Smart Road Sign Design Based on Hydraulic Power Generation and Block Section Theory

Jinshuan Peng, Lei Xu, Zhenya Yu, Yiming Shao, Jin Xu

School of Traffic & Transportation, Chongqing Jiaotong University, China
pengjinshuan@163.com, {37951759, 1822691779}@qq.com, sym@cqjtu.edu.cn, 834703417@qq.com

Abstract

In order to reduce the risk of traffic accidents caused by low visibility on highways, this study proposes a new type of energy-saving projection protruding signs based on the principle of hydraulic power generation and block section. The protruding signs utilize a hydraulic power generator comprised of a liquid pressure capsule, flow-regulating device, permanent-magnet generator, and so on, which can collect the pressure exerted by cars on the ground and convert it into electrical energy. The converted electric energy is calculated using a mathematical model, and a simulation model of hydraulic power generation is established using Matlab/Simulink. The protruding signs of this new lighting control system were designed based on the principle of block section theory, sensor technology, microcontroller technology, and Altium Designer software and other related tools. This system may dynamically and intelligently control the working condition of protruding signs and luminous colors on the road at different sections in accordance with real-time traffic conditions, which may help drivers understand road alignment conditions and the motion states of cars ahead clearly.

Keywords: Smart road sign, Hydraulic power generation, Block section, Intelligent control, Safety guidance

1 Introduction

Traffic accidents on highways are caused by the poor interactions among humans, vehicles, road, and environment, and low visibility is one of the important environmental factors causing traffic accidents. In a low-visibility environment, protruding signs can effectively convey road-alignment information and the motion states of vehicles ahead to the drivers, which will greatly improve road-traffic safety level. Existing protruding signs may be divided into self-luminous and reflective raised pavement markers, and the former can significantly improve visibility distance [1-3]. Currently, the main sources of electrical power for active-light protruding signs are grid and solar energy, but in the presence of rain and fog, the collection efficiency is low and the supply of electrical energy is insufficient [4-5]. Moreover, existing raised pavement makers were designed to show the physical boundaries of the lane or road, however, failed to provide other auxiliary information to the drivers, so as to guarantee the driving safety [6-7].

In this paper, hydraulic power generation technology is used to collect and transfer the pressure exerted by cars running over the road surface, which provides the necessary electrical energy for the protruding signs. Furthermore, in order to reduce the energy consumption of protruding signs on highways, they are section-controlled, keeping a synchronized relationship between the working state of the signs and the motion of vehicles, that is, only the protruding signs within the section that possess a vehicle will emit light. Moreover, the light color of the protruding signs is changed to ensure that the driver maintains a safe distance from the vehicle ahead [8-9].

2 System Overall Configuration

The new design of protruding signs consists of two parts: hydraulic power generation equipment and a lighting control system. By using the theory of hydraulic power generation, the hydraulic pressure exerted by cars rolling on the ground is converted into electrical energy and stored in a battery, which provides power to the protruding signs. In an environment with low visibility, the lighting control system detects the motion state of the vehicle through the pressure sensors to control the light emission of protruding signs within the section. In contrast, in an environment with good visibility, the protruding signs will in a non-working state, and the hydraulic power generation equipment can recycle, convert, and store the pressure energy in a battery. Figure 1 shows the workflow of the novel protruding signs.

*Corresponding Author: Jinshuan Peng; E-mail: pengjinshuan@163.com
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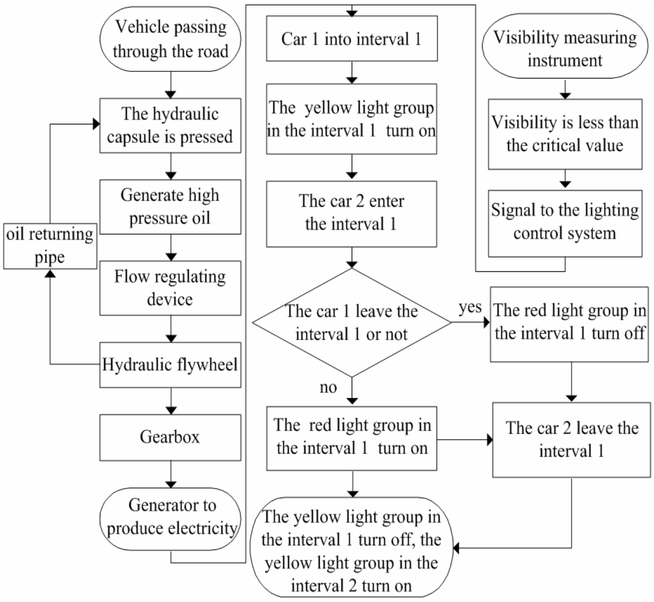

Figure 1. Flow chart of the system

3 Hydraulic Power Generation System

3.1 Composition and Working Principle

The hydraulic power generating device mainly consists of a hydraulic capsule, an outlet oil pipe, an oil returning pipe, a fixed orifice, an oil buffer chamber, a hydraulic flywheel, a speed sensor, a relay, a current proportional valve, permanent magnet generator, and other components. The flow chart of the system is shown in Figure 2. Hydraulic pressure is generated when cars roll over the hydraulic capsule, and hydraulic oil passes through a battery-driven flow control device and a fixed orifice to provide power for a constant-speed hydraulic motor, which drives the generator to produce electrical power [10-11]. The flow control device is composed of a rotational speed sensor, current proportional valve, relay, spring, connecting rod, and swash plate. In order to obtain a stable voltage, the flow control device must be designed to ensure that the generator operates at a constant speed. Figure 3 shows a visualized model of the hydraulic generator.

When the vehicle passing through the hydraulic capsule is larger than a standard car, a fixed hydraulic wheel speed sensor detects the increased rotation speed signal speed and transfers the signal to a control terminal. The control terminal compares the hydraulic rotational speed of the flywheel with an initial set value, and the difference is converted to a corresponding electric current signal to control the output current of the proportional valve. An electromagnetic relay generates a corresponding magnetic field from the current. Under the action of the magnetic field, a metal rod moves to the left, changing the inclination angle of the swash plate of the flow-regulating device to make appropriate adjustments to the flow of the swash plate. When the vehicle is smaller than a standard car, the opposite of the above actions occur. If the car is too large, oil overflow occurs through an overflow valve, thereby protecting the entire device from damaged. For this, an initial value needs to be set for the overflow valve. The workflow is shown in Figure 4.

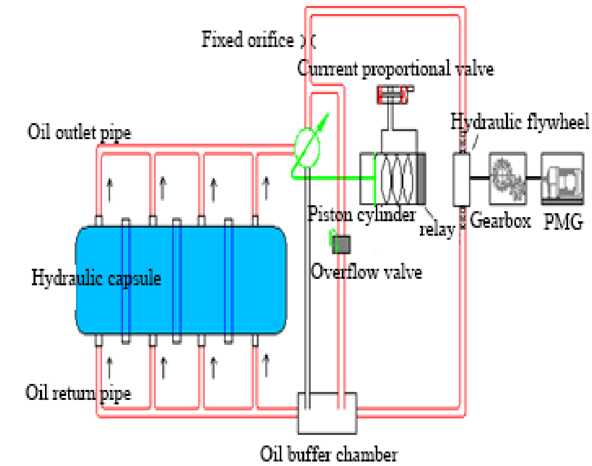

Figure 2. Schematic of hydraulic power generation equipment

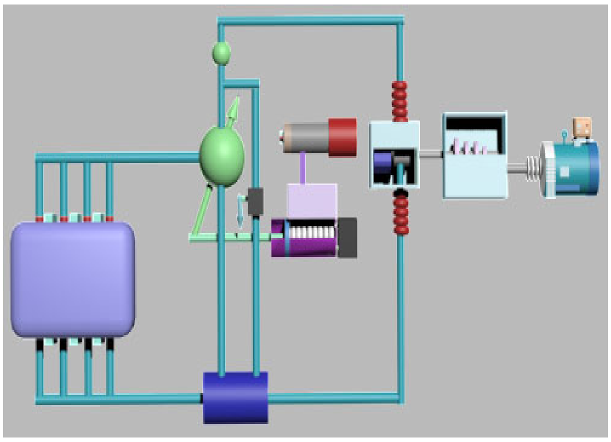

Figure 3. Visualized model of the hydraulic generator

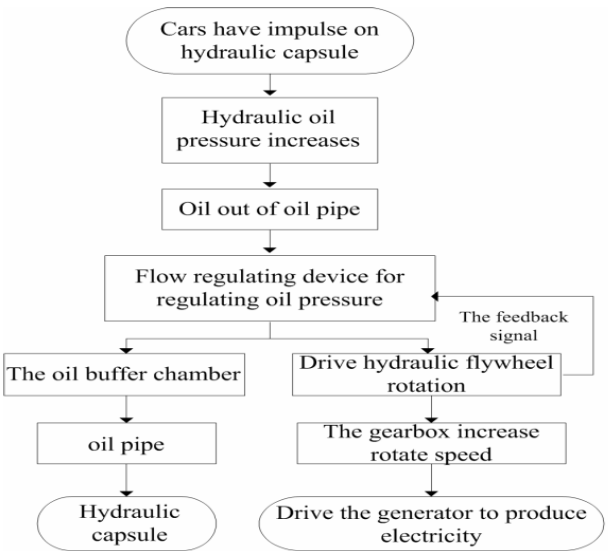

Figure 4. Workflow of the hydraulic power generator

3.2 Hydraulic Power Generation Model

3.2.1 Condition Hypothesis

(1) In a certain period, the front and rear wheel of a standard car will roll over the same hydraulic capsule chronologically;

(2) In the model, there is no leakage of liquid in the pipe; that is, the total mass of the liquid is constant;

(3) In the model, the pipe cross section of the hydraulic duct is regarded as a circle. Related parameters used in this paper are defined in Table 1.

Table 1. Definition of the parameters

Parameters	Definition	Parameters	Definition
S_0	Cross-sectional area of the hydraulic capsule out oil pipe	P_0	Setting pressure of the liquid of steady flow velocity in the feedback system
V_0	Flow velocity of liquid in the hydraulic capsule out oil pipe	S_1	Cross-sectional area of the end of the out oil pipe attached to the hydraulic flywheel
V_1	Flow velocity of the end of the out oil pipe	L_0	Length of liquid in hydraulic capsule out oil pipe
P_1	Liquid pressure at the end of the pipe	L_1	Length of liquid under no liquid flow through the pipe
S_t	Cross-sectional area of fixed orifice	S_2	Cross-sectional area of hydraulic flywheel and oil buffer chamber
V_2	Flow velocity of the end of the hydraulic flywheel	L_2	Pipe length of the hydraulic wheel that does not flow back into the liquid

3.2.2 Establishment of the Model

When cars pass over on the road, gravity acts on the hydraulic capsule. The impulse on the hydraulic capsule can be obtained as per the impulse theorem, and the deformation energy can be calculated (unit: J):

$$F_1 T_1 = \rho_0 L_0 S_0 V_0 \tag{1}$$

where F_1 is the pressure applied by the car on the hydraulic capsule [N], T_1 is the time for which the car is in contact with the hydraulic capsule [s], and ρ_0 is the liquid density [kg/m3].

The hydraulic capsule deforms the hydraulic oil, imparting kinetic energy to it. The energy E_0 stored in the oil (unit: J) is given by:

$$E_0 = \frac{1}{2}\rho_0 L_0 S_0 v_0^2 \tag{2}$$

Oil ducts of the system are interconnected; therefore, the hydraulic oil has the same properties in the hydraulic capsule out oil pipe, tubing, and hydraulic flywheel. By the conservation of mass, the following parameters are obtained:

$$2\rho_0 L_0 S_0 = \rho_0 L_1 S_1 = \rho_0 L_2 S_2 \tag{3}$$

$$P_1 = \frac{\rho_0 L_1 S_1 dV_1 / dt}{S_1} = \rho_0 L_1 dV_1 / dt \tag{4}$$

According to the conservation of energy, the kinetic energy of the flywheel is obtained from the flow of liquid (unit: J):

$$E_0 - (P_1 S_1 \cdot 2L_0 - P_0 S_t L_1) = E_1 - \frac{1}{2}\rho_0 L_2 S_2 V_2^2 \tag{5}$$

where E_1 is the kinetic energy of the liquid flowing out of the hydraulic capsule.

By substituting the above into Equations (2)-(4), we may obtain the formula of E_1 [J]:

$$\begin{aligned} E_1 &= \rho_0 L_0 S_0 V_0^2 - (P_1 S_1 \cdot 2L_0 - P_0 S_t \cdot L_1) + \frac{1}{2}\rho_0 L_2 S_2 V_2^2 \\ &= \rho_0 L_0 S_0 (V_0^2 + V_2^2) - L_1 (2\rho_0 L_0 S_1 \frac{dV_1}{dt} - P_0 S_t) \end{aligned} \tag{6}$$

Equations (2)-(6) are applied to calculate the obtained electric energy of the storage battery E_t (J):

$$E_t = K\rho_0 L_0 S_0 (V_0^2 + V_2^2 - 4L_0 \frac{dV}{dt}) + KP_0 S_t L_1 \tag{7}$$

where K is the generation efficiency of the system.

3.2.3 Model Analysis

We apply the model for a standard car moving at a speed of 60 km/h over a length of 100 m of the hydraulic power generation device. The time T for the car to pass over the hydraulic capsule is:

$$T = \frac{100}{60/3.6} = 6s$$

Because the car is fast, the section time required for the car to pass over the adjacent two hydraulic capsules can be ignored. Therefore, the hydraulic capsule can be assumed to be subjected to a continuous gravity function. Then, the obtained electric energy of the storage battery during this period E can be calculated through the following formula:

$$E = \int_0^T E_t dt \tag{8}$$

In the normal working state, the workload of the hydraulic feedback device is very low; therefore, the power consumption of the hydraulic feedback device is very small relative to the total electric energy of the storage battery. Thus,

$$E \approx K \rho_0 L_0 S_0 (V_0^2 + V_2^2) \tag{9}$$

Multiple flywheels are connected in series to form a hydraulic flywheel group so that the flow velocity V_2 of the hydraulic oil passing through the hydraulic flywheel group with respect to the hydraulic oil flow velocity V_0 of the hydraulic capsule outlet can be ignored. That is, $V_0 >> V_2$. Thus,

$$E \approx K \rho_0 L_0 S_0 V_0^2 = \frac{K F_1^2 T_1^2}{\rho_0 L_0 S_0} \tag{10}$$

Refer to relevant information, we set parameters as follows: $\rho_0 = 900 kg/m^3$, $L_0 = 0.4m$, $S_0 = 3.14 \times 10^{-4} m^2$, $F_0 = mg = 1 \times 10^4 N$; Generation efficiency K is set to 0.6, length of each hydraulic capsule d is 0.05m. Thus,

$$T_1 = \frac{d}{100} T = 3 \times 10^{-3} s$$

$$E = \frac{K F_1^2 T_1^2}{\rho_0 L_0 S_0} = 4.78 \times 10^3 J$$

3.2.4 System Simulation

Based upon the parameters we set above, simulation model of the hydraulic power generation system is established using Matlab/Simulink (Figure 5). The relationship between the effective generating capacities of the generator with contact duration is shown in Figure 6. When the system has just started to work, due to inertia effect, the flywheel cannot rotate stably with the impact of hydraulic oil. Therefore, in the first second, the hydraulic oil shocks the flywheel, generating kinetic energy, which is mainly used to overcome the inertia; at this time, the battery does not store electric energy. With the increase of time, the kinetic energy of the hydraulic oil decreases gradually; thus, the collection of energy by the battery can be gradually reduced to zero. In the case of continuous movement of the vehicle, the relationship between the energy of the battery and the time in the next generation cycle is similar to the right side of the curve in Figure 6.

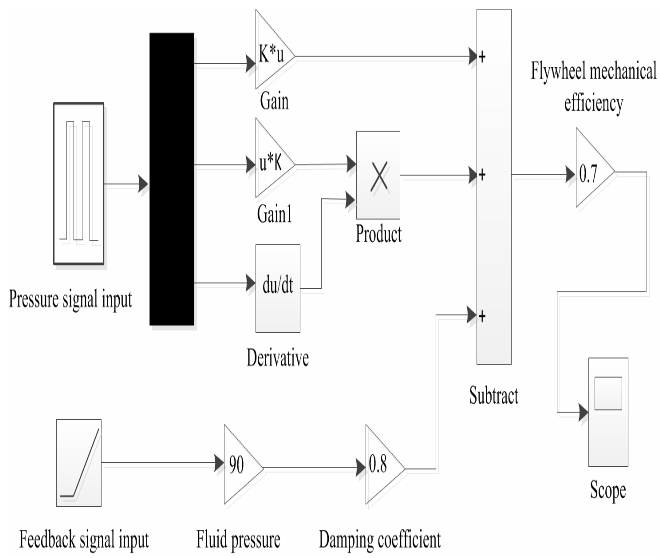

Figure 5. Simulation model of the model

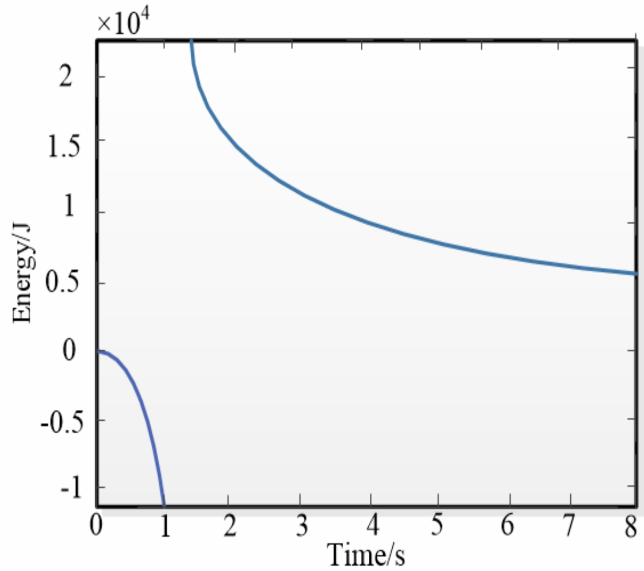

Figure 6. Relation between electric energy and contact duration

4 Protruding Signs Lighting Control System

4.1 Overall Design

According to the principle of block section, protruding signs on highways are section-controlled and use different colors of lights to remind the driver of the vehicle ahead so that the driver takes appropriate safety precautions. When the vehicle with different motion states goes into the section, pressure sensors collect the signal of the vehicle's motion states and transmit it to the lighting control system, which controls the light display status of the signs with different sections and different colors based on the signal [12-15].

4.2 Light Control Process (Take a Single Lane as the Research Object)

Scene 1: when visibility is below a certain value and each car is traveling through different sections, the relationship between the display status of the protruding signs and the location of the vehicle is as follows:

(1) When the vehicle has just entered section 1, as shown in Figure 7(a), the yellow light group on the protruding signs in section 1 is turned on, and the red light group in section 1 was in the non-working state.

(2) When the vehicle leaves section 1, as shown in Figure 7(b), the yellow light group on the protruding signs in section 1 is turned off, and the yellow light group in section 2 is turned on.

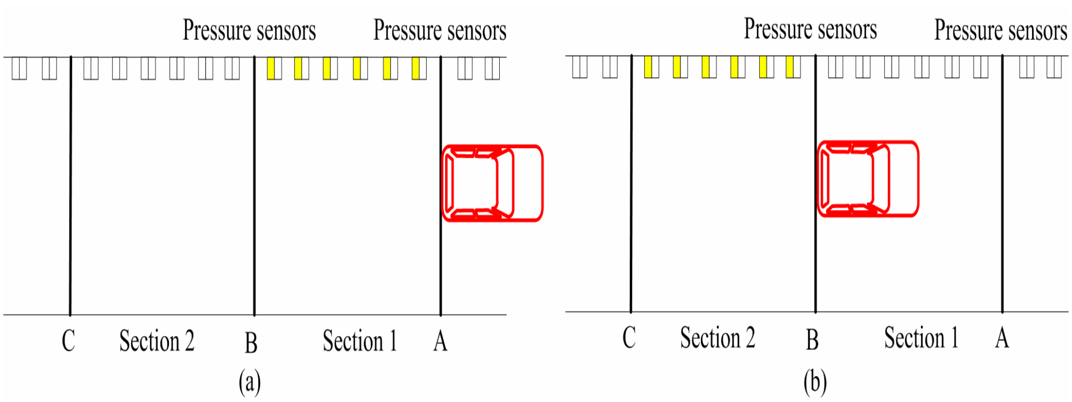

Figure 7. One car enters/leaves section 1

Scene 2: when visibility is below a certain value and two cars, one after the other, are on the road in the same section, the relationship between the display status of the protruding signs and the location of the vehicle is as follows:

(1) If the leading car has not left section 1 (as shown in Figure 8) and the trailing car is about to enter section 1 (position A), the red light group on the protruding signs in section 1 is turned on (the yellow light group is turned on when the leading car enters the section) in order to alert the driver of the trailing car to maintain a safe distance from the leading car.

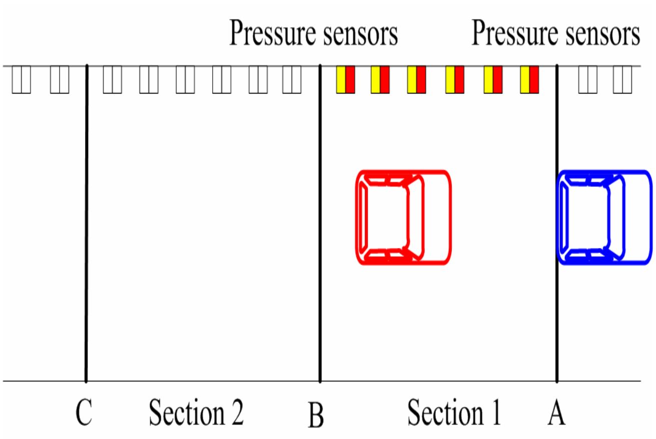

Figure 8. Two cars enter section 1

(2) When the leading car has just left section 1 (shown in Figure 9), the red light group on the protruding signs in section 1 was turned off, and the yellow light group in section 2 was turned on. Through the above light display pattern under environmental conditions of reduced visibility, the occurrence of rear-end accidents can be avoided [16-17].

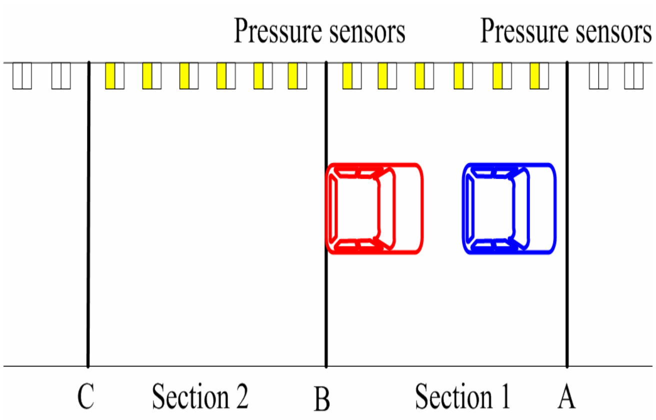

Figure 9. Leading car leaves section 1

4.3 Hardware Design

The system circuit diagram is mainly composed of power supply, a single pole, double throw (SPDT) switch, single chip microcomputer (SCM), crystal oscillator, reset circuit, light-emitting diode (LED) lamp access circuit, pressure sensor access circuit, and program download circuit. The SCM uses very large scale integrated circuit technology with data processing ability provided by a central processing unit (CPU), random access memory (RAM), read-only memory (ROM), a variety of I/O ports, and interrupt systems, timers/counters, and other functions integrated into a silicon chip constituting a small and complete microcomputer system.

The pressure sensor type we select in this study is FSR402. As the pressure increases, the resistance value of FSR402 resistive pressure sensor is gradually changed from infinity to 200 Ω. According to this feature, one end of the sensor interface is connected with the power supply, VCC, and the other end is connected to P0.0 pin and P0.1 pin of MCU. Moreover, P0.0 and P0.1 are connected to ground, GND, via a resistance of 2000Ω. When the force-sensing resistor (FSR) does not receive the pressure applied by a car, FSR is equivalent to an infinite resistance; that is, all branches of FSR are open circuits, P0.0 or P0.1 is connected to the ground, and both of them are in low level states. In contrast, when FSR receives the pressure applied by a car, the pressure resistance value is far less than that of the connecting branch of 2000 Ω resistance. The P0.0 or P0.1 port is connected to the power supply by the FSR, and each of them is in a high level. Signals of the vehicles entering or leaving the sections may be collected by judging level states of P0.0 and P0.1. According to the logical relationship between the light-emitting states of the protruding signs and vehicle motion states, programming instructions are compiled and written into the MCU, which can control the LED lamp connected with the MCU P1 port. Figure 10 shows a schematic diagram of the control system.

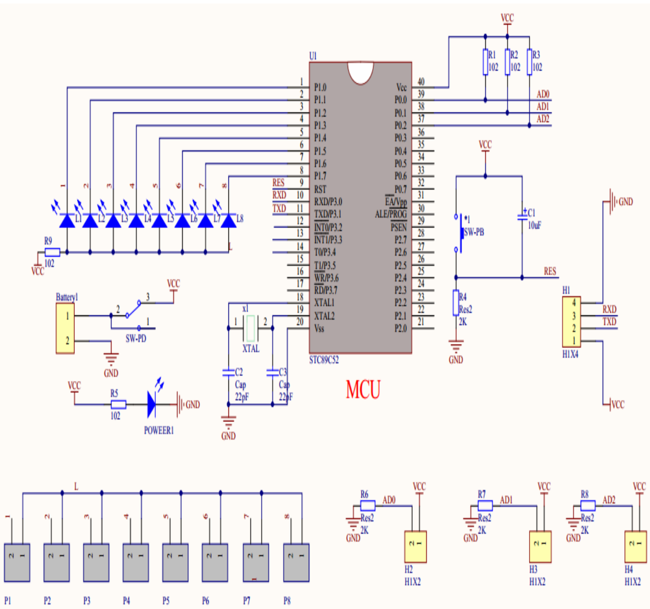

Figure 10. Schematic diagram of the light control system

4.4 Software Design

Altium Designer software is used to draw the circuit principle diagram of the lighting control system, as well as produce PCB board (as shown in Figure 11). Keil uvison2 software is used to compile the following programming instructions (fragments):

```
#include <STC12C5A60S2.H>
char count1=0, count2=0; sbit AD1=P0^0; sbit
AD2=P0^1;
void DelayUs2x(unsigned char t) { while(--t);}
void DelayMs(unsigned char t) {while(t--)
{DelayUs2x(245);DelayUs2x(245);}}
void main (void) {while (1)
{if(AD1==1) {DelayMs(10);
if(AD1==1){while(AD1==1); count1++;}}
if(count1==3) {count1=0;}
if(AD2==1) {DelayMs(10);
if(AD2==1){while(AD2==1); count2++;}}
if(count2==3) {count2=0;}
if((count1==1)&&(count2==0)) {P1=0xf5;}
if((count1==1)&&(count2==1)) {P1=0x5f;}
if((count1==2)&&(count2==0)) {P1=0xf0;}
if((count1==2)&&(count2==1)) {P1=0x55;}
if((count1==2)&&(count2==2)) {P1=0x5f;}}}
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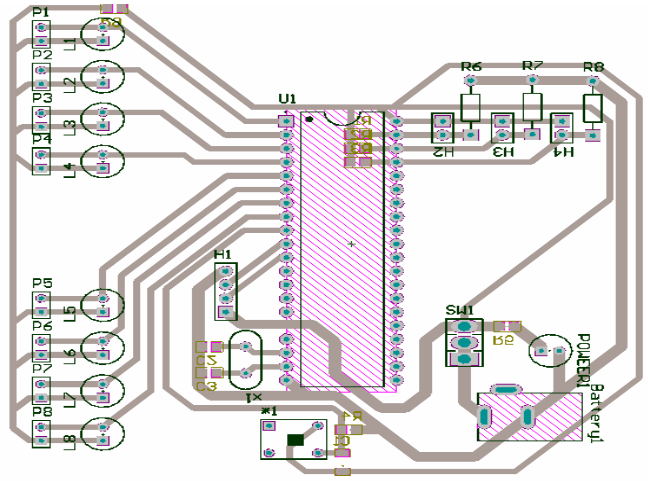

Figure 11. PCB Board

4.5 Layout Spacing and Section Length

With regard to the layout spacing of the protruding signs, the Chinese National Standard GB 5768-2009 (road traffic signs and markings) says that when used in conjunction with a common marking, the recommended layout spacing is 6-15 m. The road conditions, visibility, vehicle speed regulations, and light intensity of signs may affect the effectiveness of the protruding signs. Therefore, these factors must be comprehensively considered in determining the appropriate layout spacing [18].

The factors that affect the length of the section include the road (lane) speed limit, road alignment, driver's sight distance and reaction time characteristics. In determining the section length we should consider the impact of above factors, so as to keep the car under the induction of protruding signs to avoid colliding with the vehicle ahead by the reason of low visibility [19-21]. In view of the diversity of the actual situation, this paper simplifies some factors in the design process. Each section (the length of the section is set to 150 m) has a layout of 10 protruding signs. Based upon theoretical analysis and technical procedure mentioned above, a simple physical model (as shown in Figure 12) was constructed with the real-time description of the relationship between the light state of the protruding signs and the vehicle motion states in each section.

Figure 12. The physical model

5 Conclusion

A new type of the protruding signs was proposed using hydraulic power generation technology, the sensor technology, and the block section principle. Compared to traditional protruding signs, our new system has obvious advantages in the collection and re-use of energy, and it shows stronger induction effects due to its intelligent control mode. Future applications and developments will focus on the following four aspects:

(1) The system will be extended to multi-lane conditions in order to adapt to the actual situation of highway vehicles.

(2) The energy conversion rate of the hydraulic generator and power generation efficiency will be improved, and the stored energy will be applied to other electrical equipment on highways.

(3) When the visibility is less than a specified value, besides visual signals, other indicative signals may be enriched according to different motion states of the vehicles. For instance, a voice prompt module or liquid crystal display may be used to assist the driver better in judging the road alignment and the motion states of the vehicle ahead.

(4) Considering drivers' reaction time and other physiological properties, brightness and layout spacing of the protruding signs may be adjusted correspondingly.

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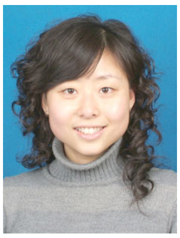
Biographies

Jinshuan Peng is a Doctor of Vehicle Operation Engineering, Professor. He received his Ph.D. in vehicle operation engineering (2012) from Chang'an university. Now he is a professor of transportation in Chongqing Jiaotong University. His current research interests include driving behavior and road traffic safety.



Lei Xu is a Doctor of Logistic Engineering. She received her Ph.D. in logistic engineering (2011) from Chang'an university. Now she is a associate professor of transportation in Chongqing Jiaotong University. Her current research interests include driving behavior and supply chain emergency management.

Zhenya Yu is a graduate major in traffic&transportations. He received his bachelor degree in Chongqing Jiaotong University in the year of 2017. He is now working in China Railway No 2 Bureau in Guiyang.

Yiming Shao is a Doctor of Vehicle Operation Engineering, now he is a professor of transportation in Chongqing Jiaotong University. His current research interests include driving behavior and road traffic safety.

Jin Xu is a Doctor of Traffic Engineering, now he is a professor of transportation in Chongqing Jiaotong University. His current research interests include driving behavior and road traffic safety.