The SMART Road[1]

A Mechantronics Demonstration Project

by

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Abstract

Motion problems are common introduction to basic high school physics. The students are taught to manipulate algebraic formulas from their basic understanding of word problems. Students with good general mathematical aptitude complete these problems and those with average ability usually have difficulty conceptualizing these problems. In order to improve student understanding and conceptualization of motion problems, this experiment attempts to use mechatronics, the integration of mechanical, electrical, control interface, and computer programming to produce a realistic demonstration of common motion problems.

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1. Curriculum Standards Correlation

This project deals with the topic of kinematics, the study of motion, and can be used during the initial instruction of the concepts of displacement, velocity, and acceleration. This in included in Standard 4 of Physical Setting, Key Idea 5:

Energy and matter interact through forces that result in changes in motion.

> 5.1 Explain and predict different patterns of motion of objects (e.g., linear and uniform circular motion, velocity and acceleration, momentum and inertia).

This project also supports the following New York State Core Standard content and process skills:

STANDARD 1—Analysis, Inquiry, and Design. Mathematical Analysis

Students will use mathematical analysis, scientific inquiry, and engineering design, as appropriate, to pose questions, seek answers, and develop solutions.

STANDARD 6—Interconnectedness: Common Themes

Students will understand the relationships and common themes that connect mathematics, science, and technology and apply the themes to these and other areas of learning.

STANDARD 7—Interdisciplinary Problem Solving

Students will apply the knowledge and thinking skills of mathematics, science, and technology to address real-life problems and make informed decisions.

2. Introduction

Would it surprise you to learn that at this very moment you are moving at a speed of more than 100,000 kilometers per hour? The explanation is simple. Since you are on the earth, it carries you along as it speeds around the sun in its orbit. Therefore you share the earth's orbital speed, which is more than 100,000 kilometers per hour. This is an example of motion, which occurs all around us. Sometimes it is more obvious and we see it in the cars on the highway, in trees that sway in the wind, and with our everyday activities. Motion is easy to recognize, but it is hard to describe. This difficulty arises because motion involves rate, a quantity divided by time. In order to better understand motion, it is best to simultaneously demonstrate it while describing it mathematically. Thus, it would be great to have an apparatus, which could be easily manipulated to not only demonstrate motion but also describe it quantitatively. In this experiment such an apparatus was designed using a simple toy car on an electric track attached to a servomotor controlled by input data from a computer. Using this simple apparatus, motion can then be studied and some fundamental questions concerning it can be answered; what exactly is motion? What is relative motion? What is speed? How does speed differ from velocity? How is acceleration different from velocity? How are distance, speed, time, and acceleration related to each

other? What is the effect of manipulating one component of motion on the others? These and other basic questions concerning motion are studied using the above apparatus.

3. Background

3.1 Theory

3.1.A Relative Motion in a Straight Line

Motion is relative. Everything moves, even things that appear to be at rest move. They move with respect to each other, or relative to the sun and stars. When you are sitting in a bus traveling at 45 kilometers per hour, you are moving with respect to the road, but not with respect to the seats, floor, or walls of the bus. Your speed with respect to the road is 45 kilometers per hour. Your speed with respect to the floor of the bus is zero. If another bus traveling 45 kilometers per hour should come towards you passing in the opposite direction, your speed with respect to that bus would be 90 kilometers per hour. This illustrates that with dealing with motion of a body, it is important to state with respect to what other body or *frame of reference* its motion is being described.

Straight Line Motion

The study of the motion of bodies that travel in a straight line is important because many complicated motions of bodies can be considered combinations of two or more straight-line motions and therefore can be analyzed in terms of straight-line motions.

3.1.B Speed and Velocity

The *speed* of a body tells us how far it travels per unit of time. The average car travels 70 kilometers per hour. This means that the automobile travels a distance of 70 kilometers for every hour that it maintains its speed. Speeds are commonly measured in kilometers per hour, meters per second, and centimeters per second. The fastest speed possible is the speed of light, 3×10^8 meters per second. Like speed, *velocity* of a body gives a description of its motion. However, unlike speed the velocity of a body tells us two things about the moving object, namely: its speed and its direction of motion. Thus the velocity of a car would be described as 70 kilometers per hour southward.

Average Speed and Instantaneous Speed

The *average speed* of a body is the distance traveled divided by the time traveled. The average speed is a very useful idea because generally on a trip we do not know the speed of travel from moment to moment because of changes in road condition, fatigue, …, etc. Thus average speed can give us a good general idea of the speed of an object over a given amount of time.

$$Average\ speed = distance\ /time \qquad or \qquad v = d\ /\ t$$

The average speed of a car tells us nothing about the speed it may have from moment to moment during a trip. A speedometer reading of a car tells us the specific speed of the car at the moment one looks at the meter. Since this reading is an instantaneous reading at any moment during a trip, we generally refer to it as the *instantaneous speed* or the speed of the body during any specific time of the journey.

3.1.C Uniform and Accelerated Motion

All the different kinds of motion, which we generally notice in the world, are of two types; *uniform motion and accelerated motion.* In uniform motion, both the speed and direction of the moving body remain the same. It is therefore described as being at constant velocity. When you are riding in your car on a straight road at a set speed you are moving in uniform motion. You cannot usually travel any great distance in a car at constant velocity. This is because of changing road condition and whether one normally has to alter the speed, direction, or both in order to get to a specific destination safely. Motion with changing velocity is called accelerated motion. Generally, accelerated motion means "speeding up". In physics accelerated motion refers to any change of velocity. This could mean either a change in direction, speed, or both speed and direction.

$$Acceleration = \Delta\ velocity/\ \Delta\ time \qquad or \qquad a = \Delta v\ /\Delta t$$

Uniformly Accelerated motion

The simplest type of accelerated motion is that of a body moving in a straight line with constant acceleration. In this case, the body will speed up or slow down at a constant rate. If the body speeds up, we say that the acceleration is positive. If it slows down, we say the acceleration is negative.

3.1.D Relating Acceleration, Speed, and Time

Acceleration is defined as the rate at which the velocity of a body changes. For a body moving in a straight line with constant acceleration, we can find the acceleration by dividing the change in the speed of the body that take place during a given time by the time. If v_o is the speed of the body at the start and v is the final speed gained by the body after being uniformly accelerated for a time t, the constant acceleration a, is

$$a = (v-v_o)/t$$

Solving for v, we have

$$v = v_o + at$$

3.1.E Average Speed and Distance Traveled During Constant Acceleration

In general, the average speed v_{avg} of a body undergoing constant acceleration for a given time t is midway between its initial speed v_o and its final speed v, and is given by:

$$v_{avg}=(v_o+v)/2 , \qquad v=v_o+at$$

$$v_{avg}=v_o+1/2at$$

$$d=v_{avg}t=(v_o+1/2at)t$$

$$d=v_o t +1/2at^2$$

All problems involving bodies moving with constant acceleration in a straight line can be solved by using either or both of the following equation relationships:

$$(a) \qquad v=v_o+at \qquad or \qquad a=(v-v_o/t)$$

$$(b) \qquad d=v_o t + 1/2at^2$$

Solving for *t* in (a) and substituting in (b) gives another useful relationship:

$$(c) \qquad v^2-v^2_o=2ad$$

3.2 Components

3.2.A Light Emitting Diodes

Diodes are semiconductor devices that allow current to flow I only one direction.[2] A typical use for diodes is rectifying alternating current to direct current. This project uses a form of diode called a **Light Emitting Diode (LED)**. These diodes give off light when there is a potential difference across the diode in the forward (conducting) direction. The LED's used for this project have an output in the infrared range.
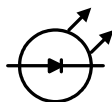

Figure 1: Schematic of LED   Figure 2: LED

3.2.B Phototransistors

Transistors are semi–conducting devices which serve two main functions; as amplifiers and as switches. All transistors have three inputs: a base, an emitter, and a collector. There are two types: NPN and PNP depending upon the types of materials used to make the transistor. The nature and operation of transistors is well documented. [3] This project uses a type of NPN transistor called a phototransistor. If the transistor receives a potential at its base that is higher than the potential at the emitter, a current flows between the collector and the emitter. The transistors used in this project are very sensitive to infrared light. Receiving light keeps the base high compare to the emitter. When the light is blocked the base goes low, turning off the current. The combination of the LED and phototransistor serves as a "photogate" which detects the

car as it passes through the gate by changing the state of a pin on the BS2 IC from high to low. A series of gates allows the motion to be monitored over time. [3]

Figure 3: Schematic of phototransistor

Figure 4: Phototransistor

3.2.C Servomotors

Motors are devices that convert electrical energy to mechanical energy. A full discussion of the operation of motors is available at several sources [4]. A servomotor is an excellent example of mechatronics, incorporating all the major fields in one device. It is a motor modified so that the amount and direction of its motion can be controlled. The addition of a gearbox (mechanical), motor and potentiometer (electro-mechanical), Control circuitry (electrical), and a control wire allows the microcontroller to access the motor (control interface and computing elements). The servomotor used in this project is controlled by the Basic Stamp circuit, which sends out a command in PBasic, PULSOUT, to have the motor shaft rotate a set amount in a specific direction.
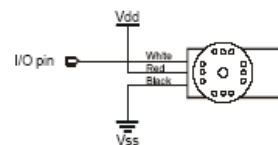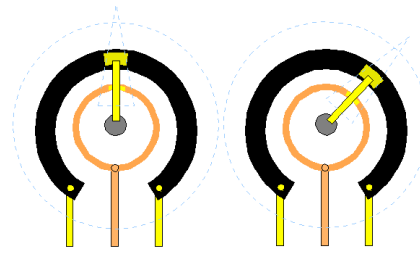

Figure 5: Servo Motor

Figure 6: Schematic of servomotor

3.2.D Potentiometer

A potentiometer is a variable resistor. By adjusting the position of a contact, the resistance between the contact and a terminal is changed. There are several types, including linear, rotary, and digital. In the diagram below [5], as the contact c is rotated clockwise, the resistance between A and C increases while the resistance between B and C decreases. [6]
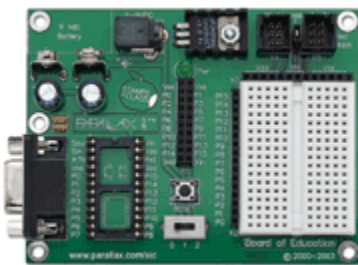
Figure 7: Rotary Potentiometer

A C B   A C B
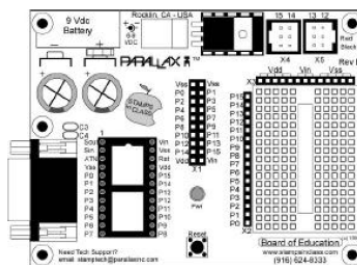
Figure 8: Schematic of potentiometer

4. Equipment List

4.1 Board of Education and Basic Stamp 2 Chip

The Basic Stamp 2 circuit and the Board of Education project board are the microcontroller used for this project. The Basic Stamp is a special purpose mini computer that contains a mircocontroller chip and a small amount of memory to hold interpreters and programs. The BOE provides regulated +5 volts (V_{dd}) and ground (V_{ss}) as well as connections to the 16 pins of the Basic Stamp IC. There is a small breadboard for circuitry and a DB9 connector for programming the BS2 IC and for serial communications while programs are running. Using a programming language, PBasic, the Stamp can be programmed to perform a variety of operations.

(a)   (b)   (c)

Figure 9: Board of Education (a), Board of Education schematic (b), and Basic Stamp 2 (c)

4.2 Project Design

This project is designed to monitor the motion of a car on a road. The program asks for three distances to be entered and then times the car as it passes through the photogates. The program then calculates the velocity for three intervals of time.

A second program allows for the input of a distance, an initial speed and a speed limit. The microcontroller then monitors the speed of the car as above, compares the speed to the "speed limit", and then, using a servo motor controlled potentiometer, reduces the car's speed if necessary. Programs to test the photogate operation and set the speed are also included.

4.3 Roadway Setup

A toy "slot car" roadway operated by four D- cell batteries forms the set up for this project. The speed control for the cars consists of a linear potentiometer, which determines the potential across the car's electric motor, and thus the car's speed. Four LED/phototransistor sets were installed along the guardrails on one portion of the roadway. The LED's are powered by the BOE's power supply and the phototransistors are connected to four input pins of the BS2. The speed control was replaced with a rotary potentiometer of similar value (20 Ohms). The shaft of the potentiometer was then connected to a servomotor to control its position and thus the speed of the car.
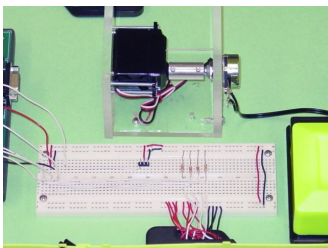

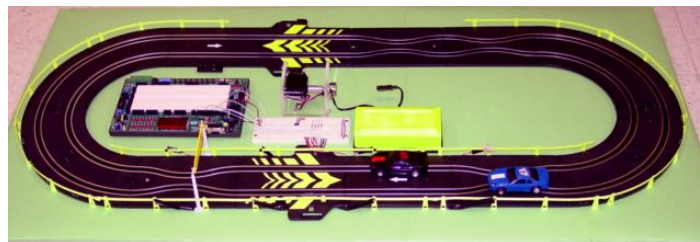Figure 11: Close up of servo motor

Figure 12: Complete roadway

4.4 Circuit Design

The LED was connected to +5Volts through a 220-Ohm resistor to limit the current flowing through it.

The phototransistor was connected with the collector connected to +5 V and the emitter connected to ground through a 4.7 kilo-ohm resistor and also to an input pin on the BS2.
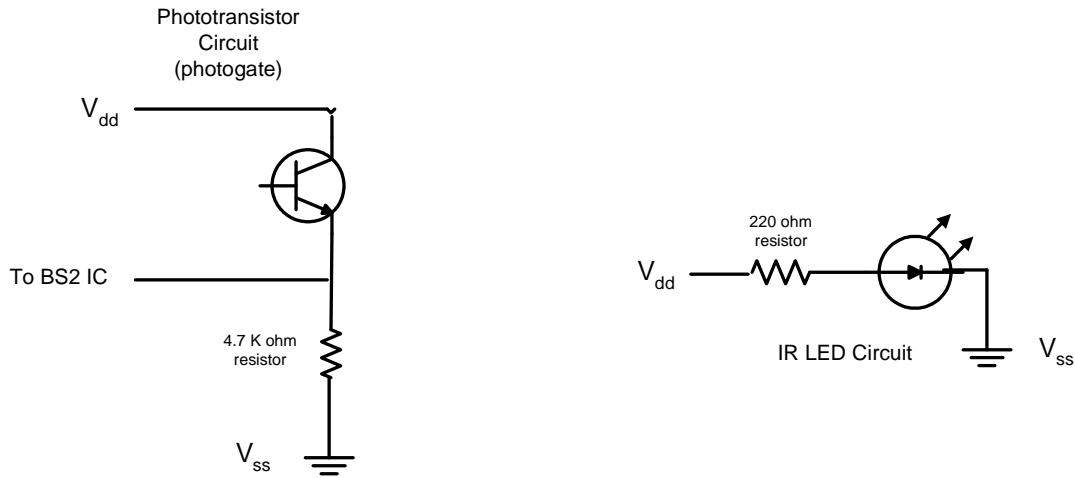
Figure 13: Schematic of phototransistor and LED photogate

The servomotor was connected to +5 V, ground, and its control wire to an output pin on the BS2.
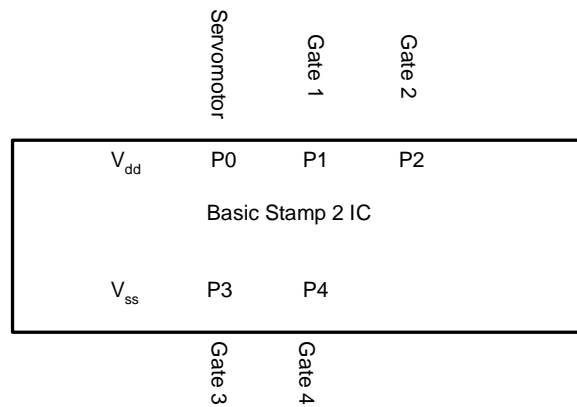

Figure 14: Basic Stamp 2 block diagram

4.5 Program Logic

4.5.A Motion Analysis Program

This program uses four photogates. The program checks the status of the first gate, looping until it detects a "0" or blocked state. It then branches to a For…Next routine that checks the status of the second gate and increments a variable. When gate two goes to zero, indicating that the car has reached there, the value of the variable is stored and the program branches to another counting routine. This process repeats, giving times for gates 1 to 2, 2 to 3, and 3 to 4. The times are then converted to seconds and displayed. The three times and distances are then used to calculate and display three velocities.

4.5.B Speed Control Program

In this program the velocity of the car is calculated as in the first program. This velocity is compared to a speed limit using an IF…Then statement. If the value is below the limit, the program loops back to the beginning and continues to monitor the velocity each time around the track. If the value is above the limit, the program branches to a subroutine that uses the PULSOUT command to rotate the servomotor (and potentiometer), reducing the speed of the car. The program then loops to the top and continues checking the velocity each time around, reducing it as necessary.

5. Experimental Procedure

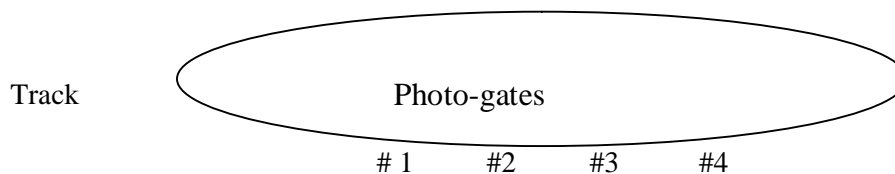Study of Motion – Distance, Time, Velocity, and Acceleration

Figure 11: Diagram of the racetrack and the position of the photo-gates

Goals:

1. Experimental determination of velocities
2. Demonstrate relative velocity by comparing the speed for each part of the track

5.1 Velocity Determination:

1. Connect the BS2 to a computer through a DB-9 serial cable.
2. Before using the track, the photo-gates should be tested by running the "Photogate tester" program. The screen will display the state of each gate. Block each gate, in turn, and verify that the state changes from "1" to "0".
3. Now measure distances between photo-gates number 1and 2, 2 and 3, and 3 and 4.
4. Run the "Set Speed" program and enter a number between 600 and 800. This gives the car an initial speed
5. Now run the "Motion analysis" program.
6. Input distance measurements as D1, D2, and D3
7. Run program. The average speed for each segment is displayed.
8. Use the speeds to determine the acceleration of the car as it moves through the four gates.

Discussion: Check the PBasic program by calculating the velocities yourself. Is the program accurate? Can you explain any discrepancies?

5.2 Velocity Control-A Smart Highway

1. Connect the BS2 to a computer through a DB-9 serial cable.
2. Test the photo-gates as above.
3. Measure the distance between gates 2 and 4.
4. Run the program " Smart Road"
5. Input the distance, an initial speed, and a speed limit as indicated.
6. The display will show the inputs and the speed of the car. Each time around the track watch the servomotor and see if it adjusts the car's speed.

Discussion: Try different initial values for the input variables. Does the set up act as you expected? Are the results consistent? Do the calculations yourselves and check the program's results.

6. Results

A slot car roadway was set up with four photo-gates and detectors aligned along the railings. These were able to detect the motion of the passing toy car. The time between detectors for the car's motion was then determined from the intervals between the gate blockings and then used to calculate the speed of the car between photo-gates. A program to control the speed of the car was made based on a set speed limit for the car's motion. This was able to reduce the speed of the car at a predetermine rate for a set duration of time. A program to calculate the velocity and acceleration of the car as is passed through the four photogates was. However, because the Basic Stamp 2 IC can only do integer math, the acceleration could not be accurately, and thus the acceleration portion has not be implemented at this time. The students must calculate the acceleration based on the computed velocities.

7. Conclusions

This racetrack apparatus can be used to demonstrate to student's changes in velocity and acceleration at various distances. Students can input various input speed and see how the system reacts based on these inputs. This demonstrates several aspects of mechatronics. A DC motor is modified to include a mechanical component (gears) and electronic components. Its speed is then controlled by a microcontroller connected to sensors that monitor the environment. A computer is interfaced with the mircocontroller to both program the microcontroller and to display system outputs and monitor system performance.

8. Suggested Projects

1. Additional Activities with Smart Road Track

    a. Incorporate traffic signals using LEDs

    b. Use RCTIME command to measure actual times

    c. Add RF transceivers and IR detectors to program a follower car

2. Real World Applications

    a. Smart speed control system: Design a self -contained to automatically monitor and control the speed of cars.

    b. Accident avoidance system: Design a system that automatically slows car whenever a car is closer than a set distance from another vehicle.

9. Projects Cost Analysis

1. Construction materials:

a. Slot Car Track (ToysRUs)	$ 21.00
b. Wood Base	$ 6.00
c. Screws and Brackets	$ 5.00
d. Paper covering	$ 5.00
e. Plexiglas	$ 10.00

2. Electrical Components

a. Potentiometer	$ 4.00
(rotary, 20 ohms, 3 watts)	
b. Resistors:	$ 4.00
220 ohm (4)	
(4.7Kohm) (4)	
c. Phototransistors (4)	$ 3.20
d. IR LEDs (4)	$ 3.20
e. Db9 pin connector	$ 4.00
f. Wire (approx. 10 ft)	$ 3.00
g. Board of Education (Parallax)	$ 65.00
h. Basic Stamp 2 IC	$ 49.00
i. Servo Motor	$ 12.00
TOTAL:	$ 195.00

10. Acknowledgements

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Finally, we would like to thank Parallax, Inc. for donating a "Homework Board", and a "What's a Microcontroller" text and parts kit to each teacher involved in the project and Polytechnic University and the National Science Foundation for making this program possible.

11. Appendix A: PBasic Programs

<u>11.A Motion Analysis Program</u>

```
'{$STAMP BS2}
'{$PBASIC 2.0}
'MOTION ANALYSIS PROGRAM
                        'DECLARATIONS: defines variables used in program
Detect1 VAR Bit
Detect2 VAR Bit
Detect3 VAR Bit
detect4 VAR Bit
b VAR Byte
tb1 VAR Byte
tb2 VAR Byte
c VAR Byte
c1 VAR Byte
c2 VAR Byte
a VAR Byte
a1 VAR Byte
a2 VAR Byte
r7 VAR Byte
x1  VAR Byte
x2  VAR Byte
r1 VAR Byte
```

```
r2 VAR Byte
r3 VAR Byte
r4 VAR Byte
r5 VAR Byte
r6 VAR Byte
y VAR Byte
vel VAR Byte
v2 VAR Byte
vel2 VAR Byte
v22 VAR Byte
vel3 VAR Byte
v32 VAR Byte


Start:                        'MAIN PROGRAM
LOOP :                        ' Check Gate 1 for car
Gate1:
Detect1 = IN5
IF Detect1 = 0 THEN Count1      'Waits for car to enter gate 1
PAUSE 20
GOTO LOOP


'Timing loop
COUNT1:                       ' Counts the time between gates 1 and 2
FOR y = 1 TO 65000
 Detect2 = IN8
IF Detect2 = 0 THEN Count2
PAUSE 10
y= y+1
NEXT
Count2:                       ' Time between gates 2 and 3
FOR b = 1 TO 65000
 Detect3 = IN15
IF Detect3 = 0 THEN Count3
PAUSE 10
```

```
b= b+1
NEXT
Count3:                         ' Time between gates 3 and 4
FOR c = 1 TO 65000
Detect4 = IN1
IF Detect4 = 0 THEN CalcTime
PAUSE 10
c= c+1
NEXT
CalcTime:                       ' Calculates three time intervals using Modulus to get three digits x1=y/145
r1=y//145
x2=100*r1/145
tb1=b/145
r2=b//145
tb2=100*r2/145
c1=y/145
r3=y//145
c2=100*r3/145
CalcSpeed:                      ' Calculates three speeds, using modulus command to get three digits
vel = 19*145/y
r4 = 19*145//y
v2 = 10*r3/y
vel2 = 19*145/b
r5 = 19*145//b
v22 = 10*r5/b
vel3 = 16*145/c
r6 = 16*145//c
v32 = 10*r6/c
'DISPLAYS VALUES FOR EACH TIME AROUND ROADWAY
DEBUG "Counts1=   ", DEC y, "   counts2 =   ", DEC b,"   Counts3=", DEC c,CR
DEBUG "D1 = 19 cm",  "  T1 =   ", DEC x1,".", DEC x2, "sec", CR
DEBUG "D2 = 19 cm",  "  T2 = ", DEC tb1,".", DEC tb2, "sec", CR
DEBUG "D3 = 16 cm",  "  T3 = ", DEC c1,".", DEC c2, "sec", CR
DEBUG "V1 = ", DEC vel, ".", DEC v2, "cm/s"  ,CR
```

```
DEBUG "v2 =  ",DEC vel2, ".", DEC v22, "cm/s", CR

DEBUG "v3 =  ",DEC vel3, ".", DEC v32, "cm/s", CR,CR

DEBUG "acc =    ", DEC a2, ".", DEC a1, "cm/s/s",CR,CR

'PAUSE 2000

GOTO LOOP

END
```

11.B SMART Road Program

```
'{$STAMP BS2}

'{$PBASIC 2.5}

 'SMART ROAD PROGRAM

                        'DECLARATIONS: defines variables used in program

Detect1 VAR Bit

Detect2 VAR Bit

x1  VAR Word

x2  VAR Word

r1 VAR Byte

r2 VAR Byte

r3 VAR Byte

x3 VAR Word

y VAR Word

vel VAR Word

v2 VAR Word

w VAR Nib

z VAR Word

speed VAR Word

Start:                              'MAIN PROGRAM

iter VAR Byte

w = 0

z = 0

'Debugin asks user to provide initial values

DEBUG " Please enter Distance.", CR

DEBUGIN DEC D1

DEBUG ? D1

DEBUG "please  enter the speed(25 - 45).",CR           'Asks for initial speed
```

```
DEBUGIN DEC speed
DEBUG ? speed
DEBUG " Please enter speed limit (35 - 60).",CR          'Asks for speed limit
DEBUGIN DEC  limit
 DEBUG ? limit
 speed  = speed * 20
 DEBUG ? speed
PULSOUT 0, speed                          ' Sets speed
LOOP1 :                                   ' Checks gate 1 for car
Gate1:
Detect1 = IN2
IF Detect1 = 0 THEN Count1
PAUSE 20
GOTO LOOP1
'Timing loop
COUNT1:
FOR y = 1 TO 65000               'Time for car to go from gate 1 to gate 2
 Detect2 = IN4
IF Detect2 = 0 THEN CalcTime
PAUSE 10
y= y+1
NEXT
CalcTime:                                 ' Calculates time between gates 1 and 2
x1=y/145
r1=y//145
x2=100*r1/145
x3=100*r1//145
CalcSpeed:                                ' Calculates velocity between gates 1 and 2
vel = D1*145/y
r3 = D1*145//y
v2 = 10*r3/y
'DISPLAYS VALUES
DEBUG "Counts =   ", DEC y,  CR
DEBUG "Distance =    cm", DEC D1,     " Time =   ", DEC x1,".", DEC x2, "sec", CR
```

```
DEBUG "Velocity = ", DEC vel, ".", DEC v2, "cm/s"  ,CR,CR
IF y < 38 THEN decrease          ' Checks to see if speed is above limit
z=z+1                            ' Runs ten laps, then starts program over
IF z=10 THEN start
GOTO  LOOP1
decrease:                        ' Lowers speed
w = w + 1
PULSOUT 12, speed - (w*20)       ' Pulses servo motor to lower speed
PAUSE 1000
GOTO LOOP1
END
```

11.C Photogate test program

```
'{$STAMP BS2}
'{$PBASIC 2.0}
                    'DECLARATIONS: defines variables used in program

IR_detect1 VAR Bit
IR_detect2 VAR Bit
IR_detect3 VAR Bit
IR_detect4 VAR Bit
x1     VAR Byte
LOOP:
PAUSE 50
Gate1:
IR_detect1 = IN1
PAUSE 20
Gate2:
IR_detect2 = IN2
PAUSE 20
Gate3:
IR_detect3 = IN3
PAUSE 20
Gate4:
```

IR_detect4 = IN4

'Display state of gates (1 = unblocked; 0 = blocked)

DEBUG HOME, "Gate1   ", BIN IR_Detect1, "   Gate2   ", BIN IR_Detect2, "   Gate3   ", BIN IR_Detect3,"   Gate4   ", BIN IR_Detect4

GOTO LOOP

11.D Set Speed program

```
'{$STAMP BS2}
'{$PBASIC 2.5}

                        'DECLARATIONS: defines variable used in program
x VAR Word
OUTPUT 0                 ' Sets pin 0 as output
FOR  x = 1 TO 100
PULSOUT 0, 800           'rotates servo motor to set speed
PAUSE 10
NEXT
END
```

12. References

 [1]   Online: http://www.howstuffworks.com/led.htm, web site on diodes.

[2]   Online: http://www.electronics-tutorials.com/basics/transistors.htm, web site with transistor tutorial.

[3]   Online: http://www.micromo.com/library/docs/notes&tutorials/MCT.pdf, explains theory of motor operation.

[4]   Online: http://www.eatel.net/~amptech/elecdisc/potentio.htm, web site on potentiometers with diagrams.

[5]   Online: http://www.thecyberiad.net/Images/Potentiometer.jpg, potentiometer diagram.

[6]   Online: http://www.parallax.com/html_pages/edu/shop/boe_fullkit.asp, web site for Stamp materials and diagrams.

[7]   Online: http://www.tcaep.co.uk/science/symbols/elect.htm, Schematic symbols and diagrams.

[8]   Taffel, A. *Physics, Its Method and Meanings*. Prentice Hall, Englewood Cliffs, NJ.(1992).