INTEGRATING COMMON VEHICLES' ACTIONS INTO THE TRAVEL TIME ASSESSMENT OF FIRE ENGINE

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ABSTRACT

Travel time is a major but complicated component of the response time of a fire brigade. It depends primarily on the travel distance, and is influenced by not only environmental factors such as road conditions and weather, but also the actions taken by the vehicles that share the road with the fire engine. In this paper, two models, the safety model and the balance model, have been developed to describe the way-yielding actions of common vehicles. A Cellular Automaton has been occupied to simulate the traveling of a fire engine on a two-lane road, with the common vehicles' actions model integrated in. The simulation results prove that both models exist in real life, and show that the way-yielding actions taken by common vehicles close to the fire engine affect the travel time, especially in some firehouse-scarce districts.

KEYWORDS: Travel time, Way-yielding model, Cellular automaton

INTRODUCTION

Travel time is a major component of the emergency response time of a fire station. It is defined as the time between the moment a unit leaves the fire station and when it arrives at the fire scene. The travel time from a specific firehouse to the location of a specific incident depends primarily on the distance between the points, but it may also be influenced by the type of the vehicle, the driver, the types of roads, the environment, and the traffic encountered.

It has been found that the travel time increases with the square root of the distance for short trips and increases linearly for longer trips[1]. Thus, the travel time can be expressed by the following mathematical model relating the travel distance, *D*, and the expected time to travel between the two points, *t(D)*.

$$\begin{cases} t = a\sqrt{D}, D < d \\ t = b + cD, D \geq d \end{cases} \tag{1}$$

Except for the travel distance, the maximum speed of the fire engine also affects its travel time. The maximum speed a vehicle could reach, which is usually called as free-flow speed in literatures, not only relies on the velocity performance of the vehicle, but also is influenced by the road condition and the environment. Several studies have examined vehicle speed under a variety of environmental conditions. Ibrahim and Hall[2] studied the effect of adverse weather on freeway operations in Canada. They conducted tests on the effects of rain and snow on speed-flow-occupancy relationships, and found the following reductions in the free-flow speed: Light rain caused a 2 km/h drop; light snow 3 km/h; heavy rain 5 to 10 km/h; and heavy snow 38 to 50 km/h. Brilon and Ponzlet[3] investigated 15 sites in Germany and concluded that darkness reduces driver speeds by 5 km/h. They also found a drop of 9.5 km/h and 12 km/h on two-lane and three-lane wet roadway segments, respectively. Kyte and Khatib[4] identified a new variable, high wind, in free-flow speed estimating. The estimated effect is a 9 km/h reduction in free-flow speeds for wind speeds above 48 km/h.

The drivers, both the fire engine driver and the common vehicles' drivers, are the other factor influencing the travel time of fire engine. The fire engine driver's experience and local knowledge will help him take appropriate actions with response to a fire alarm. But the actions taken by common vehicles' drivers also affect the speed of fire engine. If a fire engine cannot get the right of way at all, it cannot reach the incident location as fast as expected. Most laws prescribe that all the vehicles must yield the right of way to a fire engine, by which the block phenomenon is expected to be avoided. Unfortunately, people have different interpretations to the law and may not yield in time, delaying the fire engine.

A computer simulation method for travel time estimation has been proved effective[5]. In the next section, the common vehicles' actions when hearing alarm whistle are modeled. The action models were brought into the simulation of fire engine traveling, and the simulation results are presented and discussed in Section 3. Finally, conclusions are made and future outlook is given.

MATERIALS AND METHODS

There are many different reactions when drivers hear a fire whistle on the road. For simplicity, they could be classified as two models, the safety model and the balance model.

The safety model is used to model the actions taken by the drivers who care for their safety more than the requirement of emergency. To avoid being punished, they expect to yield the right of way as soon as they hear the whistle, but actually do that only when they have made sure that there is no risk of a crash to change lanes.

The balance model means the driver would balance the safety of himself and the requirement of emergency. He will first check out whether he is in the way of the fire engine through the rearview mirror. If the fire engine could be seen, he will estimate the distance and the relative velocity between his vehicle and the fire engine, while finding an appropriate gap on the other lanes to insert into. The "appropriate" gap is not fixed, but is adapted according to the emergency grade, which is determined by the available time or distance for lane changing.

When the driver of the *n*th vehicle looks through the rearview mirror, he is supposed to get the available distance d_n^{av}, and to obtain the relative velocity $\Delta v_n = v_{engine} - v_n$, by observing the engine's width w in the mirror and receipting the derivative of visual angle θ. The relationship could be expressed as follows:

$$w = \theta \cdot d_n^{av} \qquad [2]$$

Get the derivation of [2] and set $\frac{dw}{dt} = 0$,

$$\frac{\partial \theta}{\partial t} d_n^{av} + \theta \frac{\partial d_n^{av}}{\partial t} = 0 \qquad [3]$$

$$\Delta v = \frac{\partial d_n^{av}}{\partial t} = -\frac{d_n^{av}}{\theta} \frac{\partial \theta}{\partial t} = -\frac{\left(d_n^{av}\right)^2}{w} \frac{\partial \theta}{\partial t} \qquad [4]$$

Introducing the receipt threshold of the derivative of visual angle, the threshold of the relative velocity could be recognized by the driver Δv_0, is obtained. If $\Delta v_n \geq \Delta v_0$, the available time t_n^{av} for lane changing could be computed as follows:

$$t_n^{av} = \frac{d_n^{av}}{\Delta v_n} \qquad [5]$$

The driver could judge the emergency grade with it. Table 1 gives the judge rules. For different emergency grade, the driver will choose different gaps.

As shown in Table 2, the two action models are expressed as the lane-changing rules, for bringing into the traveling simulation of the fire engine.

TABLE 1. Emergency grade judge rules

When $\Delta v_n \ge \Delta v_0$	When $0 \le \Delta v_n < \Delta v_0$	When $\Delta v_n < 0$	Emergency Grade
$t_n^{av} \le t^{ne}$	$d_n^{av} \le d^{ne}$	None	I (most urgent)
$t^{ne} \le t_n^{av} \le t^{ac}$	$d^{ne} \le d_n^{av} \le d^{ac}$	None	II
$t_n^{av} > t^{ac}$	$d_n^{av} > d^{ac}$	All	III

Note: t^{ne} and d^{ne} are the necessary time and distance to change lane, t^{ac} and d^{ac} are the acceptable time and distance when the *n*th common vehicle could consider that the fire engine is far enough behind.

TABLE 2. Way-yielding rules

	Safety Model	Balance Model		
Incentive Criteria	$\left(d_n^{av} \le L_{alarm}\right)$ && $\left(Lane_n = Lane_{emer}\right)$	$\left(d_n^{av} \le L_{alarm}\right)$ && $\left(Vehi_{n+1} = FireEngine\right)$		
Safety Criteria	$\left(d_{pred}^{eff} \ge v_n\left(t\right)\right)$ && $\left(d_{succ} \ge v_{succ}\right)$	Emergency Grade I	Emergency Grade II	Emergency Grade III
		$\left(d_{pred} \ge 0\right)$ && $\left(d_{succ} \ge 0\right)$	$\left(d_{pred}^{eff} + d_{succ} \ge \left(v_n\left(t\right) + v_{succ}\right)/2\right)$ && $\left(d_{pred} \ge 0\right)$ && $\left(d_{succ} \ge 0\right)$	$\left(d_{pred}^{eff} \ge v_n\left(t\right)\right)$ && $\left(d_{succ} \ge v_{succ}\right)$

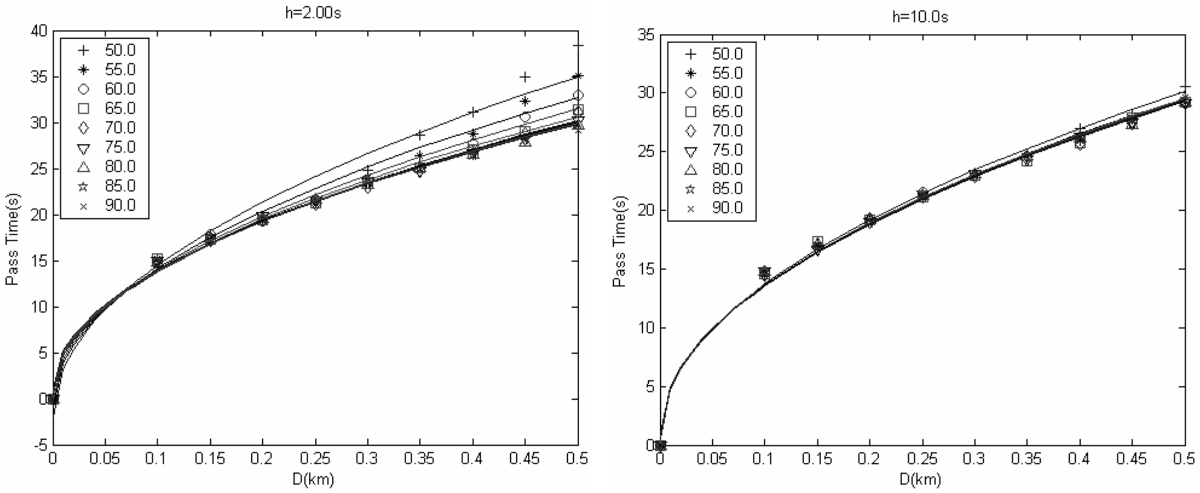
Note: L_{alarm} denotes the alarm propagation distance. $Lane_{emer}$ is the lane that fire engine occupied. $Vehi_{n+1}$ is the very successor of the nth vehicle. d_{pred} and d_{succ} are the distances between vehicle *n* and its predecessor and the successor on the destination lane. v_{succ} is the velocity of the nth vehicle's successor on the destination lane. See reference 6 and 7 for more details.

SIMULATION RESULTS AND DISCUSSION

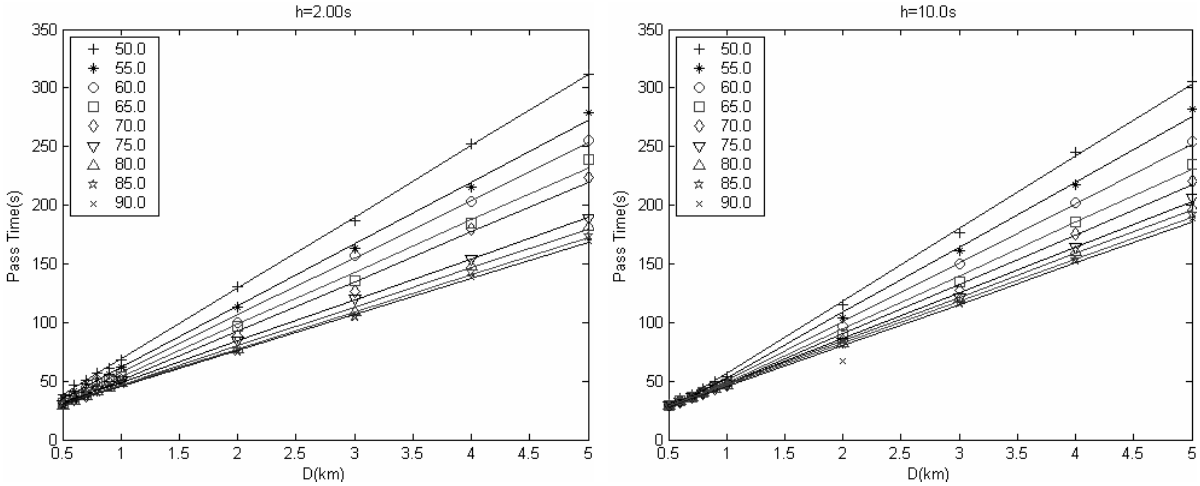
In this section, the authors simulate the fire engine's traveling on a two-lane road with the two models brought in respectively, while the simulation parameters are set same, viz. the velocity distribution at the entrance of the road and the percentages of three types of vehicles are set fixed according to the test data of reference 8, and the fire engine entering and maximum speed are set to zero and 100 km/h respectively. With the simulation results, the authenticity of both models could be proved. The difference between the results of the two will be discussed.

Average Travel Time vs. Travel Distance

Fig. 1 and Fig. 2 show the simulation results of average travel times at different travel distances *D*, speed limit v_c, and mean values of temporal entering headway *h* (i.e. the reciprocal of entering traffic volume) with the safety model and the balance model introduced in, respectively. And the fitting curves indicate that both models are coincident with the empirical formula [1], i.e., the travel time increases with the square root of the distance for short trips and increases linearly for longer trips.

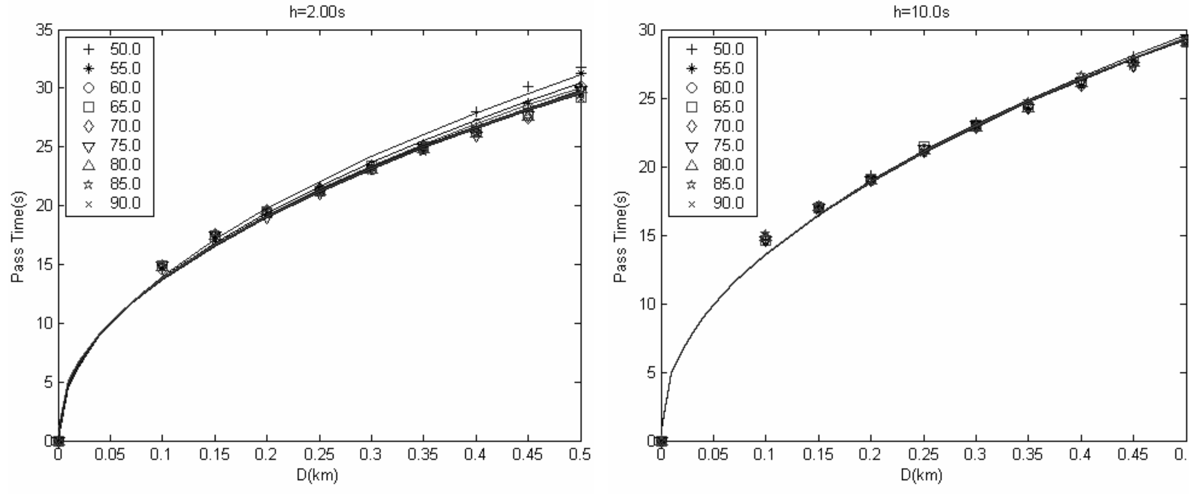


(a) $D < 0.5km, h = 2.0s$ (b) $D < 0.5km, h = 10.0s$



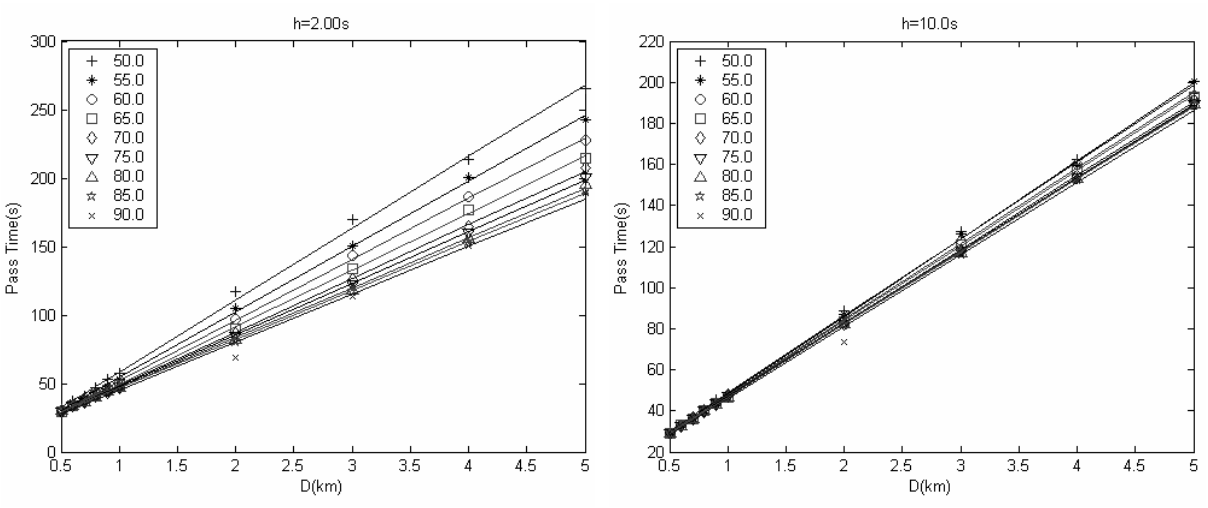
(c) $D \ge 0.5km, h = 2.0s$ (d) $D \ge 0.5km, h = 10.0s$

FIGURE 1. Average travel time of fire engine vs. travel distance (Safety model)



(a) $D < 0.5km, h = 2.0s$ (b) $D < 0.5km, h = 10.0s$

FIGURE 2. Average travel time of fire engine vs. travel distance (Balance model)



(c) $D \ge 0.5km, h = 2.0s$ (d) $D \ge 0.5km, h = 10.0s$

FIGURE 2 (Cont'd). Average travel time of fire engine vs. travel distance (Balance model)

Average Travel Time Comparison

In this part, the average travel time of fire engine, one of the different effects brought by the two models, are compared at different travel distances in Table 3, while the speed limit v_c is set to 50 km/h, and the mean value of temporal entering headway *h* is set to 2.0 s.

From Table 3, the difference between the two groups of results since *D = 0.3km* could be told, i.e., when *D < 0.3 km*, the difference between the two models' results are negligible, and when *D > 0.3 km*, the average travel time of the fire engine under the balance model is shorter than that under the safety model, and the disparity becomes bigger as *D* increases.

At the first 0.3 km of the fire engine's trip, vehicles are so dense all through that they fail to yield under either model. When the trip is longer than 0.3 km, the traffic density is small enough to make the way-yielding action happen under the balance model, which has less self-safety consideration.

TABLE 3. Average travel time comparison

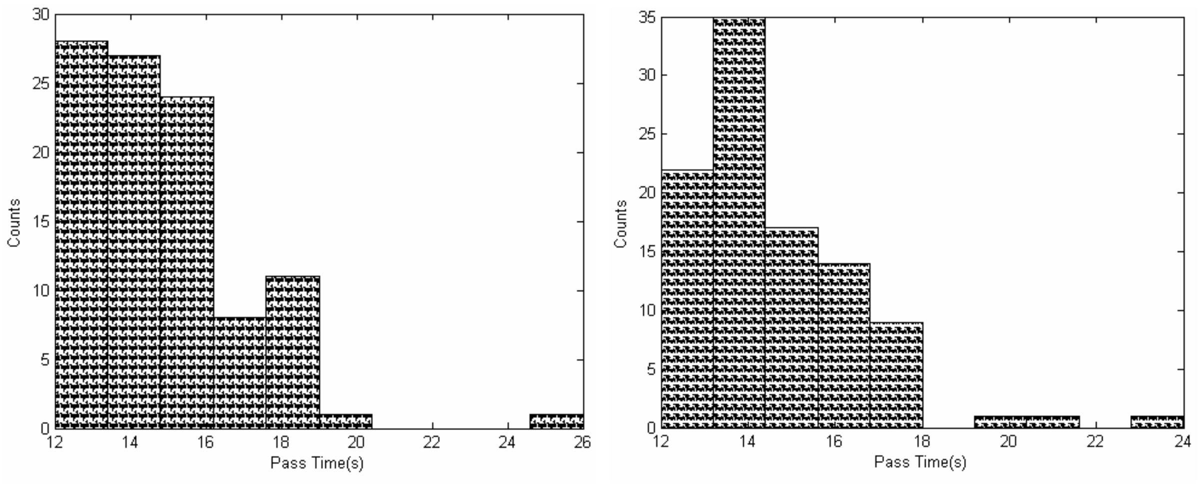
$D(km)$	Average Travel Time $t(s)$	
	Safety Model	Balance Model
0.100	14.89	14.77
0.150	17.36	17.55
0.200	19.64	19.65
0.250	21.31	21.64
0.300	24.75	23.33
0.350	28.64	25.14
0.400	31.15	27.96
0.450	34.92	30.11
0.500	38.31	31.81
0.600	46.58	37.54
0.700	51.60	40.74
0.800	58.64	46.83
0.900	65.73	53.61
1.000	73.76	57.58
3.000	220.82	169.42
5.000	367.62	265.35

Travel Time Distribution Comparison

Similar effects could be found in the distribution comparison of travel time (Figs. 3 to 10). As before, the speed limit v_c is set to 50 km/h, and the mean value of temporal entering headway h is set to 2.0 s.

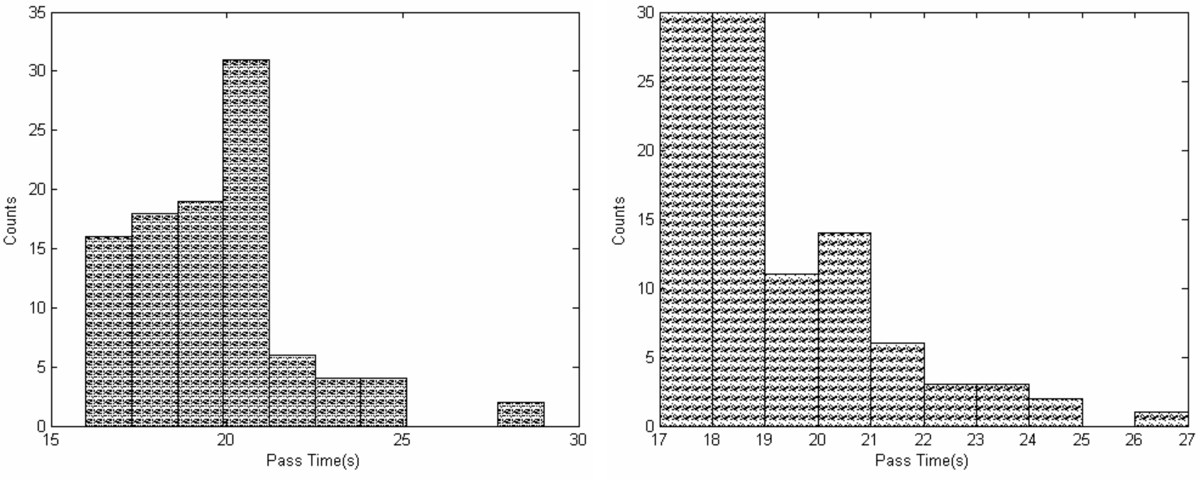
When $D < 0.3$ *km*, the distribution type and characterized parameters under both models could be considered the same.

When $D > 0.3$ *km*, there are two major differences between the travel time distribution with different way-yielding model brought in. First of all, when the distance increases, the distribution under the safety model resembles a normal distribution, while the one under the balance model resembles a uniform distribution. The minimum time under the safety model becomes larger than that under the balance model, which is near the ideal travel time (D/v_{max} *of fire engine*).



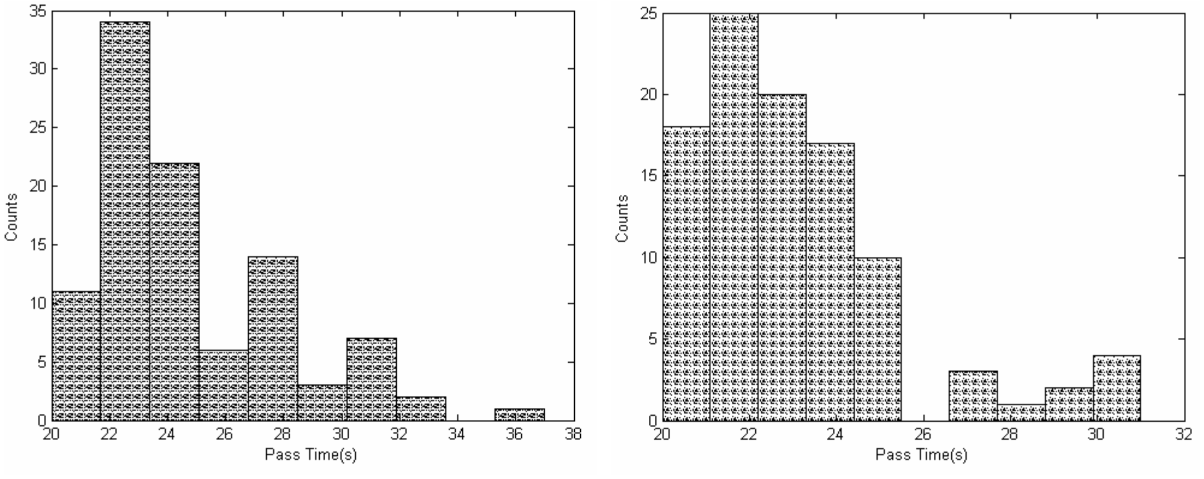
(a) Safety model (b) Balance model

FIGURE 3. Travel time distribution ($D = 0.1km$)



(a) Safety model (b) Balance model

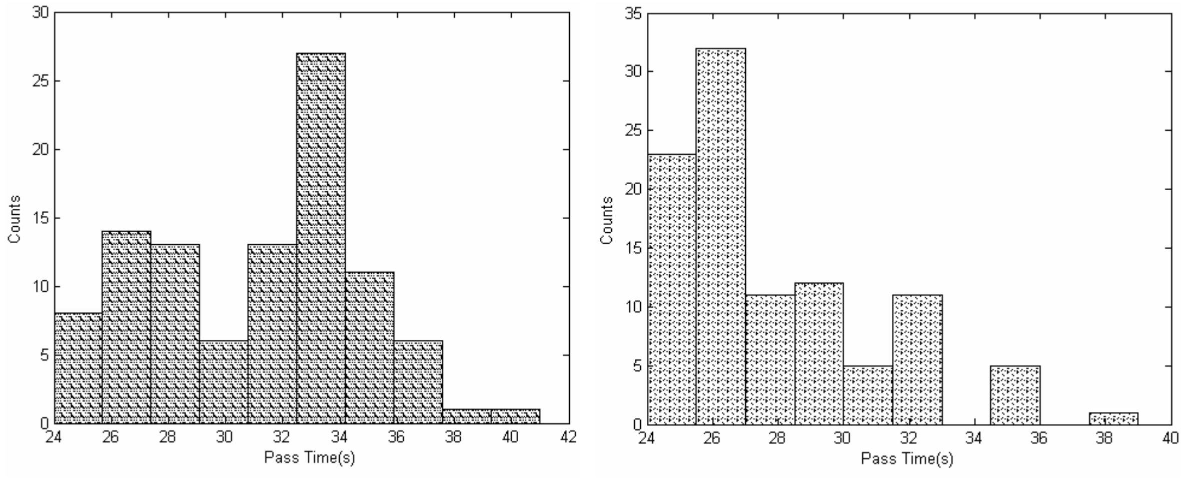
FIGURE 4. Travel time distribution **(** $D = 0.2km$ **)**



(a) Safety model

(b) Balance model

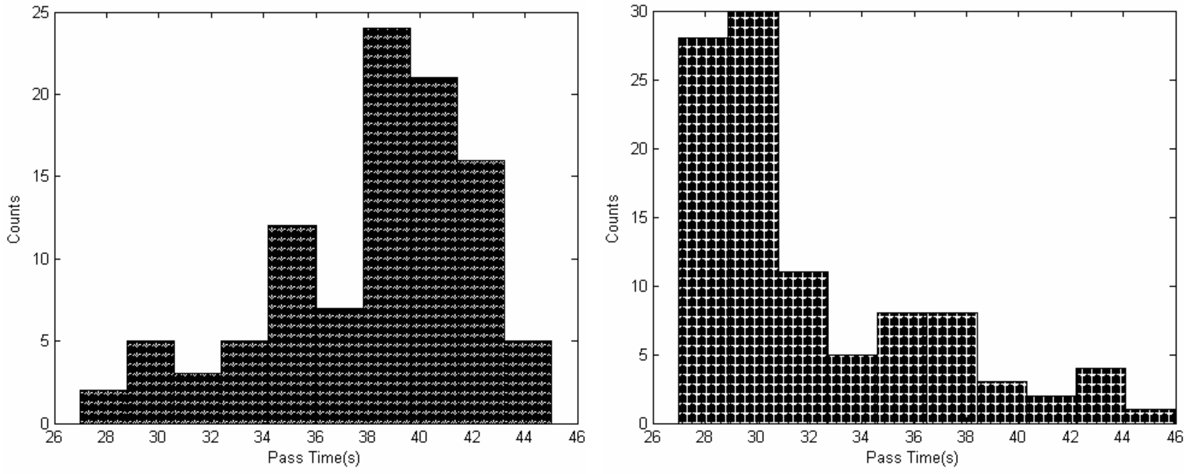
FIGURE 5. Travel time distribution ($D = 0.3km$)



(a) Safety model

(b) Balance model

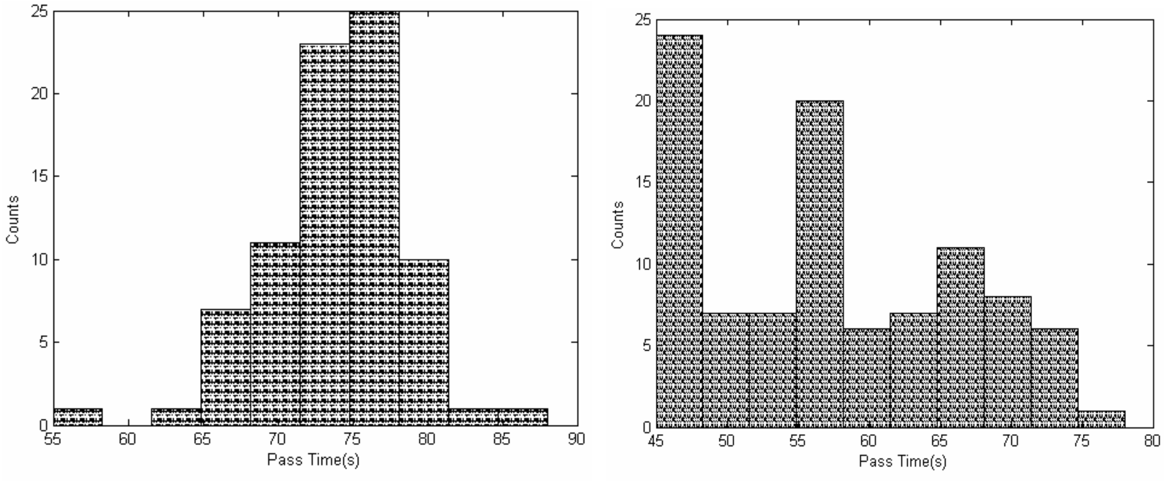
FIGURE 6. Travel time distribution ($D = 0.4km$)



(a) Safety model

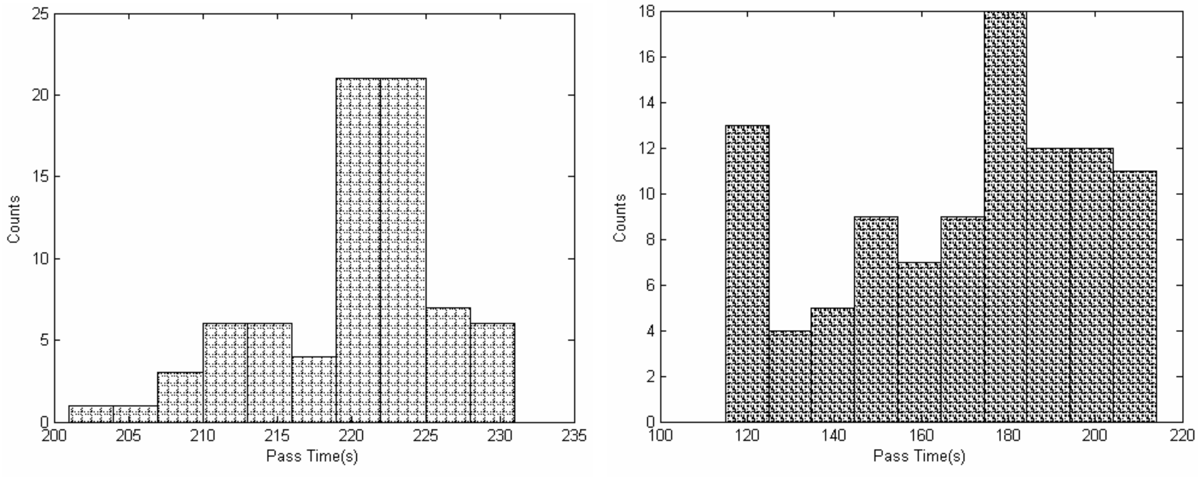
(b) Balance model

FIGURE 7. Travel time distribution ($D = 0.5km$)



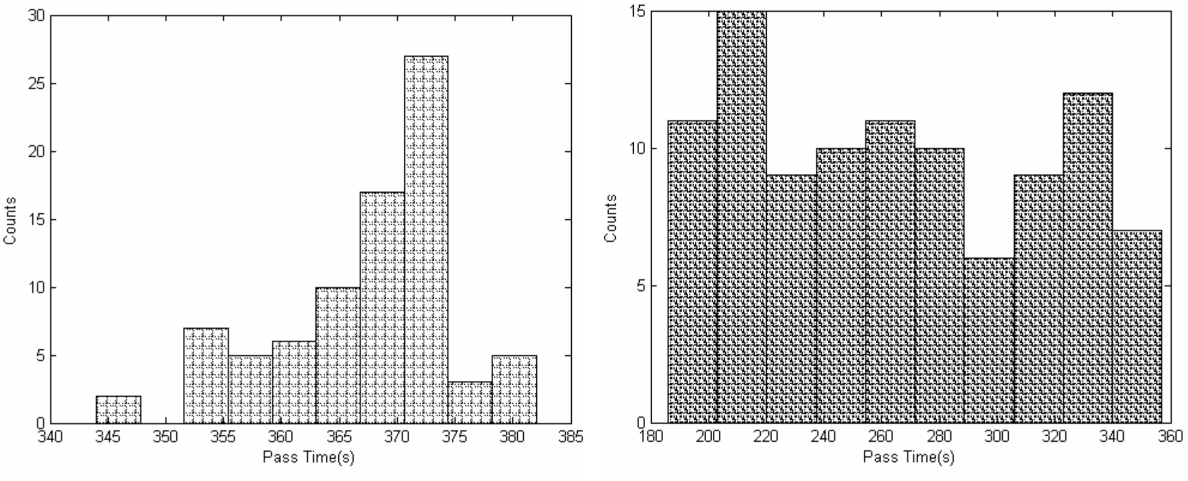
(a) Safety model (b) Balance model

FIGURE 8. Travel time distribution ($D = 1.0km$)



(a) Safety model (b) Balance model

FIGURE 9. Travel time distribution ($D = 3.0km$)



(a) Safety model (b) Balance model

FIGURE 10. Travel time distribution ($D = 5.0km$)

CONCLUSIONS

The major conclusions obtained in this paper are as follows:

1) The way-yielding actions described by the safety model and the balance model both exist in real life.
2) Laws and instructions that make common vehicles close to the fire engine yield the right of way easier and faster could shorten the travel time of the fire engine, especially in some firehouse-scarce districts.

There are various actions of common vehicles responding to an alarm whistle. If the way-yielding actions could be modeled in-depth, or the actions taken by both common vehicles and fire engine at intersection could be modeled, or the percentage of each kind of action could be obtained and introduced into the simulation, more accurate and meaningful results could be obtained, and plans can be made to make fire response faster.

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REFERENCES

1. Walker, W.E., “Fire Department Deployment Analysis”, The Rand Fire Project, 1979.
2. Ibrahim, A.T. and Hall F. L., “Effect of Adverse Weather Conditions on Speed-Flow-Occupancy Relationships”, Transportation Research Record 1457, Transportation Research Board, Washington, D.C., 1994.
3. Brilon, W. and Ponzlet M., “Variability of Speed-Flow Relationships on German Autobahns”, Transportation Research Record 1555, Transportation Research Board, Washington, D.C., 1996.
4. Kyte, M., Khatib Z., Shanon P. and Kitchener F., “Effect of Environmental Factors on Free-Flow Speed”, Proceedings of the 4th International Symposium on Highway Capacity, Maui, June 2000, National Research Council, TRB, Washington, D.C., 2001.
5. Lai, Junyan, Chen, Tao, Shen, Shifei, Liu, Yi and Yuan, Hongyong, “A Simulative Method of Emergency Rescue Response Travel Time Calculation”, International Symposium on Safety Science and Technology, 2006.
6. Knospe, W., Santen, L., Schadschneider, A. and Schreckenberg, M., “Towards a realistic microscopic description of highway traffic”, J Phys A Math Gen, 2000, 33, L477-L485.
7. Knospe, W., Santen, L., Schadschneider, A. and Schreckenberg, M., “A realistic two-lane traffic model for highway traffic”, J Phys A Math Gen, 2002, 35, 3369-3388.
8. Jin, Wen-zhou, Zhang, Jie Zheng, and Ying, Li, “The Random Input Model for Traffic Flow Simulation”, Journal of South China University of Technology (Natural Science Edition), 11:9, 92-97, 2001.