 2020). The road capacity is abruptly reduced as a result of such occurrences, which shifts the ideal density accordingly. These circumstances give rise to a phenomenon called a shockwave, which is defined by sudden variations in vehicle densities and speeds that spread across the traffic stream (Levinson et al., 2019; Sakhare et al., 2023).

Shockwaves are particularly concerning for transportation agencies because they can drastically disrupt intersection efficiency and increase the chance of crashes (Junhua et al., 2016; Sakhare et al., 2023). Although sometimes overlooked, the transition from normal flow to shockwave conditions has been connected to accidents, some of which have significant effects (Levinson et al., 2019). The traffic conditions at these crossroads have worsened over time because of rapid population expansion, increased car ownership, rising commuter demand, and overemphasis on minimum distance rules (Stępniak and Rosik, 2018; Ukonze et al., 2020). These variables increase congestion and exacerbate the occurrence of shockwaves, lowering overall traffic efficiency and safety. In this context, the purpose of this research is to investigate the generation and propagation of shockwaves at the Mobi signalized intersection in Niger State, Nigeria. The findings are intended to provide useful insights into the causes, features, and repercussions of shockwaves within the traffic stream, establishing a foundation for enhanced traffic management and safer roadway operations in Niger State and beyond.

1.1. Shockwave in the traffic stream

Shockwaves are boundary conditions between two separate traffic states with varying densities, velocities, and flow rates (Motamedidehkordi, 2016; Tsuboi, 2021). This phenomenon is distinguished by a sudden shift in roadway capacity or traffic demand, resulting in a disruption in the traffic flow. Crashes, lane restrictions, work zones, and the commencement of red signals at junctions are major causes of these disturbances (Hale et al., 2016). Under such situations, highway capacity decreases, altering the optimal density and causing vehicles to slow down when passing over the bottleneck. When the roadway capacity suddenly improves, shockwaves may propagate in the opposite direction, causing vehicles to accelerate as they travel through the improved portion. This finding highlights the bidirectionality of shockwave dynamics in traffic flow. Shockwave analysis is especially relevant at signalized crossings because of the recurring process of queue development and dissipation (Horváth and Tettamanti et al., 2021). Long lineups can exceed the available storage capacity, disrupt adjacent movements, or block adjoining junctions, emphasizing the importance of understanding and predicting shockwave behaviour in such circumstances.

1.2. Shockwave classification

The classification of shockwaves in traffic flow has been addressed by multiple researchers (Junhua et al., 2016; Anuar and Cetin, 2017; Sakhare et al., 2023), with common categories focusing on the direction of propagation and the cause of the disturbance. Garber and Hoel (2009) identified four principal types: frontal stationary shockwaves, backwards forming shockwaves, backwards recovery shockwaves, and rear stationary with forward recovery shockwaves.

These categories broadly align with earlier works, such as Lighthill and Whitham’s kinematic wave theory, which also recognized that the propagation of discontinuities is influenced by changes in demand relative to capacity. A frontal stationary shockwave forms when capacity abruptly falls to zero, typically observed during a red signal at intersections or in the aftermath of severe crashes (Garber and Hoel, 2009; Sakhare et al., 2023). These waves are stationary because the queue remains fixed at a location until the bottleneck condition is removed. In contrast, backwards-forming shockwaves emerge when demand exceeds capacity, producing a queue that propagates upstream. This form of shockwave has been widely studied in freeway congestion, where recurrent bottlenecks at merges or lane drops generate consistent upstream-moving disturbances. Backwards recovery shockwaves occur when the restrictive condition is lifted, such as when a signal turns green (Garber and Hoel, 2009; Sakhare et al., 2023). Vehicles at the front of the queue begin to accelerate, and the wave of recovery moves upstream through the queued vehicles. These processes are illustrated in Figure 1, which shows how frontal stationary, backwards forming, and backwards recovery shockwaves emerge at a signalized intersection under alternating red and green phases.

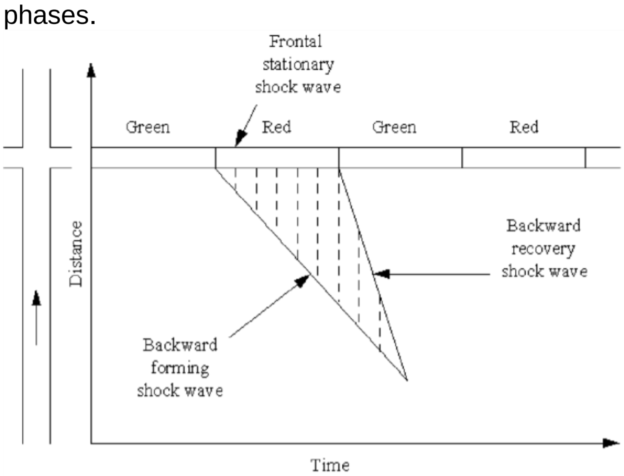

Figure 1. Shockwave phenomenon at a signalized intersection *(Source: May, 1990)*

Finally, rear stationary and forward recovery shockwaves represent mixed conditions, where upstream demand initially exceeds capacity but later stabilizes, resulting in both stationary and moving recovery effects (Garber & Hoel, 2009). Although these four categories provide a structured classification, later studies argued that the boundaries between types are often fluid. For example, Daganzo (1997) emphasized that shockwaves should be interpreted as transitions between traffic states rather than rigid types since real-world traffic often exhibits hybrid behaviours. Similarly, Levinson et al. (2019) highlighted that shockwave severity depends not only on traffic demand and capacity but also on geometric design, signal timing, and driver behaviour, making classification context dependent.

Taken together, the literature demonstrates that while the taxonomy of shockwaves provides a useful framework, the diversity of roadway environments and traffic conditions requires flexible interpretation. Researchers and practitioners often use these categories as reference points for modelling and simulation, but in practice, overlapping or compound shockwaves are frequently observed in congested networks.

1.3. Speed of Shockwave

The speed of a shockwave reflects the rate at which changes in the traffic state propagate through the flow. Conceptually, shockwaves are discontinuities in traffic density or flow and have the physical implication that vehicles change speed abruptly without gradual acceleration or deceleration (Sakhare et al., 2023). At a signalized intersection, for example, the onset of the green signal produces a recovery shockwave as queued vehicles begin moving forward. This transition is characterized by rapid changes in density and speed along the queue. The velocity of a shockwave is typically calculated via the flow–density relationship of traffic streams. The shockwave speed can be calculated as the slope of the chord connecting two locations associated with different densities, such as kA and kB, on the fundamental diagram of flow and density (May, 1990). Figure 2 depicts how changes in density and flow result in shockwave propagation along both the flow–density curve and a time–space diagram.

Understanding shockwave speed has numerous uses in traffic engineering. This enables researchers and practitioners to examine the characteristics of traffic congestion and estimate its impact on network performance. It is also used for calibrating fundamental diagrams, which are the foundation of many traffic flow models. Furthermore, the shockwave speed is critical for evaluating travel durations along highway segments, determining overall delays at intersections, and developing novel traffic operation and management approaches. Shockwave theory is a key component of current traffic flow analysis because of its capacity to forecast and quantify the spread of traffic disturbances. Data gathering for shockwave analysis can be performed manually or with the help of technology tools such as loop detectors, cameras, or other sensors. These approaches produce traffic flow data in the form of time series, with metrics including flow, speed, and occupancy (a dimensionless representation of density) monitored at regular intervals. Depending on the study's goal, data might be collected at intervals ranging from a few seconds to many minutes. Engineers can use these series to capture fluctuations in demand over time and space, such as those that occur at highway entrances, arterial segments, or signalized intersections. These data provide an empirical basis for identifying shockwave creation and estimating its speed, making them essential for both research and practice.

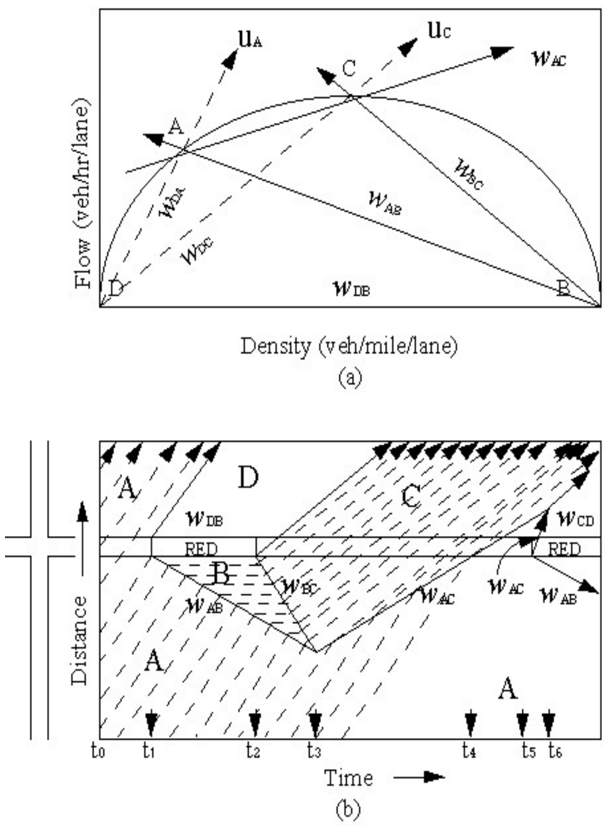

Figure 2. (a), (b) Fundamental diagram for shockwave analysis at an intersection *(Source: May, 1990)*

2. Methodology

To achieve the study's aim, quantitative (manual traffic count) and qualitative (traffic properties and interaction features) methods were employed as research techniques (Gray, 2021). Data collection was conducted via a traffic tally sheet, which facilitated the systematic recording and classification of vehicles on the basis of both vehicle type and travel direction. A validated nine-hour daily traffic count was performed from 08:00 to 17:00 for a period of seven consecutive days at the designated study site, ensuring the temporal consistency and reliability of the dataset.

2.1. Study Area

The study was conducted at the Mobi signalized intersection, which is located in a suburban area of Minna, the capital of Niger State, Nigeria. Minna lies within the Middle Belt region and is geographically situated at approximately 9°37′8.70″N latitude and 6°32′46.93″E longitude (Google Maps, 2024). The city is positioned northwest of the Federal Capital Territory (Abuja) and functions as a significant administrative and transportation hub within the region. According to the 2006 National Population Census, the population of the Chanchaga Local Government Area, which encompasses Minna, was 201,429, comprising 105,803 (National Population Commission of Nigeria, 2006).

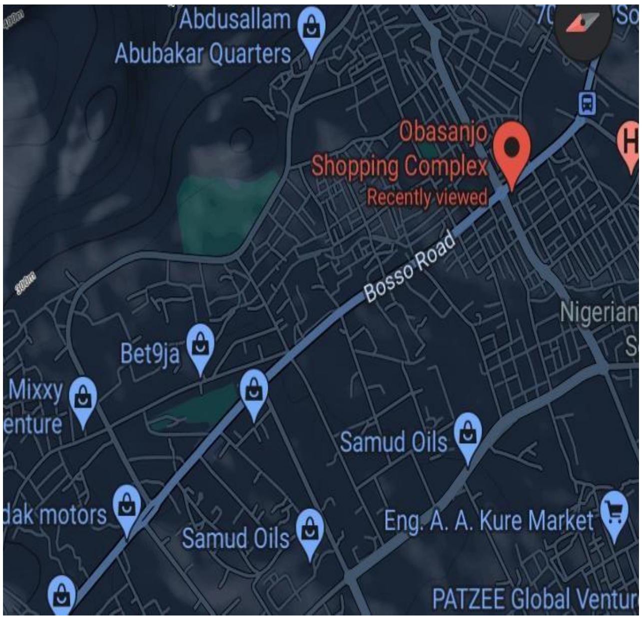

Figure 3. Study Area Map

The Mobi intersection is strategically bounded by the Obasanjo Shopping Complex along the Minna–Zungeru Road, with intersecting approaches from General Hospital Road, A.Y. Shafa Filling Station, and Bosso Road. These corridors serve as key access routes to important economic, social, and educational activity zones within the city. Owing to the presence of a signalized traffic control system, the intersection experiences periodic disruptions in traffic flow, which in turn contribute to the formation of traffic shockwaves—a phenomenon typically associated with sudden stops and queue dissipation during signal cycles.

2.2. Measurement of Traffic Flow

The flow rate, also known as the traffic volume, is the average number of vehicles, n per unit time, t at a given instance (Abramova et al., 2020). The traffic flow for the shockwave at the intersection is determined by counting the number of vehicles in the traffic stream while approaching the signal (free flow condition) and while dissipating the queue after meeting the red signal indication.

$$Q = \frac{n}{t} \quad (1)$$

2.3. Measurement of Traffic Density

Density is the number of vehicles, n per unit length, where l at any instance in a traffic stream. The traffic density for the shockwave at the intersection is determined by counting the number of vehicles occupying the intersection lane at an approach (free-flow state), when the signal turns red and is in the queue (stationary state), and when the vehicles are dissipating the queue and dividing by the length of the lane.

$$K = \frac{n}{l} \quad (2)$$

2.4. Traffic Volume Measurement

Traffic data were collected via 15-minute interval counts, denoted as vehicles per 15 minutes (vp). These raw counts were subsequently converted to vehicles per hour (vph) to determine traffic flow rates. For a given number of vehicles (n) observed passing through a specific lane of the intersection over a 15-minute interval, the flow rate (q) in vehicles per hour is calculated via the following relation:

$$q = \frac{n \; x \; 60}{15} \left(\frac{veh}{hr}\right) \quad (3)$$

3. Data analysis

Traffic data were collected over a period of seven consecutive days. For the purpose of analysis, the average vehicle volumes were computed for four distinct time categories: A.M. peak, A.M. off-peak, P.M. peak, and P.M. off-peak periods. These average values formed the basis for assessing daily traffic patterns and evaluating variations in flow characteristics across different times of the day.

3.1. Fundamental Shockwave Analysis

As shown earlier in Figure 2 (a) and (b), the density for state B represents the jam density (k_j), whereas the flow during state C is the maximum flow rate (q_{max}). Where AB is the accumulating wave and BC is the dissipating wave. Then, the speed of the shockwaves can be calculated via equations (4) and (5):

$$\omega_{AB} = \frac{q_A}{k_A - k_j} \quad (4)$$

$$\omega_{BC} = \frac{q_{max}}{k_c - k_j} \quad (5)$$

where ω_{AB} and ω_{BC} are the backwards forming and backwards recovery shockwave speeds, respectively. Additionally, the maximum queue length (Q_M) and the dissipation time (T_d) at the end of the red phase can be calculated via equations (6) and (7) (Khan, 2018):

$$Q_M = \frac{r}{3600} \; X \; \frac{\omega_{AB} \; X \; \omega_{BC}}{\omega_{BC} - \omega_{AB}} \quad (6)$$

$$T_d = r \; X \; \frac{\omega_{AB}}{\omega_{BC} - \omega_{AB}} \quad .(7)$$

4. Results and Discussion

This section presents the analysis of the data collected at the lane of the Mobi signalized intersection, which includes the determination of the speed of the shockwave (backwards forming and backwards recovery), the maximum queue length and the dissipation time at the end of the red phase for the A.M. peak, A.M. off-peak, P.M. peak and P.M. off-peak.

4.1. Traffic Flow Analysis

Shockwave analysis is of particular interest, especially for signalized intersections where the vehicle flow is distinctively transformed from one state to another.

Table 1. Traffic Properties for the Peak AM of the Days

$q_A(veh/hr)$	$k_A(veh/km)$	$q_B(veh/hr)$	$k_B = k_j(veh/km)$	$q_C = q_{max}(veh/hr)$	$k_C(veh/km)$
3176	9925	0	14975	4440	13875
2908	9088	0	16250	4492	14038
2884	9013	0	15875	4216	13175
2900	9063	0	18925	4516	14113
2896	9050	0	19113	4800	15000
2664	8325	0	16538	4328	13525
2376	7425	0	18488	4180	13063

Table 2. Traffic Properties for the Off-peak A.M. of the days

$q_A(veh/hr)$	$k_A(veh/km)$	$q_B(veh/hr)$	$k_B = k_j(veh/km)$	$q_C = q_{max}(veh/hr)$	$k_C(veh/km)$
2548	7962	0	16213	4416	13800
2296	7175	0	16550	4040	13375
2316	7238	0	16775	4008	12525
2120	6652	0	14625	3628	11338
1632	5075	0	12200	3036	9488
1472	4600	0	12013	2740	8563
1668	5213	0	14125	3092	9663

4.2. Analysis of Shockwave speed

The following are the properties of the lane determined from the field that are used for the analysis:

- Number of days = 7
- Length of the lane (L) = 80 m (0.08 km)
- Red time (r) = 63 seconds
- Green time (g) = 48 seconds
- Amber time (a) = 3 seconds

Shockwave speeds for A.M. Peak: According to equations (4) and (5), the speeds of the shockwaves for the sections are -0.34km/hr for section AB and $-1.33 km/hr$ for section BC. Therefore, the maximum queue length and the dissipation time at the end of the red phase from equations 6 and 7 are $-7.99m$ and $21.64 secs$, respectively.

Shockwave speeds *for A.M. Off-peak*: From equations (4) and (5), the speeds of the shockwaves for the sections are $-$ 0.24km/hr for section AB and $-1.05 km/hr$ for section BC. Therefore, the maximum queue length and the dissipation time at the end of the red phase from equations 6 and 7 are $-5.44m$ and $18.67 secs$, respectively.

At Peak AM, the maximum queue length is 7.99 m, and it takes 21.64 secs of the 48 secs of green time to dissipate the queue because the traffic is higher during the early hour of the day. In addition, at the Off-Peak AM, the maximum queue length is 5.44 m, and 18.67 secs of the 48 secs of the green time are needed to dissipate the queue, as the traffic is not as high as the early hour where there are more road users.

Table 3. Traffic properties for the peak P.M. of the days

q_A (veh/hr)	k_A (veh/km)	q_B (veh/hr)	$k_B = k_j(veh/km)$	$q_C = q_{max}$ (veh/hr)	$k_C(veh/km)$
3188	9963	0	21738	4876	15238
2868	8963	0	18088	4716	14738
2976	9300	0	18213	4752	14825
2852	8913	0	17550	4632	14475
3624	11325	0	25125	5652	17663
2724	8513	0	16850	4308	13463
2536	7925	0	17650	4272	13350

Shockwave Speeds *for P.M. Peak*: According to equations (4) and (5), the speeds of the shockwaves for the sections are -0.30km/hr for section AB and -1.06km/hr for section BC. Therefore, the maximum queue length and the dissipation time at the end of the red phase from equations 6 and 7 are $-7.32m$ and $24.87 secs$, respectively.

Table 4. Traffic Properties for the Off-peak P.M. of the days

$q_A(vehhr)$	$k_A(veh/km)$	$q_B(veh/hr)$	$k_B = k_j(veh/km)$	$q_C = q_{max}(veh/hr)$	$k_C(veh/km)$
2464	7700	0	16825	4264	13325
2308	7213	0	15600	3988	12463
2236	6988	0	13788	3892	12163
2296	7177	0	14088	3928	12275
2196	6863	0	14200	3980	12438
1976	6175	0	13138	3592	11225
1780	5563	0	13438	3136	9800

Shockwave Speeds *for P.M. Off*-peak: According to equations (4) and (5), the speeds of the shockwaves for the sections are -0.29 km/hr for section AB and -1.60km/hr for section BC. Therefore, the maximum queue length and the dissipation time at the end of the red phase from equations 6 and 7 are $-6.20m$ and $13.95 secs$, respectively. At peak P.M., the maximum queue length is 7.32 m, and the average dissipation time of the queue is 24.87 s, which is greater than that of peak A.M because the road users return to each of their various residences. During the off-peak P.M., the dissipation time is 13.95 s to 48 s of green time because the traffic during this period is not usually high and consists mostly of a free-flow period.

5. Discussion

The computed values of the shockwave speeds of the accumulating wave (AB) for the A.M peak, A.M off-peak, P.M peak and P.M off-peak are -0.34 km/hr, -0.24 km/hr, - 0.30 km/hr, and -0.29 $km/hr,$ and those of the dissipating wave (BC) are -1.33 km/hr, - 1.05 km/hr, - 1.06 km/hr, and -1.60 $km/hr,$ respectively. The negative signs reflect the propagation of the waves (backwards). The speed of the accumulating wave (AB) is the backwards forming speed of the shockwave at the intersection when the vehicles are approaching the signal before the signal turns red, which leads to the formation of queues being similar to the directly measured speed of 0.32 km/hr from the flow–density relationship at the intersection every day of the week, which is not expected to be much higher than it is to satisfy the intersection saturation flow rate without causing downstream spillover. The values of the dissipating wave (BC), which is the backwards recovery shockwave speed at the intersection when the signal turns green again and the vehicles leaving the queue, are greater than those when they approach the signal because they are free from the stationary state. The maximum queue lengths are 7.99 m, 5.44 m, 7.32 m, and 6.20 m, and the queue dissipation times at the end of the red phase are 21.65 s, 18.67 s, 24.87 s, and 13.95 s for the A.M. peak, A.M. off-peak, P.M. peak and P.M. off-peak hours, respectively. The maximum queue length is clearly greater during peak hours than during off-peak hours, as is the queue dissipation time at the end of the red phase.

6. Conclusion and Recommendations

The main emphasis of this study was the investigation of shockwaves at a signalized intersection, which was accomplished via an analytical method. The fundamental diagram of the traffic stream aids in the analysis of shockwaves by using the average values of the AM peak, PM peak, AM off-peak, and PM off-peak to study traffic flow characteristics in extreme scenarios such as free-flow and traffic jam conditions. The projected shockwave speeds in this study are consistent with the values obtained directly from the fundamental relationship of traffic properties. These shock wave speeds could be utilized to calibrate the fundamental diagram of a traffic stream and to predict flow speeds (journey times) along a highway stretch. The shockwave analysis, which was built via a fundamental diagram, revealed that the maximum queue length at the end of the red phase, the total time from lane opening to the time at which the last vehicle enters the queue, and the total time from lane opening to the normal condition increase linearly as the incident duration increases, whereas the total delay increases exponentially. According to the performance metrics, the queue's end has no effect on flow at a neighbouring intersection.

The two critical factors that affect shockwaves in the traffic stream are as follows:

- Driving behaviour
- Proportion of different styles.

Traffic shockwaves cannot be completely eliminated at an intersection but can at least be attenuated by the following suggested recommendation:

i. Development of a potential strategy for adjusting the proportion of unstable driving styles. This will also reduce rear-end crashes to a certain extent.
ii. Exploring the effect of each driving behaviour parameter on rear-end crash probability is useful for controlling intersection traffic and can provide an improved understanding of abnormal driving behaviour characteristics to minimize shockwaves.
iii. Deployment of vehicle-to-vehicle (V2V) communication technology, specifically in the condition of traffic jams (especially during off-peak hours) ahead of warning application, will help maintain the estimated shockwave propagation speeds.
iv. The no-overtaking assumption is relaxed by specifying a noncompliance factor.
v. The effects of nonuniform traffic flows at the intersection are incorporated as the traffic state changes with time.

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