Calculation of Right Turn Delay for Large Vehicles under the Regulation of "Right Turn Must Stop"

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Abstract

This paper studies the delay change of large vehicles when they turn right and pass through the intersection under the regulation of "right turn must stop" for large vehicles, and the delay of follow-up straight vehicles due to "right turn must stop" for large vehicles in the straight right lane. The dynamic process of large vehicles turning right through the intersection is divided into three parts: deceleration phase, parking phase and acceleration phase. Then, based on the operation characteristics of large right turn vehicles and combined with the vehicle following model, the delay calculation model under the regulation of "right turn must stop" for large vehicles and the impact of "right turn must stop" for large vehicles in the straight right lane on subsequent straight vehicles and the delay calculation model are proposed. The effectiveness of the two delay models is verified by using the actual intersection data in Shanghai. The results show that the average delay caused by the implementation of the "right turn must stop" regulation for large right turning vehicles is 6.68s, the relative error between the "right turn must stop" delay model and the actual delay of large vehicles is less than 5%, and the relative error between the delay model caused by the "right turn must stop" large vehicles and the actual delay is less than 7%. The research shows that the delay time of vehicles at intersections can be accurately calculated by using the delay model, which can provide a basis for the subsequent research on the capacity of straight right lane under the "right turn must stop" regulation and a reference for traffic organization and management.

Keywords

Right turn must stop; Straight right lane; Delay; Traffic characteristics; Drone video.

1. Introduction

With growing annual vehicle ownership, vehicle collision-related injuries continue to increase. Specifically, large truck accidents involving right-turning collisions either with pedestrians or other non-motorized vehicles account for a large portion of these fatalities. In an effort to avoid similar disasters, in 2021 Shanghai started testing regulation for "right turn must stop" for large licensed commercial vehicles, including: cement mixers, container trucks and trailers, etc., at 43 intersections. The regulation requires that if a big truck makes a right turn at an intersection it must first come to a full stop at the intersection and check its surroundings for safety before continuing to turn. The scope of application has now been expanded to all intersections throughout the city, and the range of vehicles subject to the regulation has also been extended to include buses as well. Currently, the regulation on "right turn must stop" of big trucks is still being piloted in some cities, and therefore little theoretical research has been done regarding this issue. Outstanding issues such as how this regulation may impact the operating efficiency of straight-right lanes and the overall effectiveness of traffic management need to be addressed through urgent research and study.

The focus of international studies into right hand turning behavior of heavy commercial vehicles is mainly on: understanding why these vehicles have right turning accidents; calculating the fields of view of rear view mirrors; determining inner wheel offsets; creating a plan to enhance safety; and so on, but within this realm there are also a number of other relevant topics to study. The principal aim of domestic research is to model right hand turn trajectory of heavy commercial vehicles; investigate the primary reasons behind right-hand turn collision accidents; and investigate potential right hand turn safety measures. The estimation of intersection delay time has been continually refined in the US Highway Capacity Manual (HCM) over the course of the development of its 4th to 7th editions (2000-2022). However, in domestic studies, much attention is paid to conflicts between non-motorized or pedestrian traffic and right-turn maneuvers of other types of motorized traffic and the delay models associated with these conflicts, while the focus in domestic research remains on delay models associated with right-turn maneuvers of vehicles on intersections with various traffic management systems and on various traffic lanes. Research related to right-turns conducted by HGV drivers is mostly focused on the tendency to yield while conducting right-turns, the right-turn capacity under pedestrians' priority rule, as well as various configurations of stop-on-turn maneuver associated with heavy goods vehicles. Also, delay associated with 'stop-on-turn' maneuver has been analyzed with the help of VISSIM model.

In essence, even though some progress has been made in measuring delays at intersections and evaluating how well heavy trucks make right turns, the following problems still exist: At first, the study of vehicle delays mostly looked at passive delays caused by conflicts between non-motorized vehicles or pedestrians and right-turning motor vehicles. It didn't look at active delays caused by regulations that require motor vehicles to stop. Second, modern delay calculations mostly focus on the lead vehicle and don't take into account the delays that trailing cars experience when the lead vehicle stops. This paper looks at straight and right lanes at signalised intersections, paying special attention to what makes these lanes unique. It looks into big vehicles that have to stop for right turns, like buses, big coaches, and heavy goods vehicles, as well as the vehicles that go straight through after them. There were drones used to get aerial footage of how big trucks moved through the intersection in the straight-and-right lane, following the "right turn must stop" regulation. We used tracker software to get information from the video feed and look at how these big vehicles turned right. The research examined the impact of the "right turn must stop" regulation on following straight-through vehicles, created delay models for both large and straight-through vehicles affected by this regulation, and validated their precision. The research results provide a theoretical foundation for future studies on the capacity of straight-right lanes under the "right turn must stop" regulation, guide traffic organization and management, and are highly important for balancing traffic safety and efficiency.

2. Delay Model for Large Vehicles Subject to the "Right Turn Must Stop" Regulation

When designing signalised crossroads, safety should be the top priority, with the goal of improving the flow of traffic in straight and right-turn lanes. The safety of cars making right turns is not the same as traffic efficiency. More efficiency and more traffic capacity go hand in hand with less safety. The regulation that says "right turn must stop" makes intersections safer, but it also makes delays longer. This part looks at and evaluates the delays that happen when big trucks follow the "right turn must stop" regulation. An examination of the movement patterns of heavy goods vehicles (HGVs) at intersections regulated by the "right turn must stop" regulation categorises the right-turning process into three stages: the deceleration stage, the stopping stage, and the acceleration stage. During the deceleration phase, the speed of the heavy goods vehicle slowly decreases. This is shown by a centrally symmetrical curve and a gradual decrease in deceleration. On the other hand, during the acceleration phase, the vehicle's speed goes up little by little. However, because of the vehicle's design, the rate of speed change is very small and stays the same once it reaches a certain speed. At the same time, acceleration gets stronger.

2.1. Model of Right-Turning Vehicle Travel Time

Richards' study shows that the speed at which cars turn right is linearly related to the lane width and turning radius. At a signalised intersection, vehicles turning right in the designated lane may do so without being blocked by pedestrians or other vehicles. The speed at which they turn depends on the turning radius. J. A. Bonneson[1] improved Richards' model by showing how the turning speed of vehicles that turn right is related to the turning radius, as shown in the Equation.

$$u_r = 3.59 + 0.196R_c \tag{1}$$

In the formula, u_r stands for the right-turning vehicle's speed in m/s, and R_c stands for the right-turning vehicle's turning radius in meters.

The time it takes to make a right turn is the same as the time it takes for the car to travel the arc length of the turn. The formula for figuring out how long it takes for a car to make a right turn is shown in Figure 1:

$$S = \frac{\pi R_c}{2} - l_0 - \frac{l_1}{2} \tag{2}$$

$$t_r = \frac{S}{u_r} = \frac{\frac{\pi R_c}{2} - l_0 - \frac{l_1}{2}}{3.59 + 0.196R_c} \tag{3}$$

In the formula, l_0 is the distance in meters from the stop line to the pedestrian crossing; l_1 is the width in meters of the pedestrian crossing at the junction; S is the length in meters of the turning arc of the vehicle that is turning right; and t_r is the time in seconds that the vehicle is turning right when the "right turn must stop" regulation is not followed.

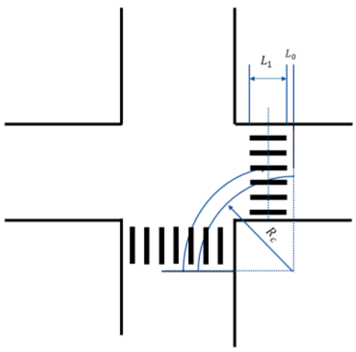

Fig.1 Calculation diagram of right turn vehicle travel time

The time it takes to turn depends on the speed and radius of the turn; it gets longer as the radius of the turn gets bigger. The time it takes to turn stays between 2.5 and 3.2 seconds when the turning radius is between 10 and 14 meters.

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[1]Bonneson J A. Delay to major-street through vehicles due to right-turn activity [J]. Trampn Rex-A,1998-32(2):139-148.

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2.2. Travel Time Model for Large Vehicles Under the "Right Turn Must Stop" Regulation

Figure 2 shows how a large vehicle goes through a signalised intersection under the "right turn must stop" regulation. The process is broken down into five steps. The large vehicle moves at a steady speed from point O to point A. At point A, the car starts to slow down. By the time it gets to the stop line at the junction at point B, it has slowed down to the turning speed. 3) The vehicle keeps slowing down from point B until it stops at point C. 4) The time between points C and D is the "stop-and-look" observation period for the "right turn must stop" regulation. The car speeds up from point D to leave the intersection. By point E, it has returned to the turning speed and left the intersection.

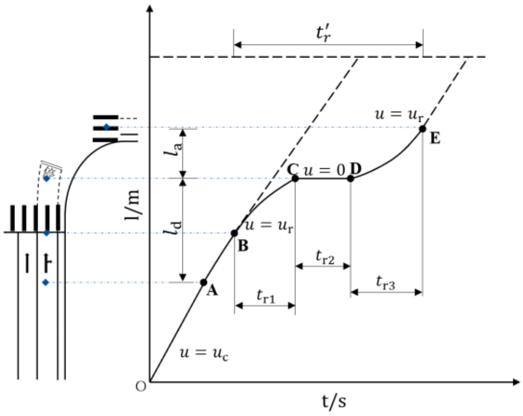

Fig.2 Travel time distance curve of right turn vehicles under the regulation of "right turn must stop" for large vehicles

In Fig. 2, u_c is the standard speed at which large vehicles cross a junction, measured in meters per second (m/s); u_r is the speed at which large vehicles turn right, also measured in m/s; and $t_r^{'}$ is the time it takes for large vehicles to turn while following the "right turn must stop" regulation, measured in seconds. t_{r1} is the time it takes for large vehicles to slow down while making a right turn, in seconds; t_{r2} is the time it takes for large vehicles to stop while making a right turn, in seconds; t_{r3} is the time it takes for large vehicles to speed up while making a right turn, in seconds; l_d is the distance it takes for large vehicles to slow down while making a right turn, in metres; l_a is the distance it takes for large vehicles to speed up while making a right turn, in metres; a_1 is the speed at which large vehicles slow down, in m/s^2; a_2 is the speed at which large vehicles speed up, in m/s^2.

2.2.1 Deceleration phase

During the deceleration phase, the vehicle's speed changes from fast to slow. At first, the deceleration rate slowly drops from $0m/s^2$, and then it slowly rises to $0m/s^2$ at the end of deceleration. The literature and the characteristics of the vehicle deceleration process indicate that the speed variation during deceleration can be represented as a hyperbolic sine function.

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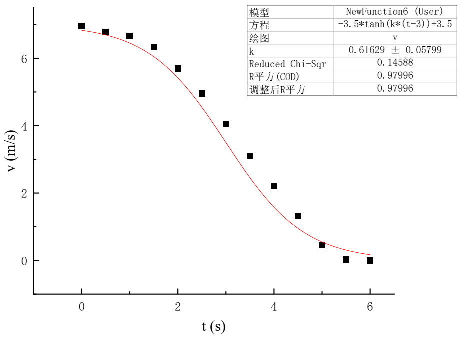

Fig.3 V-T diagram of a typical vehicle deceleration

Figure 3 illustrates the velocity characteristic curve of a bus during its deceleration phase, derived from aerial video data. The curve's tendency indicates that $R^2 = 0.979$, which is near 1; this process can be characterised by a hyperbolic sine function:

$$u_1(t) = -(\frac{u_0}{2} + \Delta b)\tanh\left[k(t\text{-}\tau)\right] + \frac{v_0}{2} \tag{4}$$

In the equation, u_0 is the initial speed of the vehicle in m/s, u_1 is the speed of the vehicle during the deceleration phase in m/s, k is the rate of change of the vehicle's speed, τ is the middle of the deceleration period, and Δb is a small positive constant.

The v-t curve for Equation (4) with $k{=}k_1, k_2 (k_1{>}k_2{>}0)$ is depicted in Figure 4. For varying values of k, the motion regulation governing the deceleration phase of a large vehicle's "right turn must stop"—where the initial speed u_0 diminishes to 0m/s—is a monotonic function of $(\tau, \frac{u_0}{2})$. As $t \to \text{-}\infty$, $v \to u_0 + \Delta b$; as $t \to +\infty$, $v \to 0 - \Delta b$. Altering the value of k regulates the rate of change of the curve. In the interval $\left[0, \tau\right]$, the vehicle's acceleration progressively diminishes from 0m/s^2, attaining its minimum at time τ; in the subsequent interval $\left[\tau, 2\tau\right]$, the vehicle's acceleration gradually ascends, reaching 0m/s^2 at time 2τ.

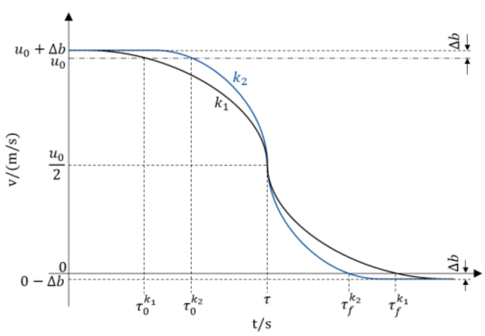

Fig.4 V-T diagram of vehicle deceleration

Considering the vehicle's beginning velocity $v_0 = u_\text{r}$ and end velocity 0, the time constant τ^* can be ascertained based on various values of k:

$$\tau^* = \frac{1}{k}\text{arctan h}(\frac{\frac{u_r}{2}}{\frac{u_r}{2} + \Delta b}) \tag{5}$$

The deceleration time $t_{r1} = 2\tau^*$ for the "right turn must stop" deceleration phase of a large vehicle; integrating Equation t_{r1} produces the distance S_{r1} traversed throughout the deceleration process:

$$S_{r1} = -\frac{2(\frac{u_r}{2} + \Delta b)}{k} \ln\left\{\cos\left[\operatorname{arctan h}\left(\frac{\frac{u_r}{2}}{\frac{u_r}{2} + \Delta b}\right)\right]\right\} + \frac{u_r}{k} \operatorname{arctan h}\left(\frac{\frac{u_r}{2}}{\frac{u_r}{2} + \Delta b}\right) \quad (6)$$

In the formula, S_{r1} is the distance in meters that the big vehicle travels when it slows down and stops while making a right turn.

The formula above shows that the parameter k determines the vehicle's intended velocity-time curve, journey duration, and distance covered based on its starting speed and how quickly it comes to a stop.

2.2.2 Stopping Time

The process of figuring out the stopping time t_{r2} for a vehicle that is turning right starts when the vehicle slows down to 0.5m/s during the right turn and ends when the vehicle's speed rises to 0.5 m/s. This time includes the time the driver is actively watching for stops and the time needed to. Give way to people walking and vehicles that don't have engines.

$$t_{r2} = t_{stop} + t_{yield} \quad (7)$$

In the formula, t_{stop} is the number of seconds it takes for the driver of a large vehicle to stop and look around; t_{yield} is the number of seconds it takes for a large vehicle to give up the right of way.

2.2.3 Acceleration phase

The acceleration phase denotes the period following a right-turning vehicle's complete halt, during which it commences to speed away from the intersection. The distance covered during the acceleration phase, S_{r2} can be determined using the deceleration distance and the distance travelled during the right turn:

$$S_{r2} = S - S_{r1} \quad (8)$$

In the formula: S_{r2} is the distance, in metres, traversed by a heavy vehicle from a stationary position to the point of exiting the junction while executing a right turn.

There has been a lot of research done on the starting and speeding up of cars in other countries. The AASHTO (American Association of State Highway and Transportation Officials) uses a uniform acceleration model to accurately describe how vehicles speed up. A model of linearly decreasing variable acceleration motion has recently been extensively utilised to characterise the initiation and acceleration process.

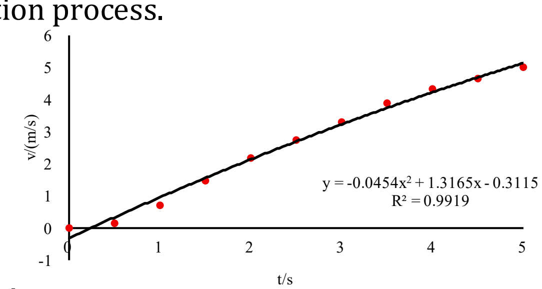

Fig.5 Speed characteristic curve of a typical vehicle during acceleration

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Figure 5 illustrates the speed characteristic curve of a bus during the initial acceleration phase, derived from aerial video data. The curve's trend demonstrates that $R^2 = 0.9919$ is near 1, indicating that this process can be characterized by a quadratic curve. From the equations governing uniformly accelerated motion, we derive:

$$S_{r2} = \frac{1}{2} a_2 t_{r3}^2 + v_0 t_{r3} \tag{9}$$

Given that the initial velocity during the acceleration phase is $v_0 = 0\text{m/s}$ inserting this value into Equation (9) results in:

$$t_{r3} = \sqrt{\frac{2S_{r2}}{a_2}} \tag{10}$$

For big trucks that have to stop before turning right at an intersection, the trip time is the sum of the three phases. Heavy vehicles have to wait longer because of the "right turn must stop" regulation. This is because the time it takes to travel when the regulation is in effect is longer than the time it takes to travel when the regulation is not in effect.

3. Analysis of the Influence of Vehicles Adhering to the "Right Turn Must Stop" Regulation on Vehicles Proceeding Straight in the Straight-right Lane, Together With a Delay Model

3.1. Impact Analysis

This paper uses video footage from a drone to collect video data at the intersection of Chang Yang Road and Jun Gong Road in Shanghai's Yangpu District. This intersection is a three-phase T-junction. The outer lane of Jun Gong Road works like a normal straight-right lane. There is a bus station and a building site near the junction, which means that a lot of buses and large trucks turn right, but pedestrians are not bothered too much. For six working days, continuous raw video data was collected for 12 hours during the morning rush hour. The intersection's location and the way the roads are set up make cars going straight on Jun Gong Road turn left when they cross the intersection. Figure 6 shows a diagram of the intersection of Jun Gong Road and Chang Yang Road.

(a) real-life image (b) Schematic diagram of rectangular coordinates

Fig.6 Schematic diagram of intersection

The "right turn must stop" regulation requires big and medium-sized vehicles to slow down and stop in the straight-right lane when they turn right. This will probably slow down the flow of cars that come after them. To assess the impact of banning buses from making right turns on vehicles that continue straight, three categories are defined based on the distance from the bus's stopping point to the road markings: standard stop, early stop, and late stop, as shown in Figure 7.

(a) standard stop (b) early stop (c) late stop

Fig.7 Schematic diagram of right turn vehicle parking position

Table 1 presents the effect of the "right turn must stop" regulation for large vehicles in the straight-right lane on vehicles travelling straight, as determined by an analysis of aerial video data.

Tab.1 Analysis of the impact of "right turn and stop" of large vehicles in the straight right lane on straight vehicles

Parking position for large vehicles	straight-going vehicle	trajectory diagram	speed variation diagram	Acceleration variation graph
standard stop	stop	The bus has a noticeable pause at the right turn parking area. The straight line is a straight line to the left, with no obvious bend.	First decrease and then increase, with the speeds of the two vehicles maintaining the same rate of change.	First decrease then increase.
	detour	The straight-going car deviated to the left after passing the stop line.	First decreasing and then increasing, the speed of the straight-line vehicle has not decreased to 0m/s.	First decrease and then increase, the change rate of straight-ahead vehicles is greater.
early stop	stop	The straight line is a straight line to the left, slightly curved to the left.	First decreasing and then increasing, the rate of speed change for both vehicles during the deceleration phase is essentially the same.	Initially decreasing and then increasing, the accelerations of the two vehicles during the acceleration phase are essentially identical.
	detour	A vehicle traveling straight ahead occupies the leftmost straight-ahead lane to pass through the intersection from the rightmost straight-ahead lane.	First decreasing and then increasing, the speed curve changes of the two vehicles during the deceleration phase are basically consistent.	First decrease then increase.
late stop	no impact	The straight-going vehicle accelerates through the intersection without any noticeable curve.	The through vehicle did not slow down and sped away from the intersection. Vehicles turning right first decrease and then increase.	The acceleration of the straight-going vehicle fluctuates slightly, while the right-turning vehicle experiences a decrease first and then an increase.

Table 1 shows the following information: 1) When cars enter the intersection, those going straight and those turning right keep a steady headway. The speeds of both cars stay the same, and their deceleration rates are fairly consistent. When straight-through vehicles leave the junction, they speed up faster than right-turning vehicles do when they first speed up. When vehicles enter the junction, both the leading and following vehicles slow down at the same rate. 2)Heavy vehicles that stop before turning right have a big effect on straight-through vehicles in the future. There are no clear regulations about how to mark right-turn guide lines and stop lines on the right-turn and straight-through lanes. The "right turn must stop" regulation and the presence of people at the intersection both affect how often cars that are turning right stop. When cars turn right, they may have to stop up to three times while crossing the intersection. 3) At the same stop for vehicles that must stop before turning right, drivers of straight-through vehicles have different options for how to get there.

3.2. Delay Model for Straight-Ahead Vehicles

This paper models and analyses the delay experienced by subsequent straight-ahead vehicles due to the "right turn must stop" regulation for large vehicles in the straight-right lane during green light conditions, considering that the delay for straight-ahead vehicles at a red light corresponds to the duration of the red light. Figure 8 shows a big vehicle making a right turn approaching the intersection at a speed of u_i. It then slows down to a stop to look around and then speeds up to leave the intersection. The vehicle going straight also slows down to a stop because of the right-turning vehicle before speeding up to go straight through the intersection. Phase AB shows how to make a right turn, and $t_r^{'}$ is the time it takes to make the right turn. In the straight-right lane, passing is not allowed. This means that vehicles going straight through must keep a constant gap, called Δ, between them. The wave of deceleration from the car that is turning right moves backward. To avoid crashes, cars that are going straight will either slow down or stop at a certain point until the right-turning car has left the intersection.

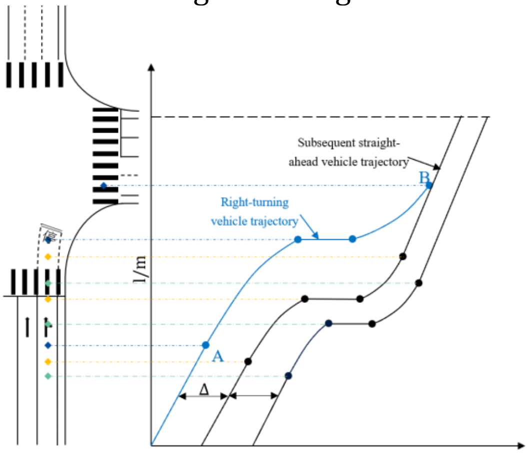


Fig.8 Construction track diagram of straight vehicles and right turning vehicles

Figure 9 shows the path of a car going straight in the straight-ahead and right-turn lane, which is affected by another car making a right turn. The path shows how long it takes for both the straight-moving and right-turning cars to get through the intersection. The car going straight slows down and stops before the stop line because the car turning right is in its way. While it waits, its speed drops from normal driving speed to 0m/s. The vehicle going straight resumes and speeds up to its normal speed after the vehicle turning right in front of it leaves the intersection. In the diagram, t_c is the time, in seconds, that it takes for the straight-ahead vehicle to cross the intersection under normal conditions. t is the total travel time, in seconds, of the straight-ahead vehicle when it is blocked by a vehicle that has to stop to turn right. d is the total delay, in seconds, of the through vehicle when it is blocked by a vehicle that has to stop to turn right. t_d is the time, in seconds, that it takes for the through vehicle to slow down when it is blocked by a vehicle that has to stop to turn right. t_a is the time, in seconds, that it takes for the through vehicle to speed up when it is blocked by a vehicle that has to stop to turn right. l_d is the distance, in seconds, that it takes for the through vehicle to slow down when it is blocked by a vehicle that has to stop to turn right by "right turn must stop" vehicle, in metres; l_a is the acceleration distance of a straight-through vehicle when obstructed by a "right turn must stop" vehicle, in metres; d_d is the deceleration delay of a straight-through vehicle when obstructed by "right turn must stop" vehicle, in seconds; d_a is the acceleration delay of a straight-through vehicle when obstructed by a "right turn must stop" vehicle, in seconds; d_s is the stopping time (stopping delay) of a straight-through vehicle when obstructed by a "right turn must stop" vehicle, in seconds; d_h is the acceleration delay experienced by a straight-through vehicle when obstructed by a vehicle subject to the "right turn must stop" regulation, in seconds; $u_c^{'}$ is the distance travelled by a straight-through vehicle when its speed decreases from normal speed to a certain positive value following obstruction by a vehicle subject to the 'must stop to turn right' regulation, in m/s²; a_1 is the deceleration, in metres per second squared; a_2 is the acceleration, in m/s².

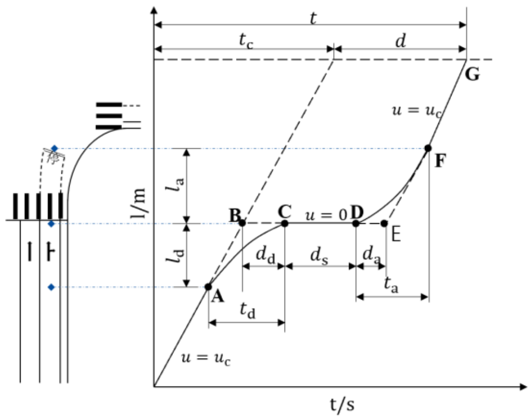


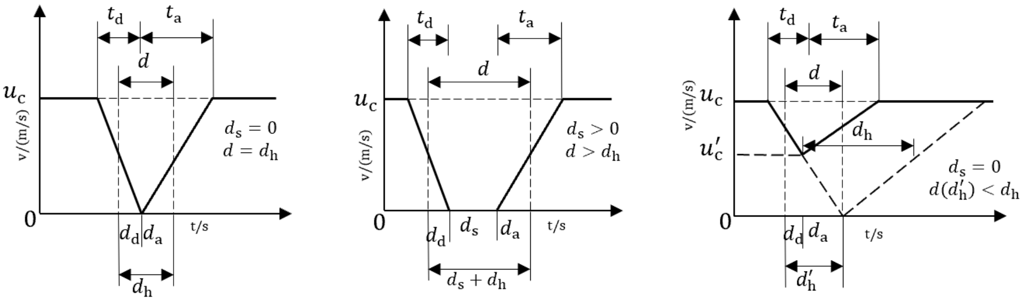
Fig.9 Track diagram of blocked straight ahead vehicle

The delay for a straight-ahead vehicle is the difference between the time it takes to get through the intersection while being blocked and the time it takes to get through the same distance under normal driving conditions. As shown in Fig. 9, the total travel time (t) of a straight ahead vehicle that hits an obstacle is the sum of the normal travel time and the total delay caused by the obstacle. The total delay time (d) is the sum of the stopping delay and the acceleration/deceleration delay. The acceleration/deceleration delay time (d_h) is the sum of the deceleration delay and the acceleration delay.

When looking at the delays for vehicles going straight in Figure 9, the time between BE shows the total delay the vehicle had to deal with when it was stopped at the intersection. 1) The delay between BC caused by deceleration while the vehicle is blocked, called deceleration delay; 2) The delay between CD caused by stopping while the vehicle is blocked, called stopping delay; and 3) The delay between DE caused by acceleration while the vehicle is blocked, called acceleration delay. If you call both deceleration and acceleration delays "acceleration-deceleration delay," then the total delay is made up of two parts: halting delay and acceleration-deceleration delay. The length of time the vehicle is stopped (or idling) is the total delay minus the acceleration-deceleration delay.

Examination of video survey data and real-time intersection operations indicates that not all vehicles come to a complete stop when obstructed; rather, some merely decelerate without halting and subsequently resume acceleration to normal driving speed before achieving a velocity of zero.

Figure 10 shows that vehicles that are stuck at a junction have three options.



(a) just complete stop (b) complete stop (c) incomplete stop

Fig.10 V-T diagram of complete stop and incomplete stop

Figures 10a) and 10b) show "complete stop," with the first one showing a just "complete halt" and being a specific example of this type; Figure 10c) shows an "incomplete stop". A "complete stop" means that a vehicle slows down from its normal speed to zero and then speeds back up to its normal speed. An "incomplete stop", on the other hand, means that the vehicle doesn't come to a complete stop before speeding up, or, in other words, that the speed at which it goes from slowing down to speeding up stays above zero.

In Figure 10a), when the vehicle hits something, its speed drops from its normal cruising speed to zero, and then it speeds up again until it reaches its normal cruising speed again. In this case, the vehicle doesn't have a stopping delay, and the total delay is the same as the sum of the deceleration and acceleration delays. In Figure 10b), when the vehicle hits an obstacle, it slows down from its normal cruising speed to zero. Instead of speeding up right away, it stops, stays still for a while, and then speeds up until it reaches its normal cruising speed. The stopping delay is more than zero, and the total delay is more than both the acceleration and deceleration delays. In Figure 10c), when the vehicle hits an obstacle, it slows down from its normal cruising speed to a speed above zero. Then it speeds back up to its normal cruising speed. In this case, the stopping delay is zero, and the total delay is the same as the delays for speeding up and slowing down. However, it is shorter than the delays for coming to a complete stop.

Figure 11 shows what happens when Car_2 follows Car_1 at a constant speed of u_0. The vehicle behind must take the right steps to slow down and stop when the lead vehicle does. Let Car_1 be the first time that deceleration starts, L_1 be the distance that Car_1 travels, L_2 be the distance that Car_2 travels, L be the distance between the two cars, and ΔL be the safe distance between them.

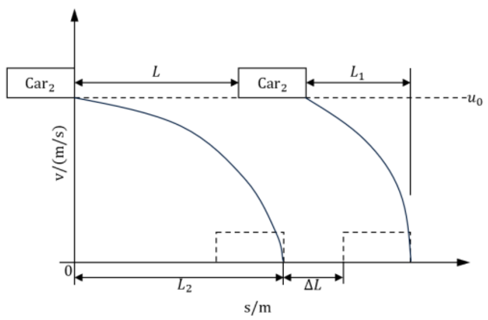


Fig.11 Car following model diagram

Car_2's initial velocity at the commencement of deceleration is u_0, and the ultimate velocity is $u_0 - 2b = 0\text{m/s}$. The equation for deceleration is:

$$u_2 = -(\frac{u_0}{2} + \Delta b)\tanh\left[k_2\left(t - \tau_2^*\right)\right] + \frac{u_0}{2} \tag{11}$$

$$\tau_2^* = \frac{1}{k_2}\text{arctan h}\left(\frac{\frac{u_0}{2}}{\frac{u_0}{2} + \Delta b}\right) \tag{12}$$

From Figure 10c) 'Incomplete stop', we derive the following using Equation (5):

$$t_d = \frac{2}{k}\text{arctan h}\left(\frac{\frac{u_c - u_c^{'}}{2}}{\frac{u_c - u_c^{'}}{2} + \Delta b}\right) \tag{13}$$

$$t_a = \frac{u_c - u_c^{'}}{a_2} \tag{14}$$

$$l_d = t_d \cdot \frac{u_c + u_c^{'}}{2} \tag{15}$$

$$l_a = t_a \cdot \frac{u_c + u_c^{'}}{2} = \frac{u_c^2 - u_c^{'2}}{2a_2} \tag{16}$$

The deceleration delay for a vehicle moving straight while blocked is the time it takes to slow down during the blockage minus the time it takes to travel the deceleration distance at normal driving speed. The same goes for a car that is moving forward but is stopped:

$$d_d = t_d - \frac{l_d}{u_c} \tag{17}$$

$$d_a = t_a - \frac{l_a}{u_c} = \frac{\left(u_c - u_c^{'}\right)^2}{2a_2u_c} \tag{18}$$

For a 'complete stop', as illustrated in Figure 9 ($u_c^{'} = 0\text{m/s}$), putting this value into Equations (12) to (17) produces the equivalent equations for Figures 11a) and 11b):

$$t_d = \frac{2}{k}\text{arctan h}\left(\frac{\frac{u_c}{2}}{\frac{u_c}{2} + \Delta b}\right) \tag{19}$$

$$t_a = \frac{u_c}{a_2} \tag{20}$$

$$l_d = t_d \cdot \frac{u_c}{2} \tag{21}$$

$$l_a = t_a \cdot \frac{u_c}{2} = \frac{u_c^2}{2a_2} \tag{22}$$

$$d_d = t_d - \frac{l_d}{u_c} \tag{23}$$

$$d_a = t_a - \frac{l_a}{u_c} = \frac{u_c}{2a_2} \tag{24}$$

4. Model validation and analysis

The empirical study section uses real intersection data to show that the two delay models that were made earlier are accurate. The models were created using data from the first four days and tested with data from the last two days. The validation method did not take into account situations where vehicles turning right have to stop again because pedestrians or non-motorized vehicles are crossing the road. The right-turn vehicle delay model figures out how long it will take different kinds of right-turning vehicles to get through the intersection while following the "right turn must stop" regulation. A relative error analysis is performed by comparing the times calculated by the model to the actual times. An analysis of the different stopping points for cars that must stop for right turns shows that they accelerate differently when they leave the intersection. Table 2 shows the information.

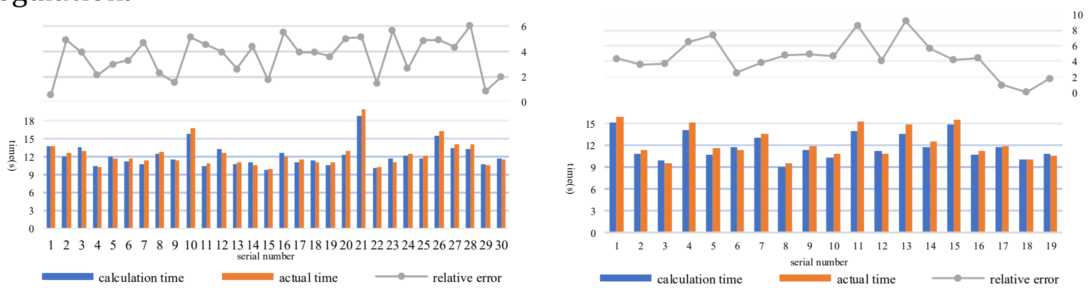
Tab.2 Statistical table of acceleration corresponding to different vehicle types and parking positions

vehicle type	Stopping point/size	$a_2(m \cdot s^{-2})$
	early stop	1.1-1.5
bus	standard stop	1.0
	late stop	0.5-0.9
	small	0.8-1.0
truck	middle	0.5-0.7
	large	0.3-0.4

4.1. Delay Model for "Right Turn Must Stop" Requirements for Large Vehicles

Aerial images were used to compare the right-turn times of 30 buses that had to stop before turning right with their actual right-turn times. Figure 12(a) shows that the absolute error in the calculated trip time for one bus was less than 1 second, and the relative error was less than 6%. The total relative error for the 30 buses was 3.613%. The "right turn must stop" regulation caused an average delay of 6.763 seconds, according to calculations.

The turning times for 19 big trucks of different sizes that had to stop before turning right were calculated and compared to their actual turning times. Figure 12(b) shows that the absolute error in the calculated trip time for each truck was less than 1.5 seconds, and the relative error was less than 10 percent. The total relative error for the 19 trucks was 4.489 percent. The study found that heavy trucks had to wait an average of 6.684 seconds because of the "right turn must stop" regulation.



(a) bus (b) large truck

Fig.12 Comparison chart of calculation results of large vehicle right turn delay model

4.2. Delay Model for Straight-through Vehicles in the Straight-right Lane Affected by Vehicles Subject To the "Right Turn Must Stop" Regulation

The amount of time it takes for cars to go straight through the straight-right lane at a junction shows how long it takes for cars that are turning right to get through. Figure 13 compares data from 13 groups of straight-through cars following large vehicles that were following the "right turn must stop" regulation, as shown in overhead footage, with the results of model calculations. The comparative analysis shows that the relative inaccuracy is less than 7%. If straight-through vehicles chose to stop next to the "right turn must stop" right-turning vehicles, the average delay was 6.511 seconds. If they chose to go around to the left, the average delay was 1.108 seconds. The average delay was shorter because the cars didn't slow down to 0 m/s and there was no time to wait.

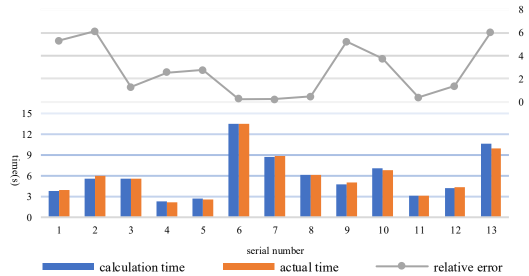


Fig.13 Comparison chart of calculation results of through train delay model

5. Conclusion

This study utilises drone-captured aerial footage to obtain video recordings of large vehicles complying with the "right turn must stop" regulation. It analyses their movement characteristics in conjunction with the operational traits of vehicles travelling straight in the straight-right lane, influenced by those adhering to this regulation. This study formulates a delay model for large vehicles impacted by the "right turn must stop" regulation at intersections, alongside a model for the delay experienced by vehicles proceeding straight in the straight-right lane as a result of the presence of these large vehicles. These models depict actual traffic conditions following the implementation of the "right turn must stop" regulation for heavy trucks. Future research will build upon these delay models to establish a framework for assessing the capacity of straight-right lanes at signalised intersections, as well as strategies for optimisation. This paper has some limitations: The aerial video data was collected at a single intersection and is not generalisable; further research and surveys are required to obtain a more comprehensive dataset to improve the model. 2) In the study, large vehicles were only divided into buses and heavy goods trucks. The heavy goods trucks were not further divided. It might be helpful to group heavy goods vehicles together to improve the delay model, since the delays that happen when a vehicle turns right depend on its size.

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