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# Crosswalk Safety Warning System for Pedestrians to Cross the Street Intelligently

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**Abstract:** During signal transitions at road sections and intersections, pedestrians and vehicles often clash and cause traffic accidents due to unclear right-of-way. To solve this problem, a vehicle safety braking distance model considering human–vehicle characteristics is established and applied to the designed crosswalk safety warning system to enable pedestrians to cross the street intelligently. The model developed to consider human–vehicle characteristics improves the parking sight distance and pedestrian crossing safety psychological distance models by adding consideration of the effect of vehicle size and type on pedestrian psychology. The established model considering human–vehicle characteristics was improved for the stopping sight distance and pedestrian crossing safety psychological distance models. The effects of vehicle size and type on pedestrian psychology were taken into account. The designed warning system can be divided into a detection module, control module, warning module, and wireless communication module. The system detects the position and speed of pedestrians and vehicles and discriminates the conflict situation, executing the corresponding warning plan for three different types of situations. The system provides warning to pedestrians and vehicles through the different color displays of the intelligent crosswalk. The results show that the proposed model, which synergistically couples vehicle speed, driver reaction time, road characteristic correlation coefficients, and the psychological impact of vehicle size and type on pedestrians, is safe and effective. The designed system solves the problem of pedestrian crossing safety from both theoretical and technical aspects.

**Keywords:** traffic safety; intelligent transportation; driving safety; pedestrian crossing; intelligent zebra crossing; safe braking distance

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## 1. Introduction

Urban road intersections are the intersection of traffic and pedestrian flow, and they are accident-prone traffic areas. According to statistics, more than 60% of traffic accidents occur at urban road intersections, and 90% occur during signal transitions [1]. A study [2] found that if pedestrians start crossing within the last 5 s of the green light, almost no one can complete the crossing before the red light comes on. As a result, when pedestrians cross the street during the signal transition, pedestrians do not usually entirely pass in time. At the same time, vehicles have been granted the right-of-way and start to start, creating conflicts between pedestrians crossing and vehicles and, thus, causing traffic accidents. Among traffic participants, pedestrians are the most numerous, widespread, and vulnerable group in the transportation system [3]. The number of pedestrian casualties in traffic accidents exceeds 20%, and the number of casualties during pedestrian crossing exceeds 50% [4]. This shows that pedestrian crossing safety on the roadway and during signal transitions at intersections needs to be addressed.

For the problem of pedestrian–vehicle conflict during the pedestrian crossing, various safety systems have been designed to reduce traffic accidents.

Sugimoto et al. [5] proposed a prototype pedestrian-to-vehicle communication system using wireless network to improve pedestrian safety. However, the model is mainly oriented towards the driver rather than from the pedestrian perspective. Keller et al. [6] proposed a novel active pedestrian safety system that combines sensing, situation analysis, and decision making to control the vehicle before an accident occurs. The advantage of this is that it can decide in a split second whether to perform braking or evasion, and has a certain reliability when the vehicle speed is high. Ogawa et al. [7] proposed a pedestrian recognition method using on-board Li-DAR that can provide techniques and methods for pedestrian safety systems. By using high-resolution LiDAR to improve environmental robustness, the system can better adapt to the congestion in urban traffic. In order to incorporate unpredictable human behavior into the evaluation of active and passive pedestrian safety systems, Doric et al. [8] introduced a virtual reality (VR) based pedestrian simulation system, but this currently only receives visual feedback, thus, limiting its applicability. Jin et al. [9] designed a crosswalk safety support system containing Bluetooth and solar modules for illuminated signs, LED crosswalk lights, text displays, and voice output devices. The system is able to convey safety messages visually and audibly to both vehicle drivers and pedestrians when there are speeding vehicles approaching pedestrians crossing the street. With the system installed at the intersection, it can reduce the speed of vehicles, increase the frequency of pedestrians looking around, and improve the safety awareness of drivers and pedestrians. Gaspar et al. [10] described development work to implement an ITS-G5 prototype designed to improve pedestrian and driver safety near crosswalks by sending ITS-G5 dispersive environment notification messages (DENM) to vehicles, but the approach only enables early warning for drivers and requires a demanding testing environment. Patella et al. [11] defined a new method, capable of improving safety performance based on realistic speed measurements, for assessing how illuminated pedestrian crossings affect the behavior of drivers approaching crosswalks in night-time conditions. Study results show a significant reduction in vehicle speeds on pedestrian crossings under illuminated conditions. Islam et al. [12] proposed to develop a vision-based approach to generate personal safety messages (PSM) in real-time using video streams from roadside traffic cameras that can be used by personnel for connected vehicle pedestrian safety applications. This method not only provides more accurate estimates of pedestrian location and speed, but also allows for the latency required for pedestrian safety applications in connected environments. Sowmiya et al. [13] designed an intelligent carriage, including a carriage module, sensor module, traffic light module, and power module to reduce the traffic accidents and deaths of pedestrians at crosswalks, which effectively improved the safety of pedestrians and vehicles. However, the operation and maintenance of the equipment is not considered, and there are some requirements for the applicable conditions. In order to ensure the crossing safety of shorter people, He Yongming et al. [14] designed a traffic safety warning system for urban pedestrians using ground color changes, flashing lights, voice prompts and ground bump changes, warning the "low-headed people" from the three aspects of vision, hearing, and touch, but ignoring the safety hazards of the ground bulge to pedestrians. Zou Ruilin et al. [15] designed a pedestrian crossing intelligent system with induction control as the core, which reduces the disorder and randomness of pedestrian crossing through adaptive control and manual request control, realizes the separation of people and vehicles in time and space, and reduces the delay time of pedestrians and road section vehicles. However, the system tends to provide priority service to pedestrians crossing the street and, therefore, is not applicable to roadways with high traffic volumes. Yang Xiaodong et al. [16] improved the existing pedestrian crossing voice prompt column, added infrared induction, a voice prompt, a blocking pole, and other devices, through voice prompts, physical obstruction, etc., to reduce pedestrians running red lights and reduce traffic accidents. Lu Yichen et al. [17] detected pedestrian and vehicle movement conditions, performed signal control based on the detection, and added physical separation and voice prompting devices to improve pedestrian crossing safety. The system controls pedestrian crossing signals by detecting the occupancy of pedestrians crossing the street, thus, limiting the applicability to line-controlled intersections. Chen Ze et al. [18] established a two-way warning for vehicles and pedestrians by displaying crosswalks with different light colors according to vehicle speed and signal control schemes for the characteristic that pedestrians react faster than vehicles. Yang Yan et al. [19] designed a safety device with a microcontroller as the core and a dual photoelectricity and sound alert to ensure traffic safety for pedestrians crossing the street in conflict with vehicles. This system improves pedestrian crossing safety and road utilization by optimizing the modular control of crossing signals. Hua Wenting et al. [20] designed a pedestrian crossing facility induction system based on AR technology, which is committed to improving the application rate of crossing facilities and the safety of pedestrian crossing. However, the system has a high degree of foresight, and given the level of development of AR technology, there are limitations to its application and popularity. Li Yajun [21] designed a pedestrian crossing civilized courtesy early warning system based on thermal imaging technology to warn vehicle drivers and shorter people, which can also reduce the safety hazards of zebra crossing blind areas caused by parking courtesy.

To summarize, in designing pedestrian crossing safety systems, a group of scholars have not considered the solution during signal transition system systematically enough, and have not considered the human–vehicle characteristics comprehensively, or given thought to fine-grained control by lane in the developed warning systems. For the pedestrian crossing safety problem at signal transitions of road sections and intersections, the innovation of this paper is to design an intelligent pedestrian crossing safety warning system based on improving the stopping sight distance model and the pedestrian crossing safety psychological model, and to propose a vehicle safety braking distance model considering human–vehicle characteristics.

The rest of this paper is organized as follows. Section 2 introduces the components and functions of each module of a vehicle–road cooperative warning system for pedestrian crossing active safety. Section 3 introduces the construction process of the vehicle safety braking distance model considering human–vehicle characteristics. Section 4 presents the comparative analysis of various models. Section 5 discusses the evaluation and analysis of the experimental results. Section 5 summarizes the conclusions obtained from the paper.

## 2. System Design

The crosswalk safety warning system for pedestrians to cross the street intelligently is divided into four modules, as follows: a detection module, control module, warning module and a wireless communication module, as shown in Figure 1. The system adopts a distributed structure and can be applied to the following two scenarios: intersection crosswalk and roadway crossing channel. If the system is placed at the intersection, four parts are placed at each intersection, including one main control and three sub-controls; if the system is placed at the roadway pedestrian crossing channel, two parts are placed, namely one main control and one sub-control each. The system has the functions of pedestrian detection, vehicle detection, pedestrian crossing time calculation, wireless communication within the system, an intelligent sidewalk changing light color warning, a voice warning, etc.

### *2.1. Detection Module*

The detection module contains the following two parts: vehicle detection and pedestrian detection. The double detection of pedestrians and vehicles helps to prevent the unsafe problems of pedestrians and vehicles due to information asymmetry.

#### 2.1.1. Vehicle Inspection

Millimeter-wave radar can detect multi-lane, multi-target object information simultaneously by sending electromagnetic waves and receiving reflected waves from obstacles. It is used to detect whether a vehicle is stopped in front of the stop line of each inlet lane at an intersection.

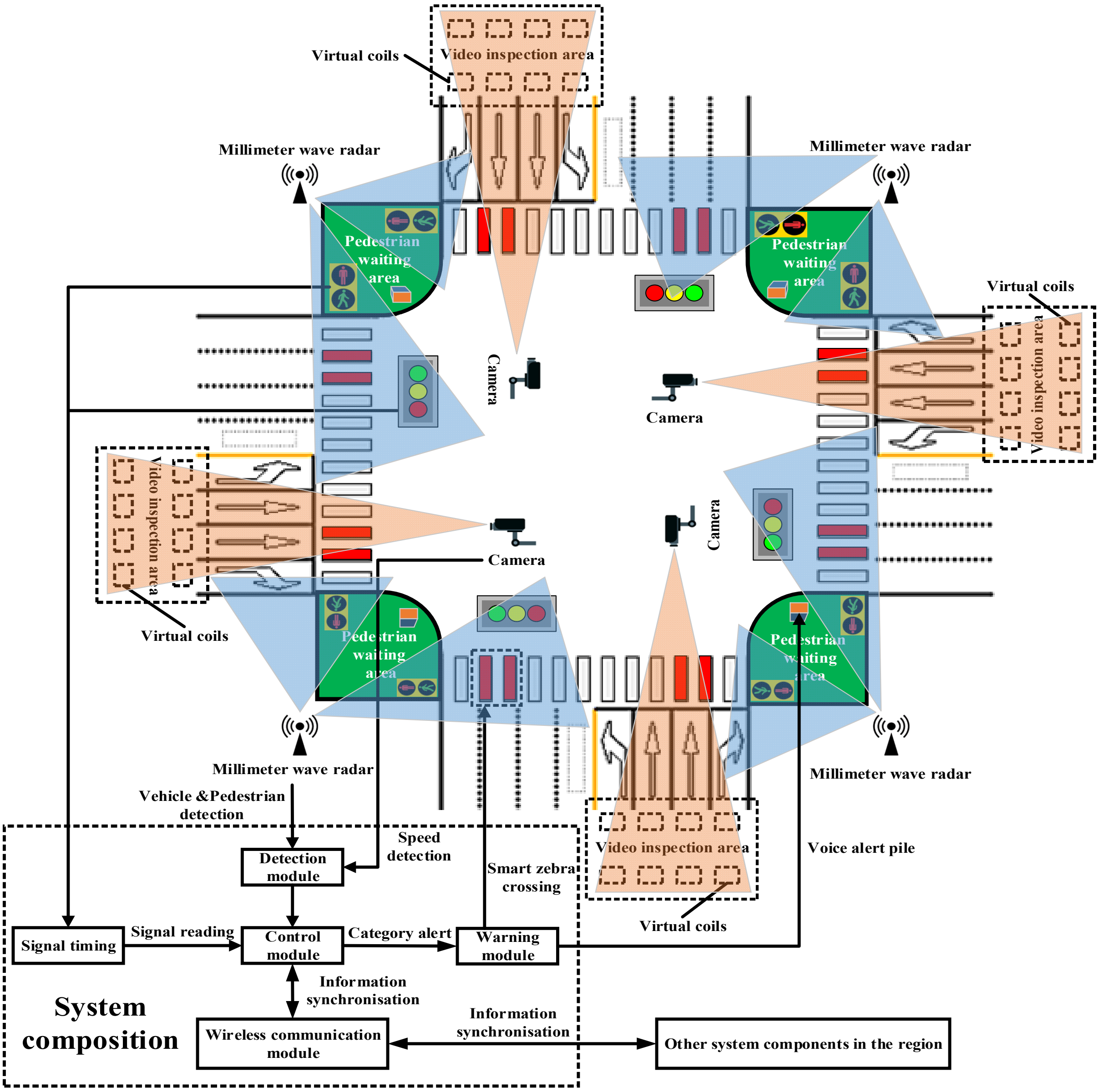



**Figure 1.** Composition of crosswalk safety warning system for pedestrians to cross the street intelligently.

The geomagnetic, coil detection methods of vehicles have a high failure rate, and the installation and maintenance need to counter the disadvantages of the ground. The video detection systems have a high accuracy rate and low failure rate, and installation and maintenance is more convenient. Therefore, the video detection method is used, and the differential image method, which is currently widely used, is selected to collect information, such as vehicle speed. The video detection area is pre-defined in front of the intersection inlet lane, and a set of virtual coils, namely Loop1 and Loop2, are delineated in the video detection area for detecting vehicle speed to achieve a speed measurement function similar to the traditional dual coil detector.

By performing image differential analysis on the captured video, we can obtain the average speed of the vehicle passing through the two virtual coils, Loop1 and Loop2. The vehicle detection part is schematically shown in Figure 2.

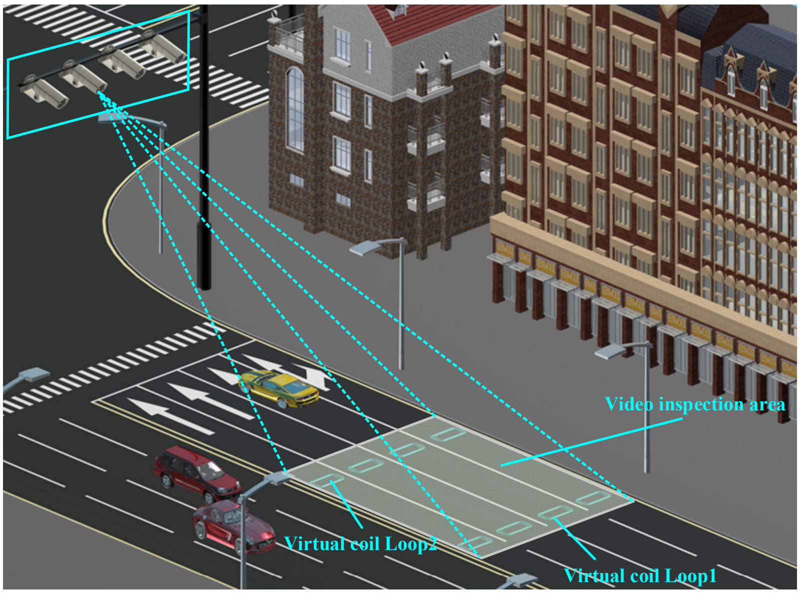



**Figure 2.** The vehicle detection part of the detection module.

The features of the adjacent two frames are extracted separately, i.e., the RGB (red, green, and blue primary colors) values of the adjacent two frames are counted, and then the two RGB statistics are differenced to obtain the signals generated when the vehicle passes through Loop1 and Loop2. The difference in the image RGB statistics [22] is as follows:

$$d_{\mathrm{RGB}} = \sum_{x=0}^{M-1}\sum_{y=0}^{N-1} RGB[f(x,y,t)] - \sum_{x=0}^{M-1}\sum_{y=0}^{N-1} RGB[f(x,y,t-1)] \tag{1}$$

where $d_{\mathrm{RGB}}$ is the difference of the image *RGB* statistics; the defined *RGB* ( ) function is used to count the red color channel value, blue color channel value, green color channel value, and grayscale value at the point $(x, y)$; $f(x,y,t)$ is the pixel value at the point $(x, y)$ of the image at frame $t$; $M$, $N$ is the length and width of the image, respectively (px).

The image differential signal generated when the vehicle passes through Loop1 and Loop2 can reflect the whole process of the vehicle passing through the virtual coil [22], as shown in Figure 3.

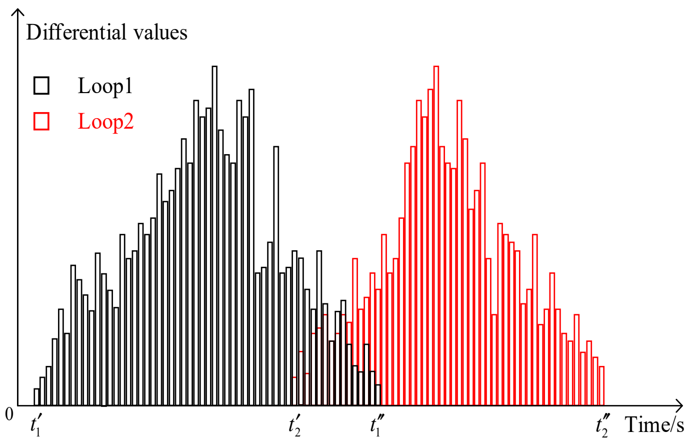



**Figure 3.** Image differential signal output generated when the vehicle passes through the virtual coil Loop1 and Loop2.

The average speed of vehicles through Loop1 and Loop2 $v_a$ (m/s) [23] is as follows:

$$v_a = 1/2\left[d/\left(t'_2 - t'_1\right) + D/\left(t''_2 - t''_1\right)\right] \tag{2}$$

where $d$ is the distance between Loop1 and Loop2 (m); $t'_1$, $t''_1$ is the time when the vehicle arrives and leaves Loop1 (s); $t'_2$, $t''_2$ is the time when the vehicle arrives and leaves Loop2 (s).

The size of the video detection area can be determined according to the actual traffic condition of each intersection, and the virtual coil location can also be delineated according to the actual demand. According to experience, it is generally recommended to be set at 40 m before the crosswalk, which can better meet the function.

After the location of the virtual coil is determined, it is necessary to calculate the initial running speed $v_0$ (m/s) at which the vehicle can safely stop from the virtual coil to the parking line. The $v_0$ is derived from the inverse of the parking sight distance model [24], as follows:

$$S_0 = v_0 t_0/3.6 + {v_0}^2/\left[2g(\varphi + \phi) \times 3.6^2\right] \tag{3}$$

where $S_0$ is the stopping sight distance (m); $t_0$ is the driver braking reaction time (s), taking into account the case of delayed reaction is taken as 2.5 s; $g$ is the acceleration of gravity (m/s$^2$), generally taken as 9.8 m/s$^2$; $\varphi$ is the humidity coefficient, taken as 0.4 in the more humid situation; $\phi$ is the roughness coefficient, taken as 0.03~0.05.

After the initial running speed $v_0$ that the vehicle can safely stop from is inferred from Equation (3), the vehicle is judged to be at a safe speed by comparing the initial running speed $v_0$ with the average speed $v_a$ of the vehicle driving through the virtual coil.

### 2.1.2. Pedestrian Detection

Pedestrian detection involves detecting and tracking multiple targets in the whole area. To ensure the accuracy and reliability of the data, FM continuous-wave millimetre-wave radar with high sensitivity and relatively high accuracy of speed and distance measurement is used. The radar has a strong anti-interference solid capability and can continuously track and measure the distance and speed of multiple targets. The pedestrian detection section is shown in Figure 4.

**Figure 4.** Pedestrian detection part of the detection module.

Since the radar capture is sensitive, other targets similar to pedestrians need to be excluded [25]. The distance from the radar to the top and bottom of the target is $l_1$, $l_2$ (m), the angle from the radar to the top and bottom of the target is $\alpha_1$, $\alpha_2$, and the height of the detected target can be obtained as follows:

$$h = \sqrt{l_1^2 + l_2^2 - 2l_1 l_2 \cos(\alpha_1 + \alpha_2)} \tag{4}$$

While the general height of pedestrians is 0.7~2 m [25], $h$ can be compared with the general height of pedestrians to determine and eliminate targets that are not in the height interval, i.e., non-pedestrian targets.

The pedestrian's position can be determined by calculating the relative distance between the pedestrian and the radar. When there is a relative motion between the pedestrian and the radar, the distance measurement formula [26] is as follows:

$$r = Tc\left(\Delta f^{-} + \Delta f^{+}\right)/(8\Delta F) \tag{5}$$

where $r$ is the relative distance between the radar and pedestrian (m); $T$ is the signal period (ms); $c$ is the speed of light (m/s); $\Delta f^{-}$, $\Delta f^{+}$ are the signal overlap after the negative (MHz), and the upbeat FM band of the differential signal frequency; $\Delta F$ is the FM bandwidth (MHz).

During the motion of the pedestrian relative to the radar, the velocity of the pedestrian's motion can also be measured as follows [26]:

$$\Delta f^{-} = \Delta f + 2f_0 v_b/c \tag{6}$$

$$\Delta f^{+} = \Delta f - 2f_0 v_b/c \tag{7}$$

$$v_{\mathrm{p}} = c\left(\Delta f^{-} - \Delta f^{+}\right)/(4f_0) \tag{8}$$

where $\Delta f$ is the frequency difference between the transmitted and reflected signals (MHz); $f_0$ is the center frequency of the transmitted signal (MHz); $v_b$ is the movement speed of the target relative to the radar (m/s); $v_{\mathrm{p}}$ is the pedestrian step speed (m/s).

By detecting the position and speed of pedestrians, the radar can accurately grasp the condition of pedestrians in front of each lane and form a match with the speed detected in each lane, which can be finely controlled for different situations in different lanes with a split-lane warning.

### *2.2. Control Module*

The control module contains the following six parts: a micro control unit, a pedestrian signal remaining time reading, vehicle speed extraction, pedestrian motion detection, an intelligent crosswalk, and a voice prompt pile control. The microcontroller unit, with MCU as the core, reads the remaining time of the pedestrian signal and starts to work when the remaining time of the green light is 10 s. When the pedestrian is detected to have the intention to cross the street, the microcontroller unit can detect the pedestrian movement. When pedestrians are detected to cross the street, but cannot complete the crossing within the remaining passage time, the voice alert pile reminds pedestrians that they cannot pass through via a sound warning. When the pedestrian ignores the voice warning and insists on crossing the street, the intelligent crosswalk is activated. It changes color according to different situations to warn pedestrians and vehicles in both directions.

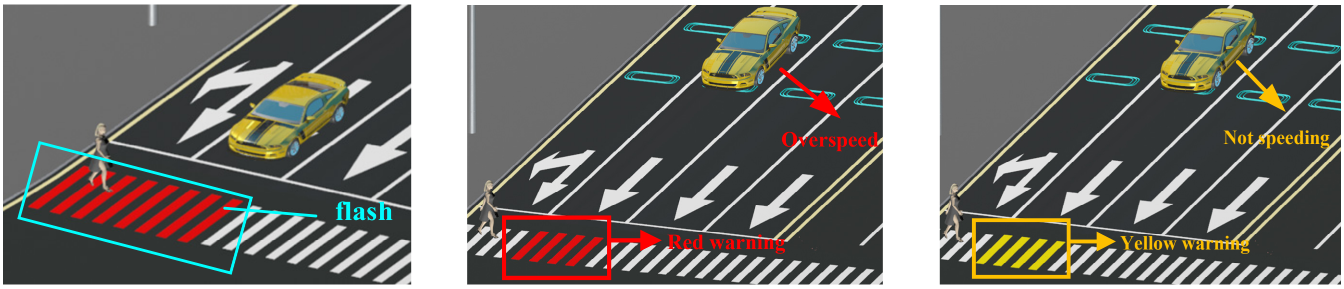
In order to determine whether the pedestrian can complete the crossing or reach the safety island, the system needs to calculate the pedestrian's crossing travel time [27], as follows:

$$t_{\mathrm{p}} = L_{\mathrm{c}}k/v_{\mathrm{p}} + \left(x' + y'\right)/s \tag{9}$$

where $t_{\mathrm{p}}$ is the pedestrian crossing travel time (s); $L_{\mathrm{c}}$ is the single-lane width; $k$ is the number of lanes (m); $x'$ and $y'$ are the number of pedestrians on the left and right sides of the crosswalk; $s$ is the safety factor, generally taken as 5.

By comparing the pedestrian travel time $t_{\mathrm{p}}$ and the remaining passage time $u$ of the pedestrian signal, the system can determine whether the pedestrian can finish crossing the street or reach the safety island in the middle of the road.

When the voice warning is invalid, and the pedestrian is already on the crosswalk, according to the status of the vehicle in front of the stop line in the next lane, the intelligent crosswalk warning can be divided into cases 1, 2, and 3, with a total of 3 cases, as shown in Figure 5.




(**a**) (**b**) (**c**)

**Figure 5.** Intelligent crosswalk warning schematic. (**a**) Case 1 Red light flashing; (**b**) Case 2 Red light warning; (**c**) Case 3 Yellow light warning.

The three cases are as follows:

(1) Case 1. If there is a vehicle stopped, the red light of the zebra crossing in front of the lane where the pedestrian is located and the next lane ahead is controlled to flash (see Figure 5a), thus, preventing the vehicle driver from starting due to inattention [28] or negligent observation when the signal is switched, and causing a traffic accident;
(2) Case 2. If no vehicle is currently stopped and there is a vehicle approaching above a safe speed, the red warning of the crosswalk in front of the next lane ahead is controlled (see Figure 5b), thus, warning vehicles and pedestrians of the impending danger;
(3) Case 3. If no vehicle is currently stopped and a vehicle not exceeding the safe speed is approaching, the yellow warning of the zebra crossing in front of the next lane ahead is controlled (see Figure 5c), thus, warning drivers and pedestrians to pass when it is judged safe to do so.

The control flow of the control module for the whole process of pedestrian crossing is shown in Figure 6.

### 2.3. Warning Module

The warning module includes the following two parts: a voice alert pile and an intelligent crosswalk. The voice alert pile can be adopted from the existing intersection voice alert pile. The control program of the existing intersection voice alert pile can be re-modified and connected to the system. If there is no voice alert pile at the intersection, additional voice alert piles can be set up.

Rista et al. [29] studied the impact of signs on driver yield situation and showed that LED embedded signs are an effective treatment solution at the sidewalk, and that they lower operating speeds. As a result, the choice of LED lights for the smart crosswalk light-emitting component was considered, and the smart crosswalk was installed in place of the traditional crosswalk.

Considering that in engineering applications, LED lights need to have high brightness, easy identification, long life, low energy consumption, etc. So, the ND16 series LED high brightness indicator is selected in this paper, and the effect is shown in Figure 7.


**Figure 6.** Control flow of control module in crosswalk safety warning system for pedestrians to cross the street intelligently. Here, *u* is time remaining for the pedestrian green light (s), and $t_p$ is time required for pedestrian crossing (s).

**Figure 7.** ND16 series light-emitting diode high brightness indicator effect.

According to the national standard GB 5768.3-2009 "Road Traffic Signs and Markings", the basic length of a crosswalk is 3~5 m, the width of each strip is 45~60 cm, and the spacing is 60 cm. Assuming that the length and width of each crosswalk are taken as the minimum value, it can be determined that the length of a crosswalk is 300 cm and the width is 45 cm under ideal circumstances.

The diameter of the ND16 series LED highlight indicator is about 3 cm, and each crosswalk is placed in five columns, thus, if the interval between two LED highlight indicators is 5 cm, then each column needs to contain about 37 ($300 \div (3+5) \approx 37$) LED highlight indicators, and each crosswalk needs to contain 185 ($37 \times 5 = 185$) LED highlight indicators.

Considering that the intelligent crosswalk needs to have waterproof and pressure resistant performance in the application process, the surface of the intelligent crosswalk is sealed and installed with high-strength tempered glass, so that the intelligent crosswalk has good durability while ensuring light transmission. At the same time, to prevent the surface from being too smooth, causing pedestrians and vehicles to slip, the surface of the tempered glass is treated with an anti-slip material.

In addition, considering that the LED high-bright indicators are prone to glare, which affects the vision of pedestrians and vehicles, the surface of the tempered glass is treated with anti-glare materials [30]. By spraying special chemicals on the surface of high-strength tempered glass, the glass surface becomes a matte diffuse reflective surface. The structure of the intelligent crosswalk is shown in Figure 8.

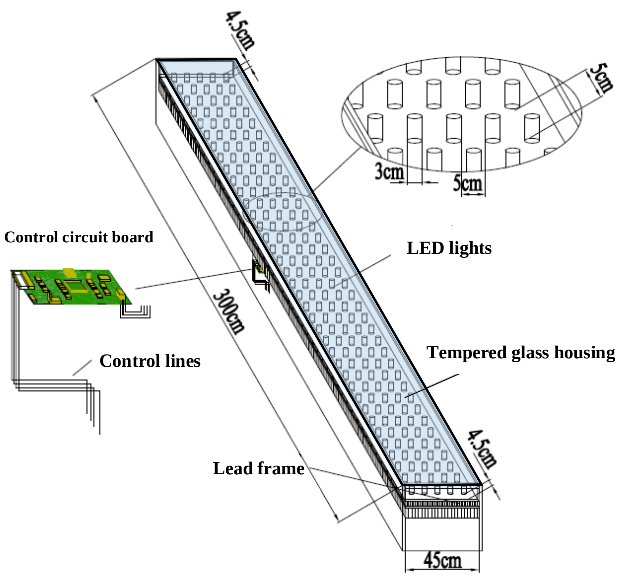



**Figure 8.** Intelligent crosswalk structure in the warning module.

*2.4. Wireless Communication Module*

Given that the laying of wired devices requires the destruction of the road surface, in order to reduce construction and improve the system's intelligence, wireless communication is chosen for data exchange within the system and multiple systems within the region, as shown in Figure 9.

Wireless communication is mainly carried out through the IoT module, secured inside the system and connected to the microcontroller through the UART interface. The IoT module enables information interaction between the distributed systems at the intersection, and also synchronizes data such as vehicles, pedestrians, and signal schemes among the modules within the system to ensure the joint operation of the whole system. The data exchanged in the system include signal scheme remaining time, vehicle speed information, pedestrian crossing intention, location and speed of pedestrians on the crosswalk, and so on.

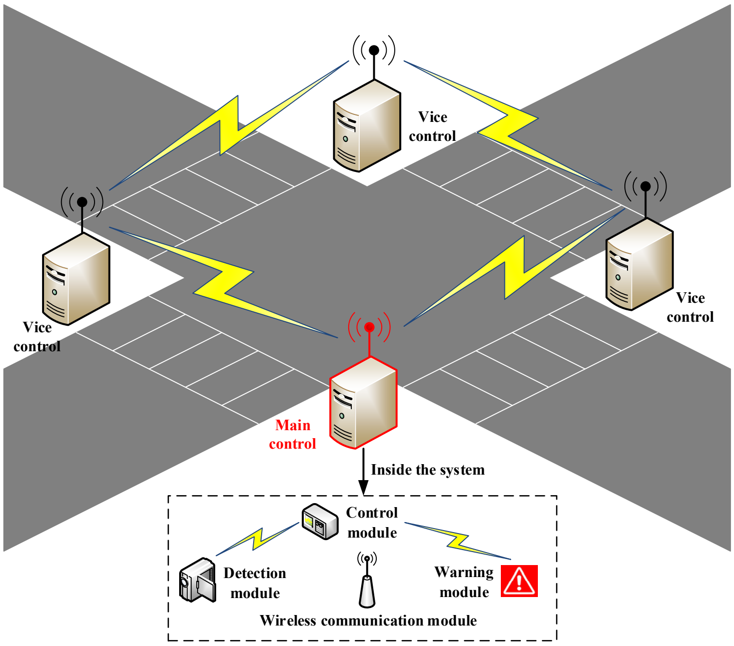



**Figure 9.** Wireless communication module in crosswalk safety warning system for pedestrians to cross the street intelligently.

## 3. Vehicle Safety Braking Distance Model Considering Human–Vehicle Characteristics

In designing the crosswalk safety warning system for pedestrians to cross the street intelligently, the vehicle detection part uses the stopping sight distance model. Combined with the actual engineering cases, it is found that when a vehicle is coming toward a pedestrian, although it can stop in front of the pedestrian, it will cause the pedestrian to exhibit random and prominent behaviors, such as shifting and steering, which are prone to safety problems. The existing stopping sight distance model only considers road factors and vehicle characteristics, but not pedestrian characteristics, thus, in this paper, we consider vehicle and pedestrian characteristics comprehensively, and construct a vehicle safety braking distance model considering human–vehicle characteristics.

### *3.1. Vehicle Minimum Safe Braking Distance Model Improvement*

The minimum safe braking distance is the shortest distance at which a vehicle can safely stop, also known as the stopping sight distance. The stopping sight distance model is shown in Equation (3).

The existing stopping sight distance calculation model only takes into account the vehicle driver's reaction time, $t_0$. At the same time, the actual braking process also involves overcoming the free travel of the brake pedal and the contact time $t_1$ between the vehicle's brake shoes and the brake drum, and the time $t_2$ when the driver presses the brake pedal harder to maximize the braking deceleration. The latter two processes of braking, although shorter, should also be considered in the modeling process.

A simplified vehicle braking process [31] is shown in Figure 10. When the driver brakes in an emergency, i.e., at point a, $t_0'$ time elapses before he or she realizes that the brake should be applied, and time $t_0''$ elapses before he or she reacts, i.e., the brake pedal is under pressure after point b. The time $t_0 = t_0' + t_0''$ from point a to point b is the reaction time. Because of the free travel of the pedal, there is a gap between the vehicle's brake shoes and the brake drum, so it takes time $t_1$ to produce the braking deceleration, that is, at point c. As the brake pedal pressure increases rapidly to the maximum, that is, at point d, after the time $t_2$, the braking deceleration also increases to the maximum, that is, at point e. After a continuous braking of time $t_3$ after point e, the driver releases the pedal. That is, at point f, the brake pedal pressure disappears, and the braking force is eliminated after the time $t_4$ and reaches point g.

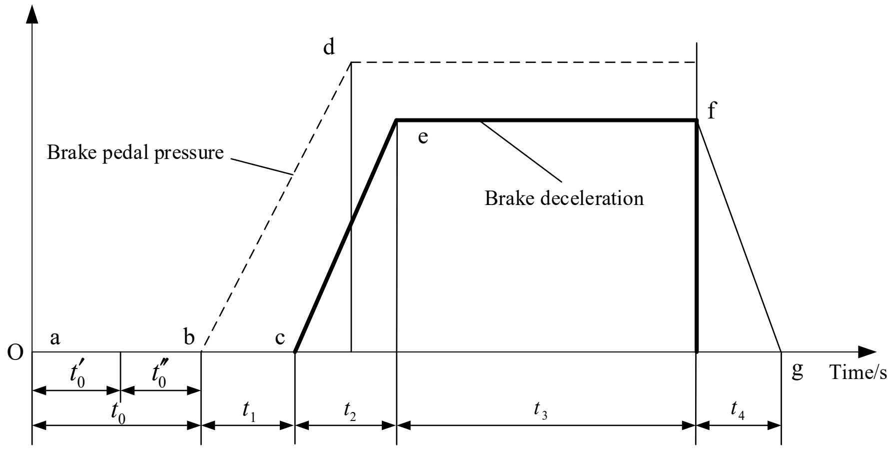



**Figure 10.** Simplified vehicle braking process schematic, where $t_0 = t_0' + t_0''$ is the driver braking reaction time (s), $t_1$ is the braking deceleration generation time (s), $t_2$ is the braking deceleration rise time (s), $t_3$ is the braking duration (s), and $t_4$ is the braking deceleration removal time (s).

The vehicle braking process, based on the stopping sight distance model (Equation (3)), while taking into account the free travel of the brake pedal, the clearance between the brake shoes and the brake drum, the rise time of the braking deceleration and the longitudinal slope of the road, the improved model of the stopping sight distance is proposed, can be illustrated as follows:

$$S_0' = \frac{v_0}{3.6}(t_0 + t_1 + \frac{t_2}{2}) + \frac{{v_0}^2}{2g(\varphi + \phi \pm \theta) \times 3.6^2} + l_0 \quad (10)$$

where $S_0'$ for the improved parking sight distance (m); $\theta$ for the longitudinal slope of the road (uphill taken as positive, downhill taken as unfavorable); $l_0$ for the safety distance (m), taken as 5 m; $t_1 + t_2$ take the value of the general 0.2~0.9 s.

### *3.2. Vehicle Minimum Safe Braking Distance Model Improvement*

When a vehicle conflicts with pedestrians and braking is required, if only the minimum safe braking distance is satisfied, the vehicle will be too fast and cause parking too close to pedestrians, which will have a substantial psychological impact on pedestrians [32]. Thus, when a conflict occurs between a vehicle and a pedestrian, not only the safe braking of the vehicle should be ensured, but also the safe psychological distance of the pedestrian should be considered to prevent the vehicle from going too fast or parking too close to the pedestrian, causing fear and other emotions in the pedestrian, which in turn will produce unpredictable, dangerous behaviors, such as advancing and running back.

The psychological distance of pedestrian crossing safety [33] is expressed as follows:

$$L_p = v_i\left(nL_c/v_p + t_r\right) + C_s \quad (11)$$

where $L_p$ is the safe psychological distance for pedestrians to cross the street (m); $v_i$ is the speed of the $i$th lane (m/s); $n$ is the number of lanes; $L_c$ is the width of a single lane (m); $t_r$ is the pedestrian reaction time (s), with an average value of 1.8 s; $C_s$ is the safe distance of the arriving vehicle from the pedestrian (m), taken as 3–5 m.

As the pedestrian crossing safety psychological distance is for the case where the vehicle does not decelerate, a deceleration term needs to be added for correction. The braking process decreases in speed very quickly, and neglecting air resistance, and the braking deceleration is obtained from the equation of force balance, as follows:

$$a_j = g(\varphi + \phi \pm \theta)/\delta \quad (12)$$

where $a_{\mathrm{j}}$ is the vehicle braking deceleration (m/s$^2$); $\delta$ is the rotating mass conversion factor, generally taken as 1.1 to 1.4.

Research [34] has shown that the pedestrian's requirement for a safe psychological distance is also related to the type and size of the vehicle. When faced with vehicles of different vehicle types and sizes, the pedestrian's psychological safety distances are calculated as follows:

$$r_s = 20K\frac{a_0 b_0}{a^* b^*} / \left(1 + \frac{a_0 b_0}{a^* b^*}\right) \tag{13}$$

where $r_s$ is the psychological safety distance of pedestrians facing different vehicles (m); $K$ is a characteristic parameter of pedestrians, related to factors, such as their gender, age, and propensity for risk-taking behaviour, and generally takes a value greater than 0; $a_0$, $b_0$ are the length and height of the target body (m); $a^*$, $b^*$ are the length and height of the reference vehicle's body (m).

The vehicle deceleration process is treated as a uniform deceleration process, and the time, velocity, and acceleration terms in Equations (11) and (12) are substituted into the physics equation of motion for uniform deceleration, while Equation (13) is introduced into the kinematics equation to take into account the effect of vehicle type on the pedestrian's psychological safety braking distance. The constant term $C_{\mathrm{s}}$ in Equation (11) can be neglected due to the large number of factors considered and the increase in the influence parameter of the model. In summary, by substituting and combining Equations (11)–(13), the pedestrian psychological safety braking distance $L'_{\mathrm{p}}$ can be obtained as follows:

$$L'_{\mathrm{p}} = v_i\left(nL_{\mathrm{c}}/v_{\mathrm{p}} + t_{\mathrm{r}}\right) - a_{\mathrm{j}}\left(nL_{\mathrm{c}}/v_{\mathrm{p}} + t_{\mathrm{r}}\right)^2/2 + 20K\frac{a_0 b_0}{a^* b^*} / \left(1 + \frac{a_0 b_0}{a^* b^*}\right) \tag{14}$$

### *3.3. Modelling of Safe Braking Distances considering Human and Vehicle Characteristics*

The improved stopping sight distance model and the pedestrian crossing safety distance calculation model are integrated, and according to the different degrees of right-of-way requirements of pedestrians and vehicles in different locations and the different access needs of vehicles and pedestrians, the two are given different weights $\beta$ under the premise of ensuring safety, and the safe braking distance $S$ (m) considering the characteristics of people and vehicles can be obtained as:

$$S = \beta S'_0 + (1-\beta)L'_{\mathrm{p}} \tag{15}$$

The value of $\beta$ is 0.5 to 1. In order to ensure that the vehicle can be braked safely and to take into account the psychological impact on pedestrians, while not making the safe stopping distance too large to be meaningful, the value of $\beta$ is generally not less than 0.5.

Neglecting the constant term and replacing vi in Equation (14) with the $v_0$ value for each lane gives a safe braking distance model that takes into account the characteristics of people and vehicles, as follows:

$$S = \beta\left[\frac{v_0}{3.6}(t_0 + t_1 + \frac{t_2}{2}) + \frac{{v_0}^2}{25.92g(\varphi + \phi \pm \theta)}\right] + (1-\beta)\cdot\left[v_0\left(\frac{nL_{\mathrm{c}}}{v_{\mathrm{p}}} + t_{\mathrm{r}}\right) - \frac{g}{2\delta}(\varphi + \phi \pm \theta)\cdot\left(\frac{nL_{\mathrm{c}}}{v_{\mathrm{p}}} + t_{\mathrm{r}}\right)^2 + 20K\frac{a_0 b_0}{a^* b^*} / \left(1 + \frac{a_0 b_0}{a^* b^*}\right)\right] \tag{16}$$

In order to visualize the role of the vehicle's initial operating speed $v_0$ and weight $\beta$ on the model, the other factors are taken as constant values, resulting in a vehicle safety braking distance surface that takes into account the human–vehicle characteristics, as shown in Figure 11.

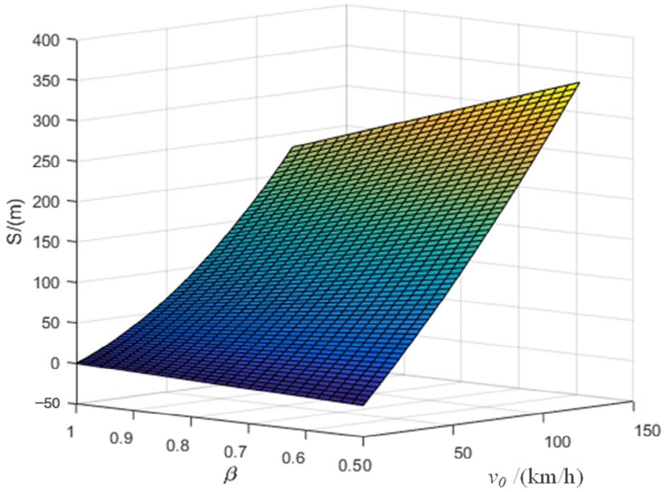



**Figure 11.** 3D surface diagram of vehicle safety braking distance model considering human–vehicle characteristics.

## 4. Comparative Model Analysis

In order to verify the rationality and safety of the proposed vehicle safety braking distance model considering human–vehicle characteristics, the model is compared and analyzed with the stopping sight distance model, the stopping sight distance improvement model, and the pedestrian psychological safety braking model through numerical calculations.

Since, in practice, road conditions and pedestrian and vehicle conditions are certain, several parameters in the model reflecting road characteristics, vehicle reaction time, pedestrian reaction time, etc. can be calibrated during the distance calculation process without analyzing their sensitivity. Therefore, for comparison purposes, all parameters except the initial vehicle running speed $v_0$ and the weight $\beta$ are calibrated and taken uniformly.

The driver's braking reaction time $t_0$ is taken as 2.5 s, taking into account the delayed reaction. The braking force rise time $t_1 + t_2/2$ is taken as 0.6 s; the acceleration of gravity $g$ is taken as 9.8 $\text{m/s}^2$; the dampness factor $\varphi$ is taken as 0.4 for wetter conditions; the roughness factor $\phi$ is taken as 0.04; the longitudinal slope of the road $\theta$ is taken as 0; the safety distance $l_0$ is taken as 5 m; only the case of pedestrians crossing a lane is discussed, and the number of lanes $n$ is taken as 1; the width of a single lane $L_c$ is set as 3.5 m. The pedestrian crossing speed $v_p$ is taken as the general standard speed of 1.5 m/s; the pedestrian reaction time $t_r$ is taken as the average value of 1.8 s; the distance $C_s$ between the arriving vehicle and the pedestrian is taken as 3 m; the rotating mass conversion factor $\delta$ is taken as 1.2; the vehicle braking deceleration $a_j$ is obtained as 3.6 $\text{m/s}^2$; the pedestrian characteristic parameter $K$ is taken as 1 according to the general situation; the target body length $a_0$ and height $b_0$ are determined according to the dimensions of ordinary small cars are 4.8 m and 1.4 m, respectively; the body length $a^*$ and height $b^*$ of the reference vehicle are taken as 5 m and 1.6 m, respectively.

After the model parameters were calibrated, the safety distances corresponding to each model were calculated according to the different initial running speeds $v_0$ of the vehicles. At the same time, the weight $\beta$ in the vehicle safety braking distance model considering the human–vehicle characteristics was taken from 0.5 to 1 in intervals of 0.1 to calculate the safety distance solved by the model at different weights, and the safety distance comparison curve is shown in Figure 12. As can be seen from the figure, the pedestrian psychological safe braking distance is much greater than the braking distance of the vehicle at the same speed so, in practice, if only the traditional stopping sight distance model is used, it does not meet the pedestrian psychological requirements for distance. The vehicle safety braking distance model considering human–vehicle characteristics, takes into account the pedestrian psychology and gives different weights to the vehicle and the pedestrian, while taking into account the fact that a long safety braking distance is difficult to achieve in practice, so that the safety braking distance is increased to a certain extent without increasing too much, giving the pedestrian a certain psychological mitigation distance. To a certain extent, the psychological impact on pedestrians caused by excessive speed or stopping too close to them is avoided, and the safe braking distance is reasonable. It can also be seen that the $S_0'$ curve is slightly higher than the $S_0$ curve, indicating that the improved vehicle safety braking distance is greater than the stopping sight distance, meaning that safety is improved; the increase in braking distance is more limited and can more realistically reflect the distance travelled by the vehicle during the brief braking force rise that is ignored in the stopping sight distance model.

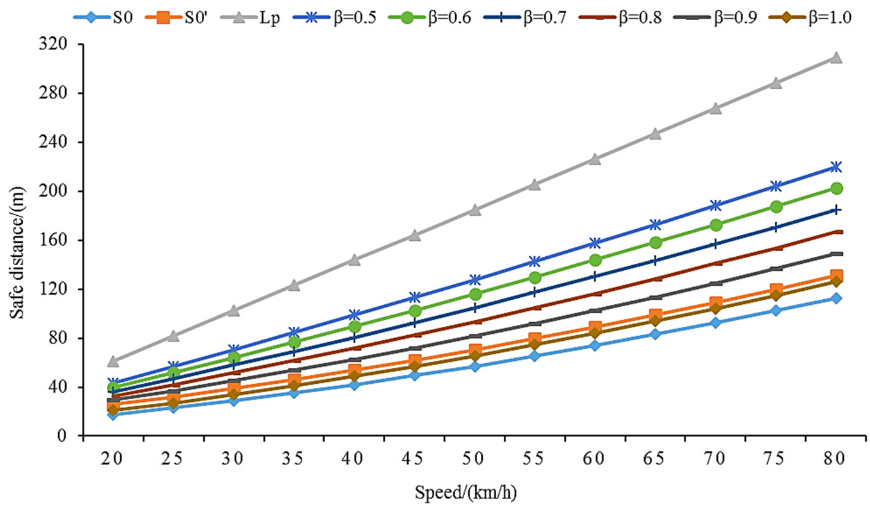



**Figure 12.** Comparison curve of safety distances.

In summary, by comparing the vehicle safety braking distance model, the stopping sight distance model, the stopping sight distance improvement model, and the pedestrian psychological safety braking distance model considering human and vehicle characteristics at different weights, the rationality, and safety of the proposed model can be visually illustrated.

## 5. Conclusions

In this paper, a crosswalk safety warning system for pedestrians to cross the street intelligently is designed for the current situation of conflicts between pedestrians and vehicles during signal transitions at intersections. A safe braking distance model that takes into account human–vehicle characteristics is proposed for the current situation of existing parking models that do not consider the psychological impact on pedestrians, and the following main conclusions are obtained:

(1) The designed system detects the position and speed of pedestrians and vehicles in real-time, discriminates between pedestrian and vehicle conflicts with reference to the situation, and runs different warning schemes for different situations. Warning for pedestrians through voice prompting stakes, and two-way warning for pedestrians and vehicles through intelligent zebra crossings with the onset of red, red flashing, yellow lights can effectively reduce conflicts between pedestrians and vehicles and avoid traffic accidents;

(2) The proposed model incorporates considerations of pedestrian psychological safety distances and the impact on vehicle models based on an improved vehicle stopping sight distance model, resulting in further improvements in vehicle braking safety while reducing the psychological impact of the braking process on pedestrians.

In this paper, an optimized solution to the pedestrian crossing safety problem is proposed from two theoretical and technical aspects, providing a new basis for solving the pedestrian crossing safety problem. However, there are some limitations in this research, such as that it is necessary to destroy the ground during the installation of smart crosswalk, and that the current technology preparation level is only level 3, which is in the laboratory stage, meaning that theoretical research, feasibility of application ideas, and technical analysis and prediction work are being carried out. In the future, the system will be further improved to be more systematic and green in terms of sustainable power utilization and road damage reduction.

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