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Study on the Median Opening Length of a Freeway Work Zone Based on a Naturalistic Driving Experiment

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Abstract: Median openings are an effective traffic organization mode for freeway crossover work zones, and their length is one of the most important control indicators to ensure traffic safety in work zones. In this paper, a theoretical calculation model of the median opening length was established according to the lane-changing demands of vehicles crossing through the median opening of the freeway. Based on the calculation model, the influencing factors of the median opening length were analyzed, and the calculation values of the median opening length under different speed limits, median widths and cross slopes were proposed. A naturalistic driving experiment of drivers' safety and comfort, with 48 participants at four opening lengths of 40, 70, 100 and 130 m in a typical freeway work zone, was carried out based on the calculated length values and the driving workload, expressing drivers' safety and comfort. It was found that the median opening length of the freeway had a positive correlation with the vehicles' running speed and the drivers' driving workload: the shorter length reduced the running speed of the vehicles and led to uncoordinated running speeds in the work zone; the longer length caused driver tension and led to the vehicles' running speed and speed variability being too high. The research results indicated that the median opening length of freeway work zones is an important factor affecting the vehicle running speed, driving workload and speed limit compliance rate.

Keywords: work zone; median opening length; driving workload; naturalistic driving experiment

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1. Introduction

With the rapid development of the economy, some of the early constructed freeways have gradually failed to meet the growing traffic volume and traffic safety needs; thus, the focus of freeway construction has gradually shifted to reconstruction and expansion projects. In order to reduce the impact on traffic, during the process of freeway reconstruction and expansion, traffic organization is often carried out by "opening to traffic during construction", which causes changes in road conditions and traffic control methods in the work zone, resulting in traffic congestion [1,2] and increasing traffic safety risks in the work zone [3,4]. According to the statistics of the Federal Highway Administration, there were 774 fatal crashes in work zones, causing 857 fatalities in 2020, which increased by about 40% compared to 2011; from 2011 to 2020, more than 400,000 people were injured due to work zone traffic accidents [5], so the traffic safety situation in work zones is becoming increasingly critical.

Regarding the factors influencing traffic safety in work zones, some scholars have conducted relevant studies [6,7], and the results indicated that the type and layout method of work zones are some of the main causes of traffic accidents in work zones [8,9]. During the construction, part of the work zone needs to occupy half of the road, forming crossover work zones. Under this condition, when a driver drives into the opposite lane through the median opening, the driver's driving behaviors, such as slowing down, changing lanes and following, are more prone to rear-end and other accidents compared to when driving in other types of work zones, leading to negative impacts on traffic safety [10–13]. When the opening length is short, drivers tend to reduce their running speed for safety reasons, and the capacity of the median opening decreases sharply, causing traffic congestion [14]; moreover, when the vehicle speed changes sharply at the opening, traffic accidents can easily be caused [15,16]. Conversely, when the opening length is too long, the vehicle will run faster and easily collide with the opposite traffic, causing traffic accidents; furthermore, if the opening is too long, the construction cost will increase. Therefore, the median opening length of freeway work zones has attracted the attention of many researchers and engineers. The "Manual on Uniform Traffic Control Devices" has formulated a temporary traffic control plan to clarify the layout and management methods of various types of work zones, but it lacks specific provisions on the median opening length of freeway work zones [17]. Richard et al. studied the characteristics of the vehicle running speed in crossover work zones and proposed a speed prediction model. They found that, when the vehicle crosses the work zone, the running speed starts to decrease from 200 m upstream of the transition area, reaching the median opening at a speed about 6~24km/h slower than in the warning area, leading to an increase in traffic safety risks. Additionally, the vehicle running speed depends on the vehicle type and lane location. These relevant research results provide a basis for the determination of the median opening length [18–20].

Currently, traffic simulation is the main method to study the median opening length. Sherif et al. simulated different areas of the work zone, studied the influences of traffic volume, proportions of trucks, lengths of different areas, vehicle acceleration and speed variance on traffic safety in the work zone, and proposed a new method for laying out the work zone [21,22]. Li et al. modeled the work zone capacity, analyzed the traffic characteristics, traffic organization and vehicle characteristics of the work zone, and studied the influences of lane closure forms, proportions of trucks, different area lengths and speed limits in the work zone on the work zone capacity by using traffic simulation [23]. Pan et al. established a vehicle track model for a median opening based on the turning driving characteristics of the vehicle and provided a recommended median opening length under the conditions of different speed limits, median widths and super elevations; when the speed limit is 40~60 km/h, the recommended length is 60~125m [24]. Through calculation and simulation, Ge found that, when the speed limit is 60 km/h, the opening length should be 80~120 m [25]; Liu obtained the length of 94~154 m for when the speed limit is 40~60 km/h through similar methods [26]. Through simulation, Wang found that, when the speed limit is 40 km/h and the opening length is 80~120 m, the impact on traffic is small [27]. Wei et al. simulated the traffic organization of a freeway work zone and concluded that the vehicle running speed and capacity were higher when the median opening length was 80~100 m, but the traffic safety was not considered [28]. Shao et al. combined model calculations with traffic simulation, analyzed the relationship between the capacity, operating speed, speed limit compliance rate and opening length, evaluated the safety of the opening using TTC (time to collision) and proposed the recommended values of the median opening length at different design speeds [29]. However, the traffic simulation methods used in the relevant studies lack validation means, and the results obtained vary widely. Most of the studies used default simulation parameters (e.g., following and lane change models), which made it difficult to reflect the influences of different opening lengths on drivers' psychological indicators and driving behaviors.

Driving simulation is one of the common methods for studying driving behavior [30]. Lorenzo et al. used driving simulation to analyze the driving behaviors under nine different layouts in freeway crossover work zones. They found that there was a significant difference in the vehicle running speed. When the median opening length was 40~80 m, the vehicle running speed was 53.5~70.2 km/h; when the opening length increased, the driver could safely complete driving at a higher speed without behaviors such as sudden deceleration [31]. Through field investigation and driving simulation, Bella et al. found that, when the vehicle passes through the median opening, its speed will drop significantly, and its running speed will not be lower than the speed limit until the opening length is less than

30 m [32]. Jing et al. employed driving simulation to investigate driving performance using metrics (speed, acceleration, maximum steering wheel speed and lane-changing track) with respect to five median opening lengths, and the results indicated that, when the opening length was too large or too small, it would impact the traffic safety in the work zone; their recommended opening length is 90 m when the speed limit is 60 km/h [33]. However, driving simulators have a limited simulation degree of real vehicles (only 70~80%). The vehicle speed is usually high while the acceleration is low. Their relative validity is only applicable to the study of driving behavior [34].

Compared with traffic simulation and driving simulation, "naturalistic driving" means installing data acquisition equipment on vehicles and drivers to monitor and record the actual driving process of drivers at all times. The data from naturalistic driving are true and reliable, as shown in Table 1. However, due to the complexity of the experiment, only a few safety studies in work zones use the natural driving experiment method.

Table 1. Comparison of the advantages and disadvantages of research methods in the work zone.

Research Methods	Applicability	Advantage	Disadvantage
Traffic simulation	Traffic flow theory Road design Traffic safety Intelligent transportation	Risk-free Flexible Repeatable Comparable Cost-efficient	Difficulty in model calibration Results differ greatly
Driving simulation	Driving behavior Traffic safety Vehicle research	Risk-free Cost-efficient Ease of data collection Repeatability	Low degree of simulation Relative validity Simulator sickness
Naturalistic driving	Driving behavior Traffic safety Vehicle research Driver's psychophysiological indicators	Real Reliable data Long-term observation	Expensive Harsh test conditions

The road and traffic conditions change dramatically in the median opening of the work zone, and drivers need to analyze, process and judge the road and traffic information, make decisions and operate the vehicle; the mental stress formed during the whole process is the driving workload [35], and different opening lengths affect drivers differently. However, there is a lack of methods and specifications for determining the median length. Most of the studies on the length of median openings are based on driving simulation or traffic simulation; the results of different studies vary greatly; and the influences of different opening lengths on the drivers' psychological indicators and driving workload are not clear. Furthermore, there is a lack of measured data on vehicle running speeds under different opening lengths. In order to determine the appropriate length of the median opening, a naturalistic driving experiment with four different opening lengths was carried out in a freeway crossover work zone to analyze the influence of different median opening lengths on the drivers' driving workload based on the theoretical calculation of the median opening length. The study results have great significance for optimizing the construction organization plan, actively guiding traffic and improving the safety and smoothness of work zones.

2. Methodology

2.1. Length of Median Opening and Its Influencing Factors

The median opening length in the crossover work zone should ensure that vehicles safely cross through the opening at a moderate running speed. The vehicles need to change lanes at the opening, turn left to reach the midpoint of the opening and then drive right into the opposite lane. According to the vehicle driving track in the median opening, it can be simplified to a model, as shown in Figure 1.

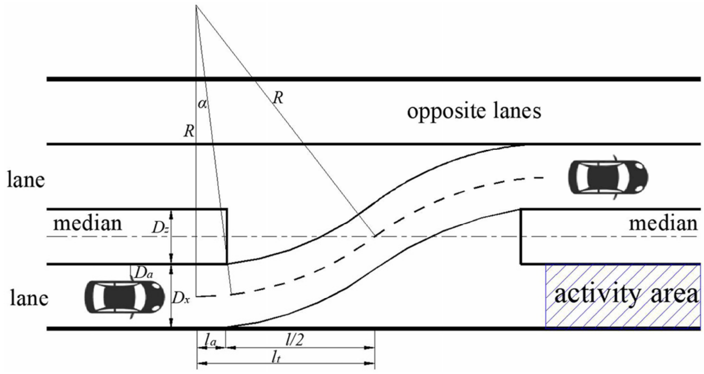

Figure 1. Schematic diagram of the median opening length calculation model.

The track of the vehicle crossing through the opening is S-shaped, forming two circular curves with the same radius connected in reverse. According to the equilibrium of the forces when a vehicle crosses through the median opening, we obtained the vehicle driving radius as follows [29]:

$$R = \frac{V^2}{127(\varphi + i)} \tag{1}$$

where R is the vehicle driving radius at the median opening, m; V is the vehicle speed at the median opening, km/h; φ is the sideway force coefficient; and i is the cross slope.

From Figure 1, Equations (2) and (3) are derived as follows:

$$R^2 = l_t^2 + (R - \frac{D_x + D_z}{2})^2 \tag{2}$$

$$l_t = \frac{\sqrt{4R(D_x + D_z) - (D_x + D_z)^2}}{2} \tag{3}$$

where D_z is the median width, m; D_x is the inside-lane width, m; and l_t is the projection length of the vehicle track line. Equations (4) and (5) can be derived as follows:

$$l_a = (R - \frac{D_x}{2}) \tan \alpha \tag{4}$$

$$\cos \alpha = \frac{R - \frac{D_x}{2}}{R - (D_x - D_a)} \tag{5}$$

The calculation model of the median opening length is as follows:

$$l = 2[l_t - (R - \frac{D_x}{2}) \tan \alpha] \tag{6}$$

where α is the deflection angle corresponding to the circular curve of the vehicle driving track; l_a is the deflection angle corresponding to the track projection; and D_a is the safety distance between the vehicle and median, taken as 0.5 m.

According to the calculation model, the length of the median opening is related to the median width, lane width and vehicle turning radius; the turning radius of the vehicle is determined by the vehicle running speed, sideway force coefficient and cross slope.

When the opening length is fixed and the vehicle crosses through the median opening, the wider the median, the greater the vehicle's lateral displacement and the smaller the turning radius, resulting in decreases in the vehicle's running speed and road capacity. According to a survey, median widths of 2 m, 3 m, 3.5 m and 4.5 m are generally used on freeways.

The lane width also affects the lateral displacement and running speed of vehicles crossing through the opening, thus affecting the length of the median opening. Most of the openings are one lane, making it difficult to meet the turning requirements of large vehicles. In work zones, the lane width is widened according to the most unfavorable vehicle crossing through the opening. The widening value on the circular curve road is 0.4~0.6 m and the lane width is taken as 4.25 m, the most unfavorable vehicle width is 2.5 m.

The sideway force coefficient, affected by the road surface conditions, will directly affect the turning radius of the vehicle, which is negatively correlated with the vehicle running speed; an increase in the vehicle running speed will reduce the sideway force coefficient and increase the turning radius, thus having a significant impact on the opening length. The sideway force coefficient adopts the recommended value of 0.12~0.23 from "A Policy on Geometric Design of Highways and Streets" [36], and the value taken is negatively correlated with the vehicle speed.

In order to facilitate drainage, a double-sided crown of 2~4% is usually adopted on freeways, with the middle point of the median as the highest point of the road. When vehicles cross through the median opening, they experience the opposite cross slope, which leads to an increase in the turning radius and the median opening length.

The vehicle running speed is the most direct influencing factor of road design. When the vehicle running speed increases, the opening length should increase; otherwise, the opening length can be smaller. The number of lanes in the work zone is relatively small, and the road conditions are complex, so the speed limit is low, usually around 40~80 km/h.

According to Equation (6), the calculated values of the median opening length (rounded up to the nearest 5 m) under different speed limits, median widths and cross slopes can be obtained, as shown in Table 2. From the calculation results, it can be seen that the speed is the most influential factor on the median opening length and, when the speed is constant, the influence of the median width on the opening length is greater than that of the cross slope.

Table 2. Calculated values of the median opening length under different cross slopes, median widths and speed limits (m).

Cross Slope (%)		**−2.0**				**−3.0**				**−4.0**			
Median Width (m)		**2**	**3**	**3.5**	**4.5**	**2**	**3**	**3.5**	**4.5**	**2**	**3**	**3.5**	**4.5**
Speed Limit (km/h)	40	40	40	45	45	40	40	45	45	40	45	45	45
	50	55	60	60	65	55	60	60	65	55	60	65	65
	60	70	75	75	80	70	75	80	80	75	80	80	85
	70	85	90	95	100	90	95	100	105	95	100	105	110
	80	105	110	115	120	105	115	120	125	110	120	125	130

The model can provide the calculated value of the median opening length in theory, but in practical application, the speed limit, running speed, speed limit compliance rate, driver workload and other factors will affect the median opening length, so it is necessary to conduct a naturalistic driving experiment, combined with the drivers' driving workload and traffic operating characteristics, to study the median opening length.

2.2. Calculation of Driving Workload

Different road, traffic and environmental conditions in work zones provide different amounts of stimulation to the driver, which determines the driver's driving workload, and the driving workload of the same driver under different road, traffic and environmental conditions can also vary. Driving workload can reflect different impacts of road and traffic conditions on drivers in real time. When the driving workload is too high, the driver cannot fully adapt to the road conditions, so he/she becomes very nervous and worried, accompanied by a busy driving operation; when the driving workload is too low, the driver's driving alertness and wakefulness are reduced, and driving fatigue is easily induced.

Studies have shown that fluctuations in heart rate variability (HRV) and the ratio of low-frequency to high-frequency (LF–HF) heart rate reflect the driver's sympathetic nerve activity and have a positive correlation with driving workload, which can be adopted to measure the driver's driving workload. The higher the driving workload, the lower the HRV, and LF will significantly increase, while HF will decrease. As a result, LF–HF will increase notably, and sympathetic nerve excitability will be enhanced. To finish the driving task and maintain working ability, drivers need to spend more energy; thus, their driving workload will be higher. The measurement model of driving workload is shown in Equation (7):

$$K_{ij} = [(\frac{LF}{HF})_{ij} - A_i]/V_{ij} \tag{7}$$

where K_{ij} is the driving workload of driver i at position j; $(LF/HF)_{ij}$ is the HRV of driver i at position j; A_i is the HRV when driver i is driving normally; and V_{ij} is the running speed when driver i is at position j, km/h.

The classification thresholds of driving workload are shown in Table 3 [35].

Table 3. Threshold values of the safety classification of driving workload on a freeway.

Driving Workload Degree	Safety Level	Passenger Car	Truck
Highest	Highly risky (nervous)	$K > 0.060$	$K > 0.070$
Higher	Relatively risky (relatively nervous)	$0.030 < K \leq 0.060$	$0.035 < K \leq 0.070$
Normal	Safe	$-0.001 < K \leq 0.030$	$-0.001 < K \leq 0.035$
Lower	Relatively risky (relatively fatigued)	$-0.012 < K \leq -0.001$	$-0.011 < K \leq -0.001$
Lowest	Highly risky (fatigue)	$K \leq -0.012$	$K \leq -0.011$

3. Experiment

3.1. Participants and Vehicles

In order to prevent different genders, ages, driving experiences and personalities of drivers from influencing the experimental results, according to the purpose of the experiment, 48 participants with good physical conditions, normal vision or corrected vision and no history of cardiovascular disease, heart disease, color blindness or other eye diseases were randomly recruited. They had a good rest before the experiment and were not allowed to drink alcohol or take drugs 72 h before or during the experiment. Briefly, the 24 passenger car (car) drivers (16 men and 8 women) were aged from 21 to 55 years (average ± SD = 36.5 ± 9.1 years), with driving experience ranging from 2 to 30 years (average ± SD = 10.6 ± 7.4 years); the 24 truck drivers (20 men and 4 women) were aged from 26 to 54 years (average ± SD = 38.7 ± 8.1 years), with driving experience ranging from 2 to 28 years (average ± SD = 10.2 ± 6.8 years).

Representative cars and trucks running on the freeway were used as experimental vehicles, as shown in Figure 2.

Figure 2. Experimental vehicles (passenger car and truck).

3.2. Instruments and Equipment

The experiment used a KF2 dynamic multi-parameter physiological detector with a sampling rate of 60 times per minute, an error of less than three times per minute and a real-time continuous working period of greater than 24 h. The KF2 detector was adopted to record the driver's psychophysiological parameters, including heart rate, respiration, HRV and surface temperature, as shown in Figure 3.

Figure 3. Equipment used in experiment: dynamic multi-parameter physiological detector.

The Novatel Dynamic GPS was used to collect the dynamic running speeds, driving track and position of the vehicle, with a sampling frequency of 10 Hz, an operating speed precision of 0.03 m/s and a coordinate error of less than 0.45 m, as shown in Figure 4.

Figure 4. Vehicle equipment used in the experiment: Dynamic GPS.

3.3. Experimental Road

A typical four-lane freeway in China undergoing expansion was selected for the experiment. Due to the construction needs, half a lane was closed, forming a crossover work zone, with two-way traffic in two opposite lanes. The alignment condition of the experimental road was good; the design speed was 100 km/h; the speed limit was 80 km/h during the expansion period; the lane width was 3.75 m; the median width was 2 m; the lateral clearance was 1.5 m; the longitudinal grade was 0; and the cross slope was −2%. The experimental road was about 6 km long, of which the standard freeway section was a 2 km straight section with a speed limit of 80 km/h; the work zone was about 4 km long, with a speed limit of 60 km/h. The traffic signs were set according to the current Chinese standard for work zones [37], and the work zone consisted of the following areas shown in Figure 5.

- Advance warning area (1600 m), composed of two lanes in one direction with a lane width of 3.75 m.
- Upstream transition area (200 m), transitioning from two lanes to one lane.
- Buffer area (200 m), composed of one lane in one direction with a lane width of 4.25 m.
- Median opening: According to the calculation results, the median opening length should be 40~130 m. Combined with the actual crossover work area of the freeway expansion project, the commonly used lengths of 40 m, 70 m, 100 m and 130 m were selected as the median opening lengths of the experimental road, with an interval

length of 30 m; this area was composed of one lane in one direction, with a lane width of 4.25 m.

- Activity area (2000 m), composed of one lane in one direction with a lane width of 4.25 m, separated from the opposite lane using traffic cones.
- The downstream median opening was 40 m long, the downstream transition area was 100 m long and the termination area was 40 m long; after the vehicle crosses through the work zone, the two-lane speed limit of 80 km/h is restored.

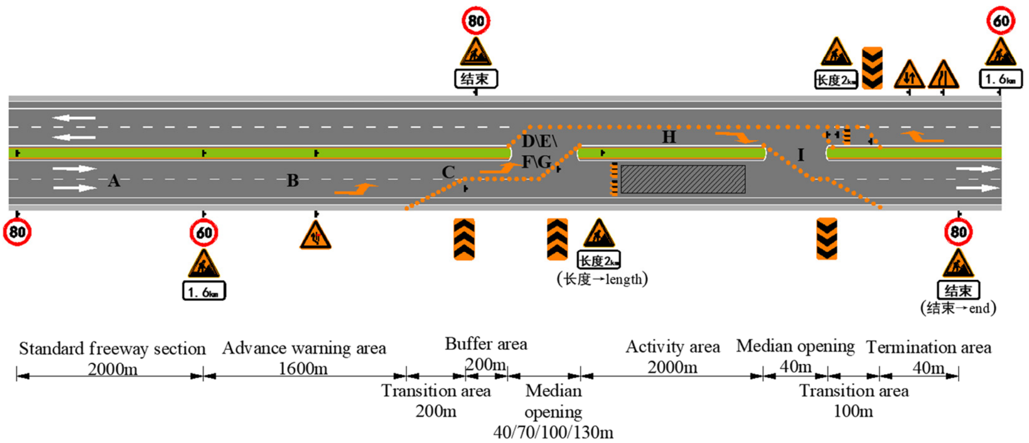

Figure 5. Details of each part of the experimental road.

3.4. Experimental Procedures

The experiment was conducted in April when the weather was good, from 8:00 to 12:00 and from 14:00 to 18:00 daily, for a total of 10 days. Before the formal experiment, the participants were required to drive the experimental vehicle on the typical freeway for 30 min so that the participants could become familiar with the vehicle. Then, the experimenter calibrated the dynamic multi-parameter physiological detector and helped the participant to put it on, calibrated and installed GPS on the vehicle and adjusted the instruments to a uniform time. After the experiment was officially started, the participants were required to sit quietly in the vehicle for 5 min to maintain a normal psychological state, and then drove the vehicle through the standard freeway section and work zone in order under free-flow traffic conditions (traffic volume $k < 7$ veh/km·ln). Each participant was required to drive 4 times depending on the length of the median opening; a total of 192 tests were conducted by the 48 participants. To ensure the objectivity of the data, the participants were not informed of the current driving road conditions in advance in each test. During the experiment, a recorder was assigned to record the time when the participant passed an important point, the participant's behaviors such as overtaking, lane changing and inattentiveness, and abnormal road conditions, to provide a basis for eliminating abnormal data during data processing. After the experiment, each participant was paid for their participation.

3.5. Data Analysis

To ensure the data acquisition accuracy of the instruments, the sampling frequencies of the dynamic multi-parameter physiological detector and GPS data were set to 1 Hz. As shown in Figure 5, during the experiment, the data were collected for the standard freeway section (A), advance warning area (B), upstream transition area (C), 40 m median opening (D), 70 m median opening (E), 100 m median opening (F), 130 m median opening (G), activity area (H) and downstream median opening (I). The data were corrected according to the recorder's records. After removing the abnormal data, the experiment yielded a total of 109,056 HRV physiological data and 106,531 vehicle GPS data for 48 participants under 4 median opening lengths.

4. Results and Descriptive Analysis

4.1. Speed

4.1.1. Speed Distribution in the Work Zone

Based on the collation and analysis of the experimental vehicle speed, it was found that the S–W normality test results for a total of 18 sets of data for different vehicles in areas A~I were 0.061~0.681 > 0.05, all of which conformed to the normal distribution. The speed distribution of different areas and vehicles is shown in Figure 6, and the statistical results are shown in Table 4.

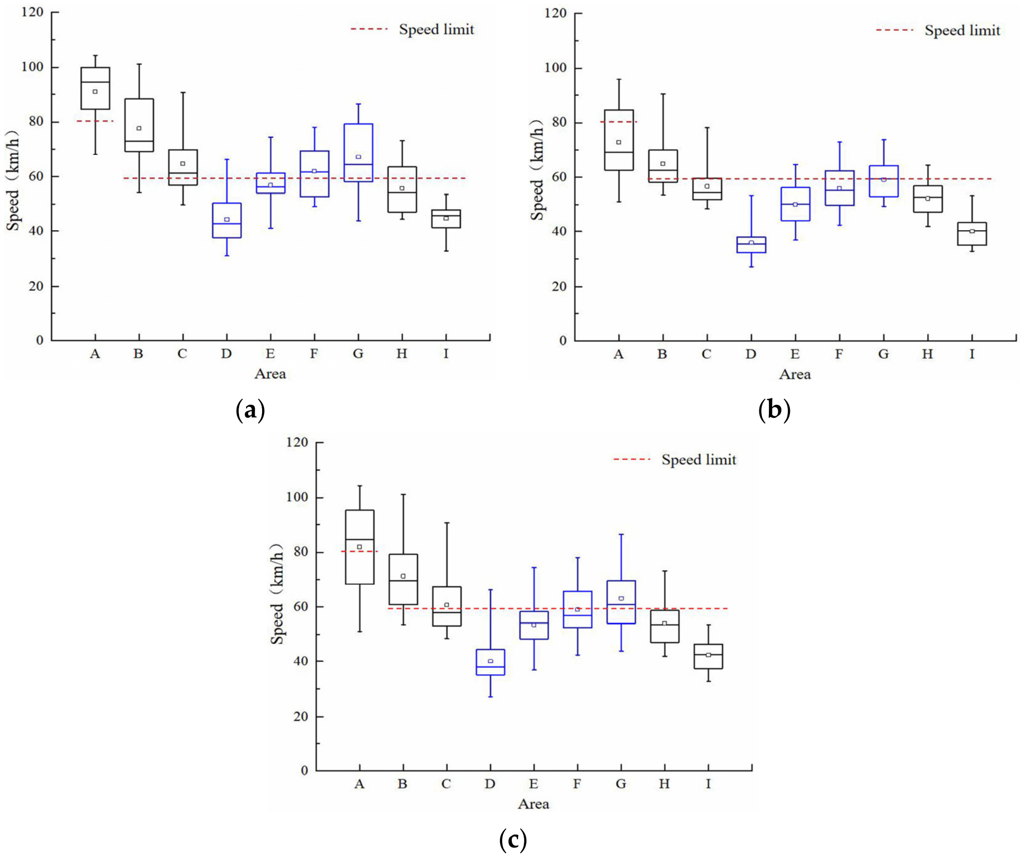

Figure 6. Distribution of vehicle speed for different areas and vehicles. (**a**) Passenger car; (**b**) truck; (**c**) all vehicles.

For freeways, the 85th-percentile speed is usually taken as the speed limit, which can be regarded as the running speed of vehicles. The U-test results indicated that there were significant differences in vehicle speeds under different areas and vehicles at a 95% confidence level. The speed and speed variability (standard deviation) of cars were larger in most areas compared to those of trucks. Different numbers of drivers adopted speeding behavior in all areas, except for the downstream median opening (I).

In the standard freeway section (A), the road condition was good, but the temporary speed limit was lower (80 km/h), leading to a higher vehicle running speed (98.23 km/h)—which was inconsistent with the speed limit—larger speed dispersion and a speed limit compliance rate of only 43.75%. After vehicles drove into the advance warning area (B), the speed limit was further reduced (60 km/h), while the road conditions did not change; therefore, the vehicle speed only reduced slightly, the vehicle running speed (87.39 km/h) was inconsistent with the speed limit and the speed limit compliance rate was further reduced. In the upstream transition area (C), the road conditions changed, the number of lanes decreased and the vehicle speed decreased significantly, but the speed limit compliance rate was still low (58.33%). After vehicles drove into the activity area (H) through the median opening, only one lane was available for driving, so there was no effective separation from the vehicles in the opposite direction; the cars with a higher speed were affected by the trucks with a lower speed, which led to a reduction in the vehicle speed and speed dispersion, and the vehicle running speed (61.88 km/h) remained the same as the speed limit. The downstream median opening (I) length was only 40 m, the road conditions changed and different vehicles interacted with each other in this area, so the vehicle speeds further converged.

Table 4. Results of vehicle speed statistics for different areas and vehicles.

Area	Maximum Speed (km/h)	Minimum Speed (km/h)	Running Speed/v_{85} (km/h)	Mean Speed/v (km/h)	SD	Speed Limit Compliance Rate
A (Car)	104.39	68.13	101.53	90.96	10.78	16.67%
A (Truck)	95.80	51.06	88.52	72.85	13.10	70.83%
A (All)	104.39	51.06	98.23	81.90	15.03	43.75%
B (Car)	101.15	54.19	91.13	77.59	12.58	8.33%
B (Truck)	90.40	53.59	72.19	64.96	9.37	33.33%
B (All)	101.15	53.59	87.39	71.27	12.76	20.83%
C (Car)	90.68	49.61	74.44	64.69	10.44	41.67%
C (Truck)	78.15	48.44	61.06	56.64	6.92	75.00%
C (All)	90.68	48.44	70.98	60.66	9.73	58.33%
D (Car)	66.18	31.02	51.43	44.33	8.46	95.83%
D (Truck)	53.38	27.19	39.14	35.89	5.48	100.00%
D (All)	66.18	27.19	50.07	40.11	8.28	97.92%
E (Car)	74.47	41.17	62.52	56.87	7.10	66.67%
E (Truck)	64.60	36.88	56.97	50.06	7.21	95.83%
E (All)	74.47	36.88	61.06	53.47	7.92	81.25%
F (Car)	78.11	49.07	73.99	61.96	9.03	41.67%
F (Truck)	72.94	42.44	65.64	55.88	8.15	70.83%
F (All)	78.11	42.44	70.72	58.92	9.12	56.25%
G (Car)	86.42	43.94	80.30	67.15	12.91	37.50%
G (Truck)	73.82	49.34	65.18	59.05	6.84	54.17%
G (All)	86.42	43.94	76.34	63.12	11.09	45.83%
H (Car)	73.28	44.40	64.08	55.74	8.77	66.67%
H (Truck)	64.36	42.04	57.16	52.19	5.67	95.83%
H (All)	73.28	42.04	61.88	53.97	7.59	81.25%
I (Car)	53.53	32.74	49.48	44.73	5.16	100.00%
I (Truck)	53.25	32.82	44.52	40.12	5.38	100.00%
I (All)	53.53	32.74	48.14	42.42	5.75	100.00%

4.1.2. Influence of Median Opening Length on Speed

Whether the vehicle running speeds of the work zones are consistent has a significant impact on the safety of traffic. When the speed difference between different areas is less than 10 km/h, the running speed coordination is good; when the speed difference is 10~20 km/h, the safety of traffic decreases with the increase in the speed difference; when the speed difference is greater than 20 km/h, the speed coordination is poor, leading to a high accident rate. Therefore, the speed difference should be kept within 10 km/h if the conditions allow [38]. As shown in Table 5, the speed difference between the running speeds of adjacent areas, the consistency of the running speed and speed limit and the analysis results of the influence of the opening length on speed under different opening lengths are reported.

The U-test results indicated that there were significant differences in the average vehicle speed and running speed under different opening lengths at a 95% confidence level; the opening length had a significant positive correlation with the running speed when the width of the median and the cross slope were constant, and the longer the opening length, the slower the speed increased.

Table 5. Speed differences and speed consistency for different median opening lengths in different areas.

Area	C	D	E *	F	G	H *
C	-	20.55 # (v) 20.91 # (v_{85})	7.19 # (v) 9.92 # (v_{85})	1.74 (v) 0.62 (v_{85})	−2.46 # (v) −5.36 # (v_{85})	-
D	−20.55 # (v) −20.91 # (v_{85})	-	−13.36 # (v) −10.99 # (v_{85})	−18.81 # (v) −20.65 # (v_{85})	−23.01 # (v) −26.27 # (v_{85})	−13.86 # (v) −11.81 # (v_{85})
E *	−7.19 # (v) −9.92 # (v_{85})	13.36 # (v) 10.99 # (v_{85})	-	−5.45 # (v) −9.66 # (v_{85})	−9.65 # (v) −15.28 # (v_{85})	−0.50 (v) −0.82 (v_{85})
F	−1.74 (v) −0.62 (v_{85})	18.81 # (v) 20.65 # (v_{85})	5.45 # (v) 9.66 # (v_{85})	-	−4.20 # (v) −5.62 # (v_{85})	4.95 # (v) 8.84 # (v_{85})
G	2.46 # (v) 5.36 # (v_{85})	23.01 # (v) 26.27 # (v_{85})	9.65 # (v) 15.28 # (v_{85})	4.20 # (v) 5.62 # (v_{85})	-	9.15 # (v) 14.46 # (v_{85})
H *	-	13.86 # (v) 11.81 # (v_{85})	0.50 (v) 0.82 (v_{85})	−4.95 # (v) −8.84 # (v_{85})	−9.15 # (v) −14.46 # (v_{85})	-

* means that the running speed is consistent with the speed limit at the 95% confidence level based on a U-test.
# means that there is a significant difference at the 95% confidence level based on a U-test.

When the opening length was 40 m, the vehicle running speed was 50.07 km/h, which is inconsistent with the theoretical value calculated by the model (40 km/h) and the speed limit (60 km/h). Its speed difference with the upstream transition area was greater than 20 km/h, and that with the activity area was greater than 10 km/h. The speed dispersion was small, and the speed limit compliance rate was high. The speed coordination was poor, so there were safety hazards. Affected by the speed limit and road conditions, the vehicle running speed was higher than the design speed and lower than the speed limit, indicating that the opening length was too small under the experimental road conditions and speed limit.

When the opening length was 70 m, the speed dispersion was small, and the speed limit compliance rate was high. The vehicle running speed was 61.06 km/h, which is consistent with the theoretical value calculated by the model (60 km/h) and the speed limit (60 km/h). Its speed difference with the upstream transition area was less than 10 km/h, while its speed difference with the activity area was not significant, so the speed coordination was good. Therefore, the opening length of 70 m was reasonable under the experimental road conditions and speed limit.

When the opening lengths were 100 m and 130 m, the vehicle running speeds were 70.72 km/h and 76.34 km/h, respectively, which are inconsistent with the theoretical values calculated by the model (80 km/h) and the speed limit (80 km/h). The speed difference with the upstream transition area and activity area was less than 10 km/h, but the speed dispersion was large, and the speed limit compliance rate was low, so there were safety hazards. Affected by the speed limit and road conditions, the vehicle running speed was lower than the design speed and higher than the speed limit, and the running speed was high, indicating that the opening length was too large under the experimental road conditions and speed limit.

4.2. Driving Workload

4.2.1. Driving Workload Distribution in the Work Zone

The heart rate of the participants in different areas of the work zone was 64~108 bpm, with an average of 87.58~89.67 bpm. The U-test results indicated that there were no significant differences in the heart rate of the participants in different areas at a 95% confidence level, which was proved to be normal.

Road alignment, traffic operation state, overtaking, lane changing and other factors will affect drivers’ driving workload. In order to analyze the relationship between the work zone layout and driving workload, the participants’ physiological data under non-work-zone road conditions were excluded, and the frequency distribution of the participants’ driving workload in different areas of the work zone was calculated, as shown in Figure 7. Since the distribution of the driving workload showed an obvious right skewness, the log-normal distribution of the driving workload in different sites was tested using the K–S test. The results were 0.266~0.958 > 0.05, with R^2 = 0.923~0.996, which meant that they all conformed to the log-normal distribution. The distribution of the driving workload for different areas and vehicles is shown in Figure 8, the statistical results are shown in Table 6 and the driving workload in each area of the experimental road is shown in Figure 9 (the median opening length of 70 m was taken as an example).

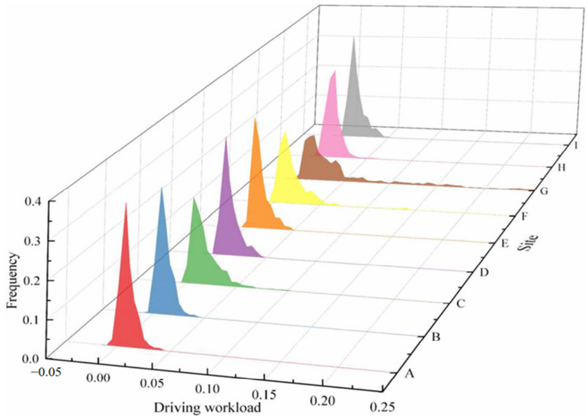

Figure 7. Frequency distribution of driving workload in different areas.

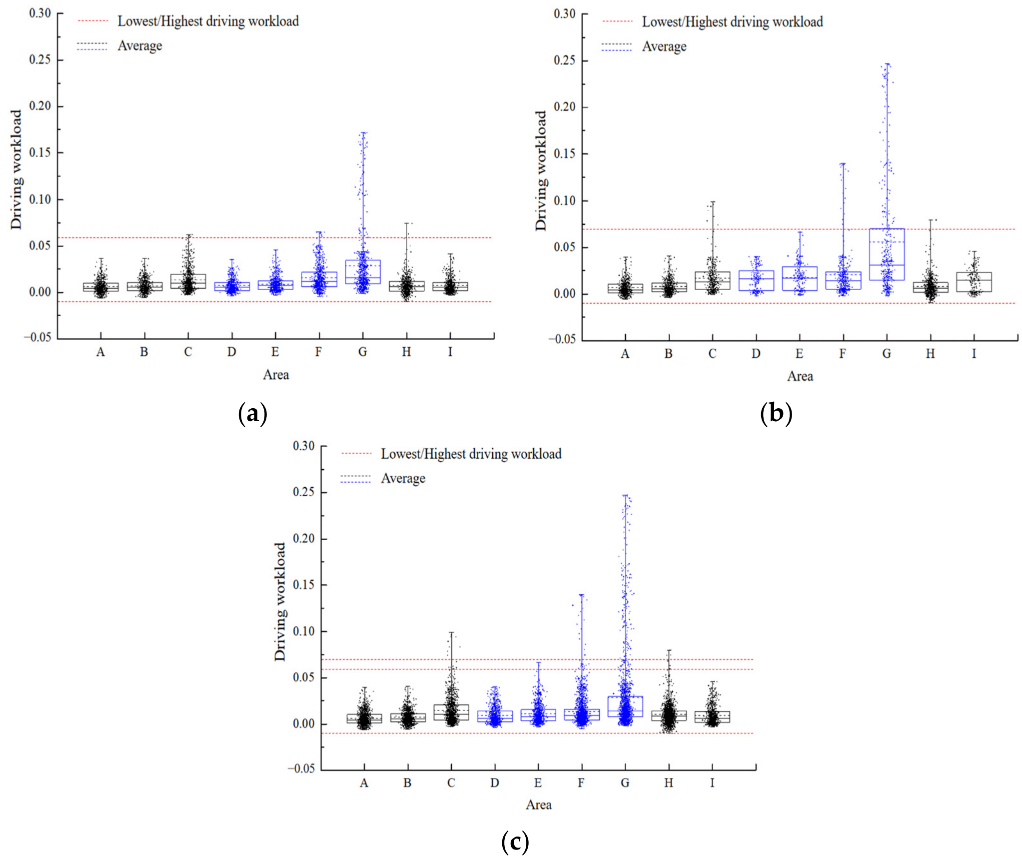

Figure 8. Distribution of driving workload for different areas and vehicles. (**a**) Passenger car; (**b**) truck; (**c**) all vehicles.

Table 6. Results of driving workload statistics for different areas and vehicles.

Area	Maximum	Minimum	Mean	SD	Higher Risk Ratio	High Risk Ratio
A (Car)	0.03663	−0.00613	0.00600	0.00716	13.73%	0.00%
A (Truck)	0.03950	−0.00563	0.00642	0.00754	12.46%	0.00%
A (All)	0.03950	−0.00613	0.00622	0.00735	13.11%	0.00%
B (Car)	0.03628	−0.00548	0.00663	0.00711	11.89%	0.00%
B (Truck)	0.04066	−0.00393	0.00756	0.00760	8.12%	0.00%
B * (All)	0.04066	−0.00548	0.00709	0.00736	10.04%	0.00%
C (Car)	0.06245	−0.00259	0.01336	0.01294	14.29%	0.58%
C (Truck)	0.09918	−0.00038	0.01704	0.01658	7.73%	2.40%
C * (All)	0.09918	−0.00259	0.01466	0.01444	11.97%	1.23%
D (Car)	0.03565	−0.00351	0.00695	0.00677	5.05%	0.00%
D (Truck)	0.04015	−0.00183	0.01614	0.01222	8.25%	0.00%
D * (All)	0.04015	−0.00351	0.00921	0.00933	5.84%	0.00%
E (Car)	0.04565	−0.00288	0.00869	0.00770	3.87%	0.00%
E (Truck)	0.06668	−0.00138	0.01803	0.01457	15.00%	0.00%
E * (All)	0.06668	−0.00288	0.01114	0.01078	6.79%	0.00%
F (Car)	0.06538	−0.00463	0.01553	0.01400	17.86%	0.00%
F (Truck)	0.13975	−0.00150	0.02083	0.02641	10.97%	5.24%
F * (All)	0.13975	−0.00463	0.01741	0.01951	15.41%	1.86%
G (Car)	0.17175	−0.00138	0.02889	0.03545	19.44%	10.99%
G (Truck)	0.24712	−0.00188	0.05611	0.06532	21.46%	25.00%
G * (All)	0.24712	−0.00188	0.03833	0.04968	20.14%	15.85%
H (Car)	0.07432	−0.00971	0.00745	0.00943	16.03%	0.17%
H (Truck)	0.07961	−0.00915	0.00793	0.00989	14.48%	0.17%
H (All)	0.07961	−0.00971	0.00769	0.00966	15.78%	0.17%
I (Car)	0.04151	−0.00331	0.00695	0.00743	7.95%	0.00%
I (Truck)	0.04615	0.00280	0.01475	0.01241	9.69%	0.00%
I * (All)	0.04615	−0.00331	0.00889	0.00955	8.39%	0.00%

* means that there was a significant difference in driving workload between cars and trucks at the 95% confidence level based on a U-test.

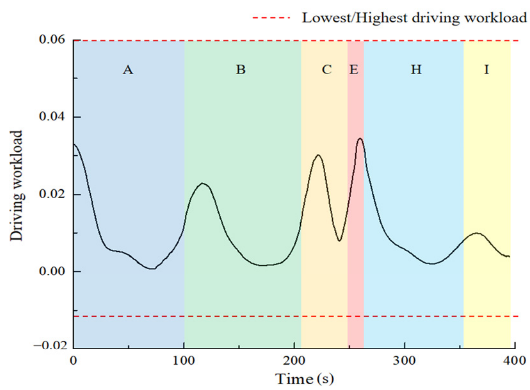

Figure 9. Change trend of driving workload in different areas of the work zone.

The U-test results indicated that there were significant differences in driving workload in different areas (A, B, C, H, I) at a 95% confidence level. A significant difference was found in the driving workload of different vehicles in areas B, C and I, where the road traffic conditions changed significantly; the mean value and volatility were both higher for trucks than for cars.

In the standard freeway section (A), the road alignment and traffic conditions were good, so the driving task was relatively simple, and the driving workload was not significantly different between different vehicles, being low overall; at the beginning of the experiment, participants maintained a better mental state for driving, but after driving for a period of time, the driving workload decreased and remained stable, and some participants (12.5%) had slight driving fatigue at the end of the standard freeway section. Therefore, during the construction and operation of the freeway, the straight alignment should not be too monotonous; moreover, the road landscape and other means can be used in some areas to stimulate the drivers to avoid driving fatigue. At about 200 m before the advance warning area (B), the participants could clearly recognize the work zone and speed limit signs, which stimulated them, so the driving workload started to rise significantly at first, and then presented a similar trend to that of the standard freeway section; however, only a small number of participants (6.25%) had slight driving fatigue, and truck drivers had greater fluctuations in their driving workload than car drivers. At about 200 m before the upstream transition area (C), participants noticed the change in road conditions and signs and needed to adopt driving behaviors such as changing lanes, so their driving workload increased sharply, reached the highest value in the middle of the upstream transition area and began to decline in the buffer area; some participants (12.5%), especially truck drivers, had strong driving tension, affecting driving safety. Under the influence of the median opening, the driving workload at the starting point of the activity area (H) was high. However, the activity area had only one lane, so the vehicle running speed was slow, the driving task was simpler than that of the standard freeway and the drivers were in a state of following without overtaking, meaning their driving workload decreased more rapidly than when driving on the standard freeway. A total of 20.83% of the participants at the end of the activity area had driving fatigue, and there was no significant difference in the workload between participants of different vehicles. Therefore, the length of the activity area should be controlled so that participants can pass as soon as possible to prevent driving fatigue from affecting the safety of driving in the work zones. Subsequently, the areas with changes in alignment conditions, such as the downstream median opening (I) and the downstream transition area, slightly stimulated the participants, meaning their driving workload increased to the normal state before driving out of the work zone.

4.2.2. Influence of the Median Opening Length on the Driving Workload

When the participants drove the vehicle to the middle of the buffer area, which was about 100 m from the median opening, they noticed the change in road alignment conditions in front of the median opening, and their driving workload was affected and showed a rising trend, reaching the maximum value until driving to the middle and rear sections of the median opening, and then declining with the influence of the activity area. Statistically, out of a total of 192 tests in this experiment, the driving workload in about 93.75% of the tests was in line with the above trend at the median opening.

The U-test results indicated that there were significant differences in driving workload under different median opening lengths and vehicles at a 95% confidence level; the mean value and volatility of driving workload were higher for trucks than for cars. The opening length had a significant positive correlation with the driving workload when the width of the median and the cross slope were constant, and the longer the opening length, the faster the driving workload increased.

The track of the vehicles crossing through the opening is S-shaped, forming two circular curves with the same radius connected in reverse. The participants need to complete multiple driving tasks, such as road information perception, judgment, deceleration, left turn and right turn in a short time, which can lead to tension, worry and panic, resulting in an increase in the driving workload. When the median opening length increases, the road alignment conditions become better, and the vehicle speed increases, but the turning radius is small when the vehicle crosses through the opening; the fast running speed of the vehicle will cause the sideway force coefficient between the vehicle and the road to decrease significantly while the centrifugal force increases significantly. Moreover, the direction of the centrifugal force will change in a short time due to the opposite turning direction; this phenomenon will also be exacerbated due to the existence of a crown in the opposite direction on the road. In order to maintain a uniform driving state, participants need to exert considerable mental and physical effort beyond their experience or ability; therefore, their driving workload increases significantly, leading to them easily omit important information and make judgment errors, with further driving safety risks. At this point, some participants will reduce their running speed to decrease the amount of information input per unit time to match their driving ability.

The average vehicle speed, vehicle running speed and average driving workload under different median opening lengths were fitted using a cubic function, which can sufficiently explain the changing trend of vehicle speed and driving workload under different opening lengths compared with other function forms. The correlation model was established, as shown in Table 7 and Figure 10, with $R^2 > 0.9999$, indicating a good fitting effect. When the opening length increased, the vehicle running speed, speed standard deviation and driving workload increased. However, the longer the opening length, the slower the running speed growth and the more rapidly the driving workload grows, which will greatly aggravate the psychological impact on the participants, thereby affecting their driving behavior, and leading to an increase in road safety risks.

Table 7. Fitting results of different opening lengths with vehicle speed and driving workload in the work zone.

Independent Variable	Dependent Variable	Fitting Formula	Domain	Range
Opening length	Running speed	$y = -1.673*10^{-5\times 3} + 0.003 \times {}^{2} + 0.217x + 38.032$	[40, 130]	[50.07, 76.34]
	Mean speed	$y = 4.111*10^{-8}x^5 - 0.013x^2 + 1.496x - 1.519$		[40.11, 63.12]
	Driving workload	$y = 6.364*10^{-8}x^3 - 1.095*10^{-5}x^2 + 0.001x - 0.004$		[0.00921, 0.03833]

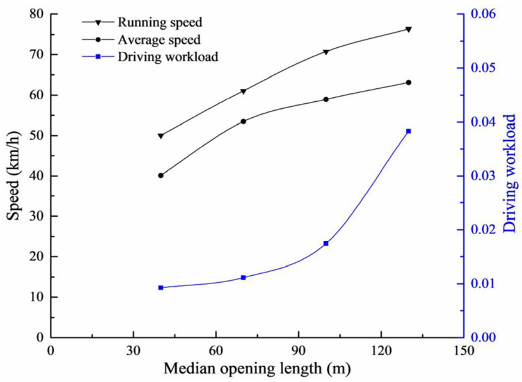

Figure 10. Fitting curve of different opening lengths with vehicle speed and driving workload in the work zone.

When the opening length was 40 m, the average driving workload was only 0.00921, which is consistent with the downstream median opening. The proportion of higher risk was low, due to the slight driving fatigue; however, a lower driving workload can likely cause a greater driving fatigue in the activity area, which indicates that this length selection was conservative under the experimental road and traffic conditions.

When the opening length was 70 m, the average driving workload increased by 20.95% compared with that at 40 m. Truck drivers began to appear slightly nervous, but more than 85% of the participants were still in a normal driving condition. The driving safety risk was low, which indicates that the opening length of 70 m was more reasonable under the experimental road and traffic conditions.

When the opening length was 100 m, the average driving workload significant increased by 56.28% compared with that at 70 m. Some truck drivers experienced serious tension and anxiety, and the proportion of higher risk was more than 15.41%, which indicates that this length was more radical under the experimental road and traffic conditions, making it difficult to ensure driving safety.

When the opening length was 130 m, the average driving workload was 4.16 times, 3.44 times and 2.20 times that at 40 m, 70 m and 100 m, respectively. More participants were in a high-tension state in the middle of the median opening. The proportion of high risk exceeded 15.85%, and the proportion of risk exceeded 38.99%, indicating that this opening length was too large under the experimental road and traffic conditions, resulting in higher driving safety risks at the median opening.

5. Discussion

This paper aimed to investigate the influence of different median opening lengths on the vehicle speed and driving workload in crossover work zones through a naturalistic driving experiment. This study illustrated that better road traffic conditions in the work zone will lead to an increase in vehicle speed. Since a lower speed limit is often used in work zones, some drivers think that the speed limit is too low and adopt speeding behaviors, causing other following drivers to accelerate, resulting in a low speed limit compliance rate in some areas of the work zone. In addition, drivers with different driving styles will form a heterogeneous speed preference, resulting in increased speed variability. In different areas of work zones, due to the differences in road and traffic conditions, the driving workload has a linear positive correlation with vehicle speed, but has no fixed relationship with acceleration. A lower median opening length will lead to a sharp deceleration of vehicles and increase the speed difference between adjacent areas. When the opening length is large, aggressive drivers will cross at a high speed, while conservative drivers will feel nervous due to the high driving workload and tend to slow down, resulting in an increased standard deviation of acceleration and speed; when the median opening length is moderate, it corresponds to the lowest standard deviation of acceleration and speed, and the lowest collision probability [29]. Higher vehicle running speeds and speed variability can increase the risk of accidents such as rear-end collisions in work zones [12]; a good speed limit strategy will reduce the risk of accidents [39], and variable speed limits in work zones are more effective than fixed speed limits [40,41]. Therefore, during the layout and control processes of work zones, the mutual coordination of the areas such as the median opening should be considered, and an appropriate speed limit strategy should be adopted to improve the speed limit compliance rate, reduce the speed variability and avoid the impacts of bad driving behaviors on the road safety in work zones.

Factors such as the median width, lane width, vehicle operating speed, sideway force coefficient and cross slope determine the median opening length, and all these road traffic conditions will have different influences on the driving workload. Relevant research shows that a large cross slope, high vehicle running speed and small lane width and turning radius will cause driver tension [35], which should be taken into account when arranging the median opening.

In practical application, operation efficiency and safety factors should be considered when determining the opening length; safety is mainly related to vehicle speed characteristics, while operational efficiency is mainly related to capacity. Instead of using the traditional method of calculating the maximum flow in uncongested conditions, Wayne et al. estimated the work zone capacity using the mean queue–discharge flow rate from the resulting bottleneck at the end of a bottleneck area [42]. An increasing number of studies have shown that it is more reasonable to use a queuing flow to calculate the work zone capacity [43]. The capacity at the median opening can be obtained by combining experimental observation with simulation. It has been shown that the capacity has a positive correlation with the opening length, and the capacity increases quickly at low speeds while increasing slowly at high speeds [44,45]. When the opening length is 40, 70, 100 and 130 m, the capacity is 1280, 1380, 1460 and 1520 pcu/h, respectively; when the opening length increases to 200 m, the capacity becomes 1610 pcu/h. Herein, the capacity tends to be constant, and the capacity at the opening is consistent with the upstream transitional area and buffer area of the work zone. The opening length is an important influencing factor for the capacity of work zones. When determining the median opening length, the running speed and traffic capacity of the work zone should be taken into consideration; especially in areas with a large flow, the coordination of the traffic capacity should be noted to avoid the "double bottleneck" phenomenon.

Due to the limitations of the experimental conditions, this experiment only studied the influence of the median opening length on the vehicle speed and the driving workload in a one-lane scenario. With the development of reconstruction and expansion projects, 2~3-lane median openings are increasingly applied in practical projects, and some scholars have studied these conditions. Jing et al. used a driving simulator to analyze the relationship of vehicle speed, acceleration, maximum steering wheel speed and lane-changing trajectory with safety for different median opening lengths in the case of two lanes without separation, concluding that the opening length should be 90 m [33]; however, it is difficult for driving simulations to fully simulate the real situation, and they lack consideration of the impacts of different traffic conditions, road conditions, fatigued driving, opposing traffic and other factors on the drivers. Shao et al. considered a two-lane opening length in the case of being unable to change lanes, in terms of traffic operation status, road capacity and time to collision; the results indicated that each index was relatively good with an opening width of 100 m [29]. At present, relevant studies have not reported actual measured data for the traffic operation status of 2~3-lane median openings, and have not carried out the relevant naturalistic driving experiments. Since the increase in the turning radius and vehicle running speed, separation types, vehicle lane changing, interaction between vehicles, etc., under multi-lane traffic conditions will all have an impact on the driving workload, more factors should be considered compared to one-lane scenarios when laying out the work zone. This can be focused on in future research.

The driver's driving workload will change instantly with the external conditions, the driver's psychology, the vehicle operation, etc. The environment of standard freeway sections and the activity area are monotonous, with little interaction between vehicles and simple driving tasks, making drivers prone to driving fatigue. Relevant research has illustrated that, if the road traffic conditions do not change, drivers will experience driving fatigue after driving for 146~205 s (2.44~5.7 km) at a running speed of 60~100 km/h, which sharply increases traffic safety risks. Therefore, stimulation should be provided timely to enable the driver to resume a normal driving condition. Attention should be paid to the work zone layout to avoid excessive lengths of the activity area. In addition to the median opening, the average and standard deviation of the driving workload in the upstream transition area are both large, so drivers need to slow down, change lanes and adopt other driving behaviors in the upstream transition area, which is also a blackspot. However, the traffic operation state, driver's psychological characteristics, setting methods, etc., in other types of transition areas are not clear, and the relevant experiments are scarce; therefore, further pertinent studies are needed.

6. Conclusions

Based on a theoretical model and a naturalistic driving experiment, this paper studied the median opening length, traffic operation characteristics and driving workload in freeway crossover work zones. The following conclusions were drawn:

1. A theoretical calculation model of the median opening length was established according to the demands of vehicles changing lanes when crossing through the median opening of the freeway. Based on the calculation model, the influencing factors of the median opening length were analyzed, and the calculation values of the median opening length under different speed limits, median widths and cross slopes were proposed.

2. The characteristics of the vehicle speed and driving workload in different sites of the work zone were obtained based on a naturalistic driving experiment. It was found that the median opening length was positively correlated with the vehicle speed and driving workload. Furthermore, different median opening lengths had different impacts on the operation status of the drivers and traffic: a shorter opening length reduced the vehicle running speed and led to an uncoordinated running speed in the work zone; a longer

opening length caused driver tension and led to the vehicle running speed and speed variability being too high.

3. The theoretical calculation results of the median opening length of the freeway are consistent with the results of the naturalistic driving experiment. The theoretical calculation model is reliable and can be used in the layout of actual work zones. The median opening length is an important influencing factor for the running speed, driving workload and road capacity. In practical application, it should be determined by considering the combined effects of the running speed of different vehicles, the speed limit, the capacity of the work zone and other factors. In this experiment scenario, the opening length of 70 m was reasonable.

This paper only studied the median opening length of a freeway work zone when the median opening was one lane. Further research and verification are needed to assess the influences of the median opening width, lane width, cross slope, etc., on the driving workload and opening length under the condition of multiple lanes.

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References

1. Thapa, R.; Codjoe, J.; Osafo, A. Survey of work zone practices and validation of highway capacity manual work zone capacity model. *Transp. Res. Rec.* **2021**, *2675*, 1083–1091. [CrossRef]
2. Weng, J.; Qiang, M. Estimating capacity and traffic delay in work zones: An overview. *Transp. Res. C-Emer.* **2013**, *35*, 34–45. [CrossRef]
3. Khattak, A.J.; Khattak, A.J.; Council, F.M. Effects of work zone presence on injury and non-injury crashes. *Accident Anal. Prev.* **2002**, *34*, 19–29. [CrossRef]
4. Cheng, Y.; Parker, S.T.; Ran, B.; Noyce, D.A. Enhanced analysis of work zone safety through integration of statewide crash and lane closure system data. *Transp. Res. Rec.* **2012**, *2291*, 17–25. [CrossRef]
5. Work Zone Facts and Statistics Retrieved. Available online: https://ops.fhwa.dot.gov/wz/resources/factsstats.htm (accessed on 20 October 2022).
6. Chen, E.; Tarko, A.P. Modeling safety of highway work zones with random parameters and random effects models. *Anal. Methods Accid. R.* **2014**, *1*, 86–95. [CrossRef]
7. Zhang, K.; Hassan, M.; Yahaya, M.; Yang, S. Analysis of work-zone crashes using the ordered probit model with factor analysis in Egypt. *J. Adv. Transp.* **2018**, *2018*, 1784. [CrossRef]
8. Kummetha, V.C.; Kondyli, A.; Chrysikou, E.G.; Schrock, S.D. Safety analysis of work zone complexity with respect to driver characteristics—A simulator study employing performance and gaze measures. *Accident Anal. Prev.* **2020**, *142*, 105566. [CrossRef]
9. Nasrollahzadeh, A.A.; Sof, A.R.; Ravani, B. Identifying factors associated with roadside work zone collisions using machine learning techniques. *Accident Anal. Prev.* **2021**, *158*, 106203. [CrossRef]
10. Osman, M.; Paleti, R.; Mishra, S. Analysis of passenger-car crash injury severity in different work zone configurations. *Accident Anal. Prev.* **2018**, *111*, 161–172. [CrossRef]
11. Torre, F.L.; Domenichini, L.; Nocentini, A. Effects of stationary work zones on motorway crashes. *Saf. Sci.* **2017**, *92*, 148–159. [CrossRef]
12. Meng, Q.; Weng, J. Evaluation of rear-end crash risk at work zone using work zone traffic data. *Accident Anal. Prev.* **2010**, *43*, 1291–1300. [CrossRef]

13. Hou, G.; Chen, S. An improved cellular automaton model for work zone traffic simulation considering realistic driving behavior. *J. Phys. Soc. Jpn.* **2019**, *88*, 084001. [CrossRef]
14. Lu, C.; Dong, J.; Sharma, A.; Huang, T.; Knickerbocker, S. Predicting freeway work zone capacity distribution based on logistic speed-density models. *J. Adv. Transp.* **2018**, *1442*, 9614501. [CrossRef]
15. Migletz, J.; Graham, J.L.; Harwood, D.W. *Procedure for Determining Work Zone Speed Limits, National Cooperative Highway Research Program, Project 3-41*; Transportation Research Board: Washington, DC, USA, 1993; pp. 214–218.
16. Salem, O.M.; Genaidy, A.M.; Wei, H.; Deshpande, N. Spatial distribution and characteristics of accident crashes at work zones of interstate freeways in Ohio. In Proceedings of the IEEE Intelligent Transportation Systems Conference, Toronto, Canada, 17–20 September 2006; pp. 1642–1647.
17. Fhwa, U.S. Department of Transportation. In *Manual on Uniform Traffic Control Devices, 2009*; FHWA: Washington, DC, USA, 2009; pp. 547–559.
18. Finley, M.D.; Jenkins, J.; McAvoy, D.S. Motorists' speed response to non-variable and variable work zone speed limits and other work zone conditions. *Transp. Res. Rec.* **2015**, *2485*, 70–77. [CrossRef]
19. Wang, Z.; He, W.; Zhang, X.; Wang, Y.; Wu, B.; Wang, Y. Lane-based vehicular speed characteristics analysis for freeway work zones using aerial videos. *Can. J. Civil Eng.* **2021**, *48*, 274–283. [CrossRef]
20. Porter, R.J.; Mahoney, K.M.; Mason, J.M. Seemingly unrelated regression model of car speeds and speed deviations in freeway work zones. *Transp. Res. Rec.* **2018**, *2023*, 44–51. [CrossRef]
21. Ishak, S.; Qi, Y.; Rayaprolu, P. Safety evaluation of joint and conventional lane merge configurations for freeway work zones. *Traffic Inj. Prev.* **2012**, *13*, 199–208. [CrossRef]
22. Zhang, C.; Wang, B.; Yang, S.; Zhang, M.; Gong, Q.; Zhang, H. The driving risk analysis and evaluation in rightward zone of expressway reconstruction and extension engineering. *J. Adv. Transp.* **2020**, *1*, 8943463. [CrossRef]
23. Li, Y.X.; Ding, Q.; Kong, Y.Y. Modeling and analysis of the impact of urban and rural road reconstruction construction on vehicle capacity. *Adv. Transp. Stud.* **2019**, *1*, 97–110. [CrossRef]
24. Pan, B.; Wu, M.; Wang, Z. Development of road surface inspection system based on computer vision with improved neural network. *Highway* **2012**, *9*, 214–217.
25. Ge, T. Study on Traffic Organization of Expressway Expansion Engineering during Construction. Master's Thesis, South China University of Technology, Guangzhou, China, 2012.
26. Liu, X.F. Study on the Key Technologies of Traffic Organization in Freeway Reconstruction and Project Implementation. Master's Thesis, Chang'an University, Xi'an, China, 2017.
27. Wang, W. Study on Key Technologies in Expressway Maintenance Work-Zone Traffic Organization Optimization. Master's Thesis, Chang'an University, Xi'an, China, 2014.
28. Wei, Y.; Zhao, L.; Yuan, C.; Xu, M. Traffic organization simulation of expressway rebuilding project. *J. Chang. Univ. Nat. Sci. Ed.* **2012**, *32*, 38–43.
29. Shao, C.; Ma, S.; Luo, K.; Qin, Y. Study on the length of median opening in expressway reconstruction and extension work zones. In Proceedings of the CICTP 2020: Advanced Transportation Technologies and Development-Enhancing Connections, Xi'an, China, 14–16 August 2020. [CrossRef]
30. Yang, Y.; Chen, J.; Easa, S.M.; Zheng, X.; Lin, W.; Peng, Y. Driving simulator study of the comparative effectiveness of monolingual and bilingual guide signs on Chinese highways. *Transp. Res. F-Traf.* **2019**, *68*, 67–78. [CrossRef]
31. Domenichini, L.; Torre, F.L.; Branzi, V.; Nocentini, A. Speed behaviour in work zone crossovers. A driving simulator study. *Accident Anal. Prev.* **2017**, *98*, 10–24. [CrossRef]
32. Bella, F. Validation of a driving simulator for work zone design. *Transp. Res. Rec.* **2005**, *1937*, 136–144. [CrossRef]
33. Jing, D.; Song, C.; Guo, Z.; Li, R. Influence of the median opening length on driving behaviors in the crossover work zone-A driving simulation study. *Transp. Res. F-Traf.* **2021**, *82*, 333–347. [CrossRef]
34. Pawar, N.M.; Velaga, N.R.; Sharmila, R.B. Exploring behavioral validity of driving simulator under time pressure driving conditions of professional drivers. *Transp. Res. F-Traf.* **2022**, *89*, 67–78. [CrossRef]
35. Hu, J.; Gao, X.; Wang, R.; Sun, S. Research on comfort and safety threshold of pavement roughness. *Transp. Res. Rec.* **2017**, *2641*, 149–155. [CrossRef]
36. American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, 7th ed.; AASHTO: Washington, DC, USA, 2018.
37. *JTG H30-2015*; Safety Work Rules for Highway Maintenance. China Communications Press: Beijing, China, 2015.
38. Lee, Y.M.; Chong, S.Y.; Goonting, K.; Sheppard, E. The effect of speed limit credibility on drivers' speed choice. *Transp. Res. F-Traf.* **2017**, *45*, 43–53. [CrossRef]
39. Weng, J.; Qiang, M. Analysis of driver casualty risk for different work zone types. *Accident Anal. Prev.* **2011**, *43*, 1811–1817. [CrossRef]
40. Nes, N.; Brandenburg, S.; Twisk, D. Improving homogeneity by dynamic speed limit systems. *Accident Anal. Prev.* **2010**, *42*, 944–952. [CrossRef]
41. Du, S.; Razavi, S. Variable speed limit for freeway work zone with capacity drop using discrete-time sliding mode control. *J. Comput. Civil Eng.* **2019**, *33*, 04019001.1–04019001.15. [CrossRef]

42. Sarasua, W.A.; Davis, W.J.; Clarke, D.B.; Kottapally, J.; Mulukutla, P. Evaluation of interstate highway capacity for short-term work zone lane closures. *Transp. Res. Rec.* **2004**, *1877*, 85–94. [CrossRef]
43. Cassidy, M.J.; Bertini, R.L. Some traffic features at freeway bottleneck. *Transp. Res. F-Meth.* **1999**, *33*, 25–42. [CrossRef]
44. Al-Kaisy, A.; Hall, F. Guidelines for estimating capacity at freeway reconstruction zones. *J. Transp. Eng.* **2003**, *129*, 572–577. [CrossRef]
45. Kianfar, J.; Abdoli, S. Deterministic and stochastic capacity in work zones: Findings from a long-term work zone. *J. Transp. Eng. A-Syst.* **2021**, *147*, 04020141. [CrossRef]