Title
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Global Warning Signal Integration as a Tool for Work Zone Safety and Efficiency

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ABSTRACT

A work zone (WZ) is visually confusing, and while no WZ looks like any other, they all share a common feature. All of them present an array of flashing light signals which are especially prominent at night. These signals ignite with no relation to one another. Each, by itself, is designed to be highly visible, attention-getting and salient, being positioned high on vehicles, along barriers and on other equipment. In this two-part study we investigated ways to make the overall visual appearance of a WZ more compatible with the needs of passers-by. The first part consisted of psychophysical tests to assess the effect on lane keeping ability when the WZ signals were ignited synchronously, as opposed to asynchronous ignition. The second part investigated the feasibility of using wireless communication to coordinate light ignition times and to create coherence among the warning lights. The feasibility of triggering the signals in sequence to create a visible pattern that is instructive to the passing driver was also considered.

Key Words: Work Zone, Work Zone Conspicuity, Work Zone Lighting

EXECUTIVE SUMMARY

In the first phase of our study, we tested lane-keeping ability under three WZ lighting conditions: no WZ (**none**), asynchronous ignition (**asynch**), and synchronous ignition (**synch**). Synchronously flashing lights give more information as to a work zone's boundary (which in our experiments is also the roadway's right-side boundary) because the entire work zone boundary is exposed and outlined for a brief period each time the lights flash on. In contrast, the work zone boundary is not revealed in its entirety at any time in the asynchronous case, where each light is flashing independently of the others. Hence, synchronously flashing lights should translate into better driving performance, as measured by the mean deviation from the desired vehicle trajectory near the roadway's right-side boundary. We found, consistent with this hypothesis, that the deviation between the actual and desired vehicle trajectory, under conditions where synchronously flashing lights delineate the work zone, is less than when the lights flash asynchronously, while the deviation is least when no work zone is present. Moreover, we were able to demonstrate this hierarchy in all three classes of experiments we conducted, (simulated) daytime, nighttime, and extended nighttime. We were unable, within the scope of these experiments, to demonstrate statistical significance of these results, and thus a confirmation of our hypothesis will require additional research. Based on the promising results we did achieve, however, we anticipate that our goal can be reached, and our hypothesis verified, given a more realistic simulation.

In the second phase of our study, a simple (and therefore relatively inexpensive and robust) system for firing work zone lights in synchrony was demonstrated. If questions of FCC compliance are laid aside, the system could be adopted as it stands with only minor changes. But even given the need to comply with FCC regulations to avoid interference, the solutions could well be very straightforward.

I. INTRODUCTION

A work zone (WZ) is visually confusing, and while no WZ looks like any other, they all share a common feature. All of them present an array of flashing light signals which are especially prominent at night. These signals ignite with no relation to one another. Each, by itself, is designed to be highly visible, attention-getting and salient, being positioned high on vehicles, along barriers and on other equipment. Our idea is that the overall visual appearance of a WZ could be made much more compatible with the needs of passers-by, if the signaling were coordinated in time. The project was undertaken in two phases:

A. Using standard laboratory psychophysical procedures, we tested the conjecture that a coordinated signal pattern is less confusing to an observer.

B. We studied the feasibility of using wireless communication to coordinate light ignition times and to create coherence among the warning lights. We also studied the feasibility of triggering the signals in sequence to create a visible pattern that is instructive to the passing driver.

We call this approach Global Visual Signal Integration (GVSI). Our hypothesis is that GVSI can lessen the cognitive demands on passing drivers enabling them to more safely and reliably negotiate the WZ.

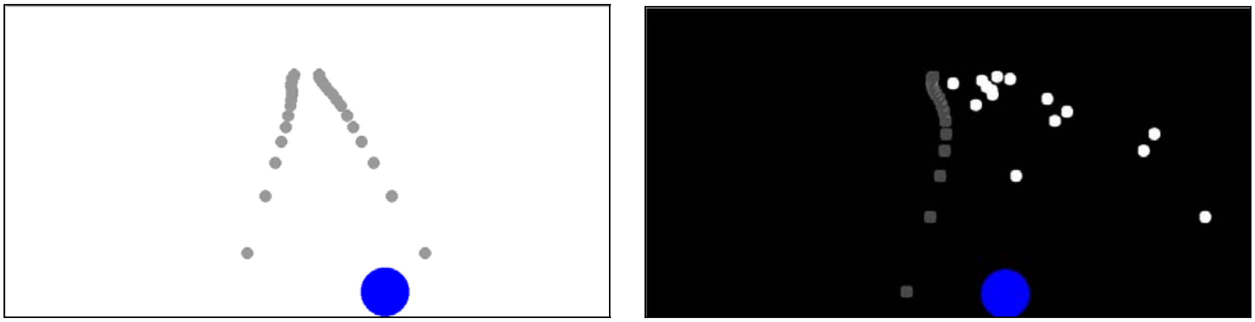
II. A. PSYCHOPHYSICAL TESTS

1. Test Methodology

Our experimental setup consisted of a real time PC-generated animation of a roadway scene as viewed by an automobile driver. The application used to generate this scene is a modified form of one used in TO 5203 ("Optimizing Comprehension of Changeable Message Signs"). It simulates the view through the front windshield of an automobile traveling along a roadway at approximately 60 mph. The road's course consists of random curves which are generated by adding together three sinusoids, according to

$$f(t) = 20\left\{\sin\left(2\pi\cdot 0.10t\right) + 2\sin\left(2\pi\cdot 0.25t\right) + 3\sin\left(2\pi\cdot 0.14t\right)\right\}.$$

This generates a random (to the observer) pattern of curves that cannot be "learned". Examples of the views presented to the observer (simulating both daytime and nighttime driving conditions) are shown in Figure 1. The observer operates a game steering wheel to keep the large ball at the bottom of the scene as far to the right in the lane as possible. A ball that is seen by the observer as blue on the computer monitor indicates that it is properly positioned; a ball that appears red indicates that it is not. A roadside construction scene is represented as in Figure 1b. The right lane boundary is obscured by the construction, and the series of small disks (that appear to the observer as white in the nighttime simulation and as orange in the daytime simulation) represent various warning lights and signals that have been erected by the construction crews. Several of these small disks, however, remain on the lane boundary. The observer's task is to keep the car as far to the right as possible, using the lane boundary markers and warning lights to guide him/her. An individual test consisted of "driving" along the road for approximately 15 minutes. At random intervals normal road conditions (no construction zone, or "none") were interrupted with a simulated construction zone, in which the "lights" blinked on and off in either an asynchronous ("asynch") or synchronous ("synch") fashion. Deviation from the desired lateral position was recorded throughout the test. Afterwards, deviations for each driving condition (no work zone, or "none", "asynch", "synch") were aggregated together for each test and the statistics for each computed.



a) Daytime Simulation b) Nighttime Simulation

Figure 1

Three college students (two females and one male), all in their early 20's and having (corrected) normal vision, participated. They are identified as TS1, TS2, and TS3.

2. Results

We tested the ability of human observers to keep a simulated automobile as close to the lane's right boundary as possible under the three different lighting conditions described previously. Afterwards, deviation statistics for each case were compiled and compared. Mean deviation (μ) from the desired path (in screen pixels) and standard error (s) were computed (assuming that deviations were approximately normally distributed.) Aggregate summary statistics for the daytime simulation over all tests are shown in Table 1. (Detailed data for all lighting conditions are included in Appendix I.) Our hypothesis is that deviations from the desired path will be least of all when no work zone is present, and that they will be smaller when synchronized warning signals are encountered than when asynchronous signals are. To test this

Table 1a: Daytime Simulation

		None	Asynch		Synch	
Subject	**mean (μ)**	**std error (s)**	**μ**	**s**	**μ**	**s**
TS1	21.7	14.3	21.7	15.5	22.0	15.8
TS2	19.1	14.7	30.2	23.6	23.4	21.2
TS3	21.9	17.1	21.3	14.7	21.3	14.6
Overall	20.9	16.4	24.3	19.7	22.2	18.9
Expected Deviation	**ref**		**>> ref**		**> ref**	

Table 1b: Test of Hypothesis—Daytime Simulation

Case	μ_{1-2}	s_{1-2}	95% Confidence Interval
Asynch - None	3.4	3.6	$-3.7 \le \mu_{1-2} \le 10.4$
Synch - None	1.3	3.5	$-5.6 \le \mu_{1-2} \le 8.2$
Asynch - Synch	2.1	3.8	$-9.5 \le \mu_{1-2} \le 5.5$

hypothesis we constructed the differences **Asynch - None, Synch - None,** and **Asynch - Synch** and their 95% confidence intervals, as shown in Tables 2. Though the differences μ_{1-2} are all positive, and thus consistent with our expectations, they are not unambiguously positive at the 95% level of confidence, as indicated in the right-most column of Table 1b.

In an effort to lend statistical significance to the trends demonstrated in the daytime condition, we next sought to reduce the visibility (or contrast) of the lane boundaries in the simulation, relative to that of the work zone lights, by use of simulated nighttime conditions. This served to increase the test subjects' reliance on the positions of the work zone lights in order to negotiate the work zone. In the first of these nighttime conditions (Figure 1b), the background color was changed to black, the regular lane boundary markings were made a darker shade of gray, and the work zone warning lights were made white. The results of this test are shown in Table 2. From Table 2b we see that μ_{1-2} experiences a shift in the right direction, towards more positive values, and that it is unambiguously positive for the first two (but less important) cases. However, for the most important case (**Asynch - Synch)**, we are still unable to demonstrate statistical significance of the result, even though the trend is in the appropriate direction.

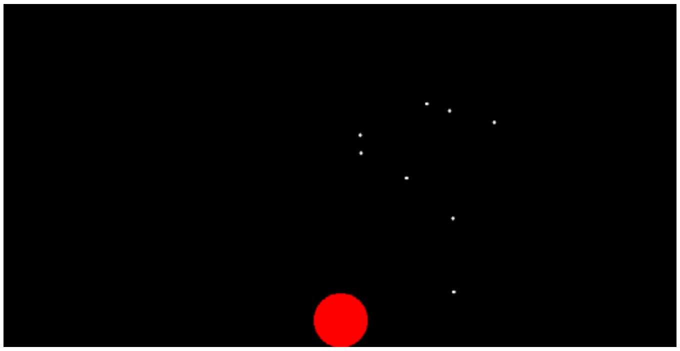
Table 2a: Nighttime Simulation

	None		Asynch		Synch	
Subject	μ	s	μ	s	μ	s
TS1	22.4	15.3	19.4	14.0	19.8	14.5
TS2	15.1	11.5	43.8	27.5	43.3	28.1
TS3	21.5	16.8	20.2	13.8	19.4	13.4
Overall	19.4	14.4	28.6	20.1	28.4	20.4
Expected Deviation	**ref**		**>> ref**		**> ref**	

Table 2b: Test of Hypothesis—Nighttime Simulation

Case	μ_{1-2}	s_{1-2}	95% Confidence Interval
Asynch - None	9.2	3.6	$2.1 \leq \mu_{1-2} \leq 16.3$
Synch - None	9.0	3.7	$1.7 \leq \mu_{1-2} \leq 16.2$
Asynch - Synch	0.2	4.2	$-8.5 \leq \mu_{1-2} \leq 8.0$

Encouraged by this result, we extended the night-time simulation to the limits that the simulation software and equipment would allow in one final attempt to show the expected result. This simulation, shown in Figure 2, eschews the left-side lane boundary altogether, reduces the size of the right-side lane boundary and work zone markers to the minimum possible (2x2 pixels), and masks the right-side lane boundary markers whenever a work zone is encountered, so that the test subject has only the work zone markers by which to navigate. Two college students took part in this test; TS2, who participated in the previous tests, and TS4, who was taking part for the first time. The results of this test are shown in Table 3. The modifications made it more difficult to maintain proper lane position, as evidenced by both greater mean deviations and standard errors. This evidently also obscured the effect we sought, however. Though the differences μ_{1-2} are all positive, none are unambiguously so at the 95% confidence level.



Night-Time Simulation

Figure 2

Table 3a: Extended Nighttime Simulation						
	None		Asynch		Synch	
Subject	μ	s	μ	s	μ	s
TS2	17.1	14.2	23.8	17.9	23.7	18.2
TS4	48.0	35.3	48.1	36.3	45.7	34.6
Overall	26.9	23.1	31.6	25.3	30.7	24.6
Expected Deviation	**ref**		**>> ref**		**> ref**	

Table 3b: Test of Hypothesis—Extended Nighttime Simulation			
Case	μ_{1-2}	s_{1-2}	**95% Confidence Interval**
Asynch - None	4.6	7.3	$-9.7 \le \mu_{1-2} \le 18.9$
Synch - None	3.8	7.2	$-10.3 \le \mu_{1-2} \le 17.9$
Asynch - Synch	0.8	7.5	$-13.9 \le \mu_{1-2} \le 15.5$

3. Discussion

We expect synchronously flashing lights to give more information as to a work zone's boundary (which is also the roadway's right-side boundary in our experiments) because the entire work zone boundary is exposed and outlined for a brief period each time the lights flash on. In contrast, the work zone boundary is not revealed in its entirety at any time in the asynchronous case, where each light is flashing independently of the others. Hence, synchronously flashing lights should translate into better driving performance, as measured by the mean deviation from the desired vehicle trajectory near the roadway's right-side boundary. The results of these experiments are encouraging, in that the results reveal a trend that is consistent with our hypothesis that the deviation under conditions where synchronously flashing lights delineate the work zone, is less than when the lights flash asynchronously, while the deviation is least when no work zone is present. Moreover, we were able to demonstrate this hierarchy in all three classes of experiments we conducted: daytime, nighttime, and extended nighttime simulated conditions.

However, we were unable, within the scope of these experiments, to demonstrate statistical significance of these results, and thus a confirmation of our hypothesis will require additional research. We had hoped to be able to confirm our hypothesis within the limited resources provided under the terms of this project, which in turn required us to employ off-the-shelf hardware and readily available free software for the tests. Because we were limited in how life-like we could make the simulations, test subjects throughout all of our experiments reported that the task of guiding the simulated vehicle along the roadway, whether in the presence of a work zone or not, was more difficult than its real-world counterpart. This gave rise to an elevated level of variability in the data, and thus explains, in part, our inability to achieve statistically significant results. The other problem with our simulation is its non-veridical nature – the present simulation contains no 3D cues and is an impoverished version of what would strike the eye in the real world setting. Based on the promising results we did achieve, however, we anticipate that our goal can be reached, and our hypothesis verified, given a more realistic simulation. Ideally, we would like to continue this research and in Section III (Concluding Remarks) describe three experiments that we believe will accomplish this.

II. B. Work Light Coordination

The goal of this portion of the project is to make (mockups of) work zone lights flash in a coherent manner. Since work zone lights typically flash in an uncoordinated manner the information presented to a driver passing by a work zone is not maximized. In fact, the incoherent flashing could be confusing in certain situations, other than to say to the passing motorist “something is there”. Coordinated flashing on the other hand could (for instance) visually outline the boundary of the work zone imparting a better sense of the situation to a driver who is quickly passing by and has only a short time to process the information. The question we faced was how to coordinate the flashing. Infrared communication between work zone lights was rejected because of the line-of-sight requirements. Even if sensitive detectors and broad beams were used, sight-lines could be blocked and optical alignment, or at least a crude version of it, becomes a requirement without omni directional emitters and receivers. A radio frequency (RF) solution seemed best. While an implementation involving wireless cards for portable computers was considered, this approach seemed to be overkill. More to the point, any solution should be robust and inexpensive if it is ever to be carried over to large-scale field deployment or adopted in production. Attaching computers to the receivers or worrying about network communication protocols did not seem like the optimal way to achieve these goals.

A much simpler approach was deemed necessary. Despite the desirability of duplex transmission (between the work zone lights) or even alternating two-way communication because of possible extensions to this work, we decided to follow a “broadcast” model. A master light or “broadcast center” would command the work zone lights to fire in synchrony, either simultaneously or in turn depending on how the “broadcast” is set. There would be no communication back from the lights to the controller. While losing some ability to directly extend this model in likely future directions (such as sequential rather than simultaneously ignition of WZ lights), the tradeoff in favor of reliability and low cost was sufficient compensation.

1. Test Methodology

Fortunately a very good solution immediately presents itself. *Remote Keyless Entry* (RKE) systems are mass produced (hence inexpensive), have a reasonable range (which can be easily extended if necessary with an RF amplifier), have a straightforward modulation or encoding scheme and already meet FCC regulations (at least until an RF amplifier is added). The primary examples of RKE are key fob transmitters for remotely locking/unlocking modern car doors and garage door openers. RKE is also used in some home security systems. Although these systems transmit at different frequencies and have slightly different ranges, they all operate on the same principles. The transmitters are (essentially) omni directional and encode or modulate their signal using *Amplitude-Shift Keying* (ASK). This is illustrated in Figure 3 for a garage door opener. ASK uses a simple type of amplitude modulation, namely a binary one where the carrier frequency is at one of two amplitudes, usually on or off. The signal in Figure 3, although still ASK, uses a slightly different kind of binary coding from that typical method.

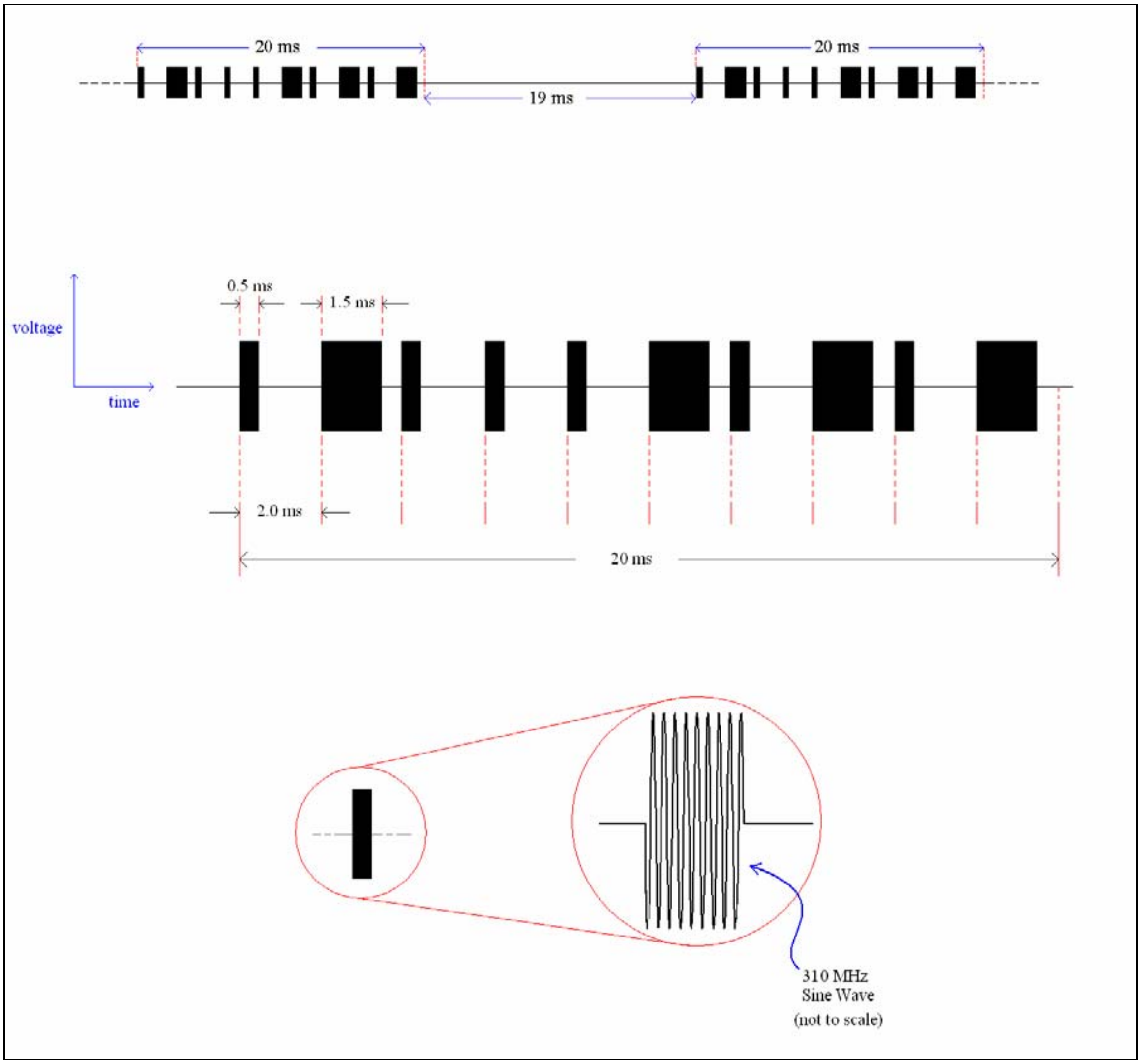


Illustration of one type of amplitude-shift keying modulation

Figure 3

The uppermost part of Figure 3 shows a typical wave train, here comprising two bursts giving the encoded signal with the repeated encodings separated by an interval of no transmission. The encoded portion of the signal lasts 20 milliseconds (ms) and is followed by an interval of no signal for (approximately) 19 ms. This pattern of encoded signal followed by silence followed by encoded signal repeats for as long as the transmit button is held down. The middle portion of Figure 3 shows the 20 ms of encoded signal. The garage door opener transmitter has a DIP switch inside comprised of ten individual single-pole, single-throw switches each of which is labeled 1 through 10. Setting each individual switch to open or closed determines the (binary) form of the code. For example, the switch settings corresponding to the middle portion of Figure 3 are as follows [O = open, C = closed]:

1	2	3	4	5	6	7	8	9	10
O	*C*	*O*	*O*	*O*	*C*	*O*	*C*	*O*	*C*.

The 20 ms block is divided up into ten sequential 2 ms blocks corresponding to the ten encoding switches. If an encoding switch is open then the two-millisecond block corresponding to that switch is filled with a 0.5 ms burst of a 310 MHz sine wave followed by 1.5 ms of zero amplitude. Conversely, a closed encoding switch results in a 1.5 ms burst of the 310 MHz sine wave followed by 0.5 ms of silence. Thus the ASK binary encoding used here is a) 0.5 ms burst followed by a 1.5 ms silence or b) 1.5 ms burst followed by a silence of 0.5 ms. The last part of Figure 3 just shows a burst being "magnified". It is not to (time) scale.

Unfortunately, for our purposes, criminals engaged in code-scanning garage door opener transmitters has led to the use of *rollover codes*. The basic encoding of the signal is similar to what was discussed above, but instead of the *same* (binary) code being sent every time the transmit button is depressed (and being set by the DIP switch), the transmitter sends a *different numeric code each time the transmit button is depressed* (while the button is being held down a given code still repeats in the wavetrain however—as shown in the first part of Figure 3). Obviously the use of rollover codes requires the synchronization of the transmitter and receiver. In the above example there are only $2^{10} = 1,024$ possible codes. When rollover codes are used, there might be 2^{30} or about a billion possibilities (or more). The numeric code for each transmit button depression is chosen pseudo-randomly and is not numerically sequential. If the receiver requires that the code wavetrain be maintained for, say, a tenth of a second before responding then running through all possible codes would take a criminal over 3 years of continuous transmission—something that obviously won't happen. Similarly, knowing the code from the last use (from scanning) does a criminal no good for the next use. There are provisions for keeping the transmitter codes and receiver codes synchronized if the transmitter is activated out of range, such as accepting any of the next 250 numeric codes in the pseudo-random sequence. While this lowers the odds of breaking in, the would-be crook still faces a very difficult challenge. This is why your key fob transmitter will never open somebody else's car even though it transmits on the same frequency as the other guy's fob; the odds are usually several billion to one.

What is good for security though, is bad for our project because it needlessly complicates matters. Fortunately, while almost all modern garage door openers use rollover codes, there are enough old systems deployed that replacement transmitters and receivers for legacy systems are still sold. This is what we used—replacement transmitters and receivers for garage door openers of twenty years ago. The project now becomes conceptually very straightforward: replace the mechanical DIP switch in the transmitter with an electronic switch (a so-called "*analog switch*"), which is in turn activated by a microcontroller. The DIP switches in the receivers remain in place though and are set to fixed codes. The microcontroller then runs through the code sequence it is programmed with. Those codes are fed to the analog switch and the transmitter then outputs those codes in sequence. The receivers control the lights. As the code for each receiver is transmitted, the receiver triggers the light. If the receivers are all set to the same code then the lights fire simultaneously. (If the receivers were set with sequential codes, then the lights would fire sequentially. While sequential ignition is of potential interest because of its attention-getting properties, we would not use the receiver codes to effect sequential ignition of WZ lighting. This would require that each individual light be placed in the WZ in accordance with its assigned code for the correct firing order to be maintained, and thus represent an extra time-consuming task to the workers setting up the WZ. Ultimately, if a sequential firing sequence is desired, a technology should be employed that allows each individual WZ light to automatically sense its position within the array so that the infrastructure can determine the firing sequence, as described in the Discussion section.)

While this line of attack is conceptually very clear and straightforward, implementing the analog switch in practice was not. We attempted to use a CMOS CD4016 (Quad Bilateral Switch) in place of the DIP switch. While this only provides a possible 4 of the 10 individual switches on the DIP package, we actually only needed two of the integrated circuit switches since we were only activating three lights for demonstration purposes. Since $2^2 = 4$ (i.e. OO, OC, CO and OO) we actually had spare capacity. The remaining 8 DIP switch positions on the transmitter were replaced with wires. They were set either open or closed. The corresponding portion of this encoding (i.e. those 8 positions) was the same on all receivers. While the CD4016 chip did, in fact, work, it didn't work *reliably*. After being unable to determine the source of the instability despite much investigation, it was decided that we would substitute discrete transistors for the analog switch. This was a much more robust solution. The schematic for this discrete switch, used in two of the DIP switch positions is shown in Figure 4.

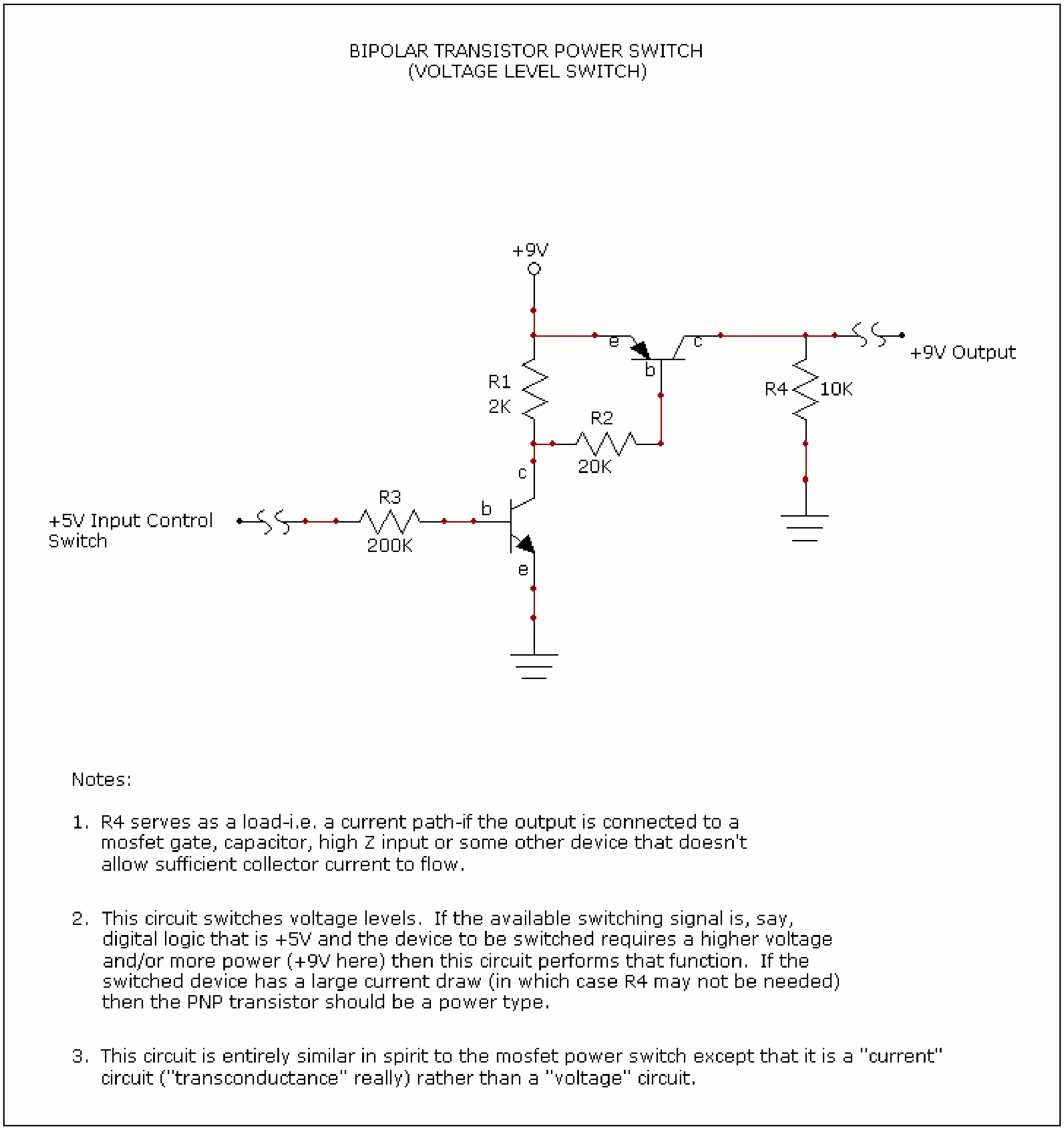
In addition to the DIP switch, the "transmit" button had to be replaced with something that could be activated electronically rather than mechanically. The transmitter we used was a Stanley 1050 that is the current replacement for the old Stanley 1027 which we had determined met our needs (no rollover codes). This transmitter's "transmit" or "send" switch connects one side of a single-pole, single-throw switch to ground (i.e. the other side of the switch) when the button is momentarily depressed. We removed this switch and left the one side connected to ground. The other side was connected to the output of the circuit in Figure 5. This allowed the transmitter to send its signal when activated by the microcontroller sending a +5V control signal to the input shown in Figure 5.

The microcontroller used was the OEM version of the *Basic Stamp 2* from *Parallax® Inc.* This microcontroller has the advantage of being programmable in a (modified) version of the BASIC language. If sub-millisecond timing is not required the programming advantage of a high-level language more than outweighs the higher cost in comparison to a controller programmed in assembly language. The schematic is shown for reference in Figure 6. The microcontroller is programmed on an ordinary PC via a serial cable attached to the DB9 connector shown in Figure 6. The input/output pins labeled P0-P15 in Figure 6 can be used to send +5V digital signals to controlling circuits like those in Figures 4 and 5. When the above-mentioned circuitry is combined, the result is Figure 7. A block diagram is shown below in Figure 8. The wires that have replaced the DIP switch positions are either left open or are closed by connecting them to +9 volts. This encodes a signal as outlined in Figure 3. The encoding in Figure 8 is,

1	2	3	4	5	6	7	8	9	10
X	*X*	*O*	*O*	*O*	*C*	*O*	*C*	*O*	*C*

where *X* is either *O* (open) or *C* (closed—i.e. connected to +9V) as determined by the control lines P2 and P4 on the microcontroller. If the output P2 has zero volts then DIP switch position 1 is open. If it has +5V then DIP switch position 1 is at +9V (closed). A similar result holds for microcontroller output P4 and DIP switch position 2. The other DIP switch positions are held fixed as shown. The microcontroller thus encodes the signal by its outputs to P2 and P4 and it causes this signal to be transmitted by driving P0 high (to +5V). The receiver type used was the Stanley Garage Door/Gate Opener Replacement Digital Receiver 201906. This type of receiver is compatible with the legacy (non-rollover) system we employed. The only difficulty in using these comes from the fact that they are normally powered by an AC transformer.

Although an AC transformer can certainly be used for initial experiments we wanted to come closer to a more field-deployable system by finding a way to run them off of DC, albeit using a higher voltage than would probably be used in the field (25 V). Fortunately, the receivers had an internal diode for rectification and we only had to connect the power with the associated polarity. The only drawback was that the negative terminal rather than the positive terminal was switched in when the receiver was activated. In other words, contrary to the usual practice, the high side was “common” and the low side was the one that was switched on when the appropriate transmission was received. As was mentioned above, each receiver had a DIP switch on which a code could be set.


BIPOLAR TRANSISTOR POWER SWITCH
(VOLTAGE LEVEL SWITCH)

Notes:

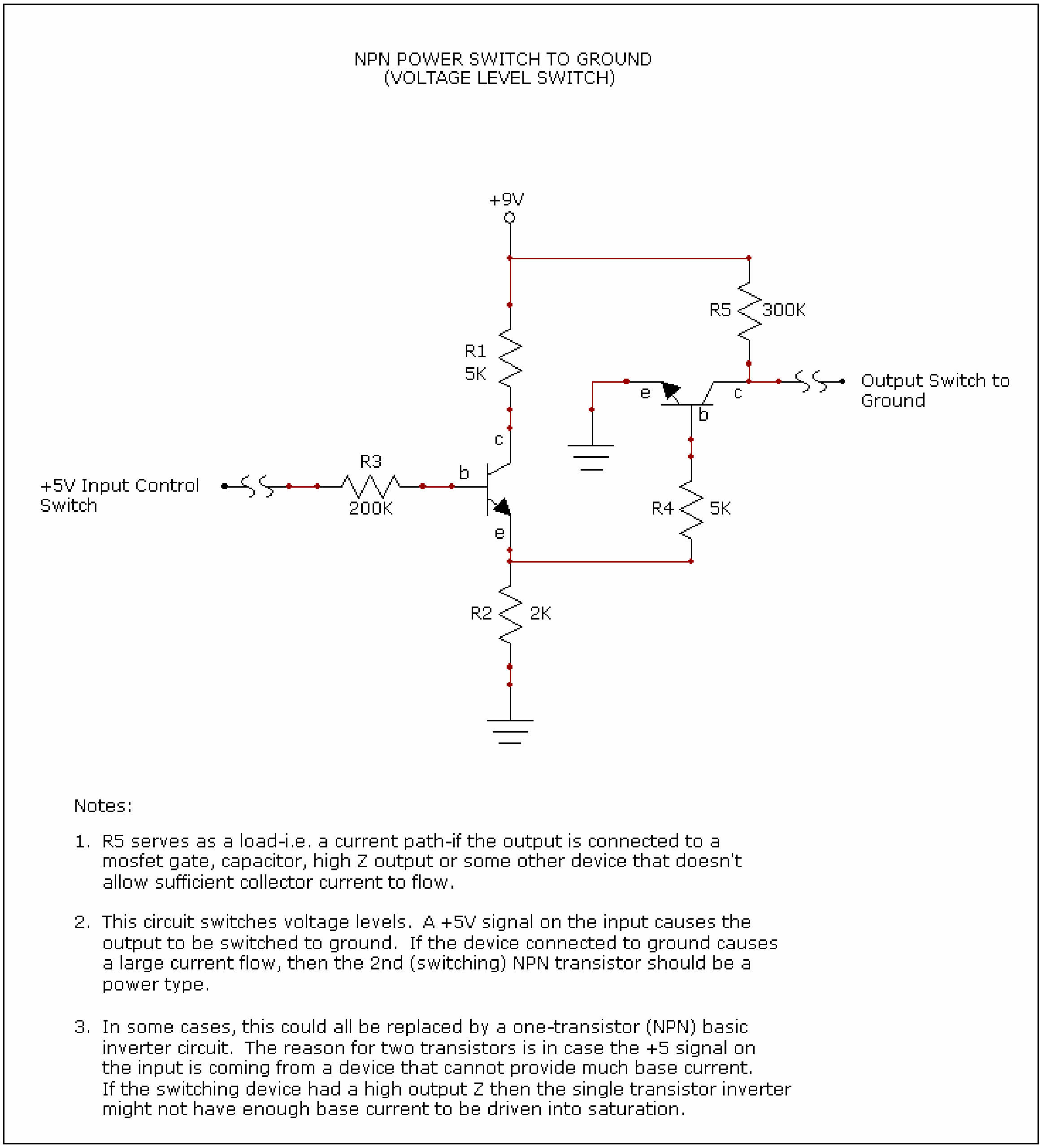
1. R4 serves as a load-i.e. a current path-if the output is connected to a mosfet gate, capacitor, high Z input or some other device that doesn't allow sufficient collector current to flow.

2. This circuit switches voltage levels. If the available switching signal is, say, digital logic that is +5V and the device to be switched requires a higher voltage and/or more power (+9V here) then this circuit performs that function. If the switched device has a large current draw (in which case R4 may not be needed) then the PNP transistor should be a power type.

3. This circuit is entirely similar in spirit to the mosfet power switch except that it is a "current" circuit ("transconductance" really) rather than a "voltage" circuit.

Schematic of the discrete replacement for the analog switch

Figure 4

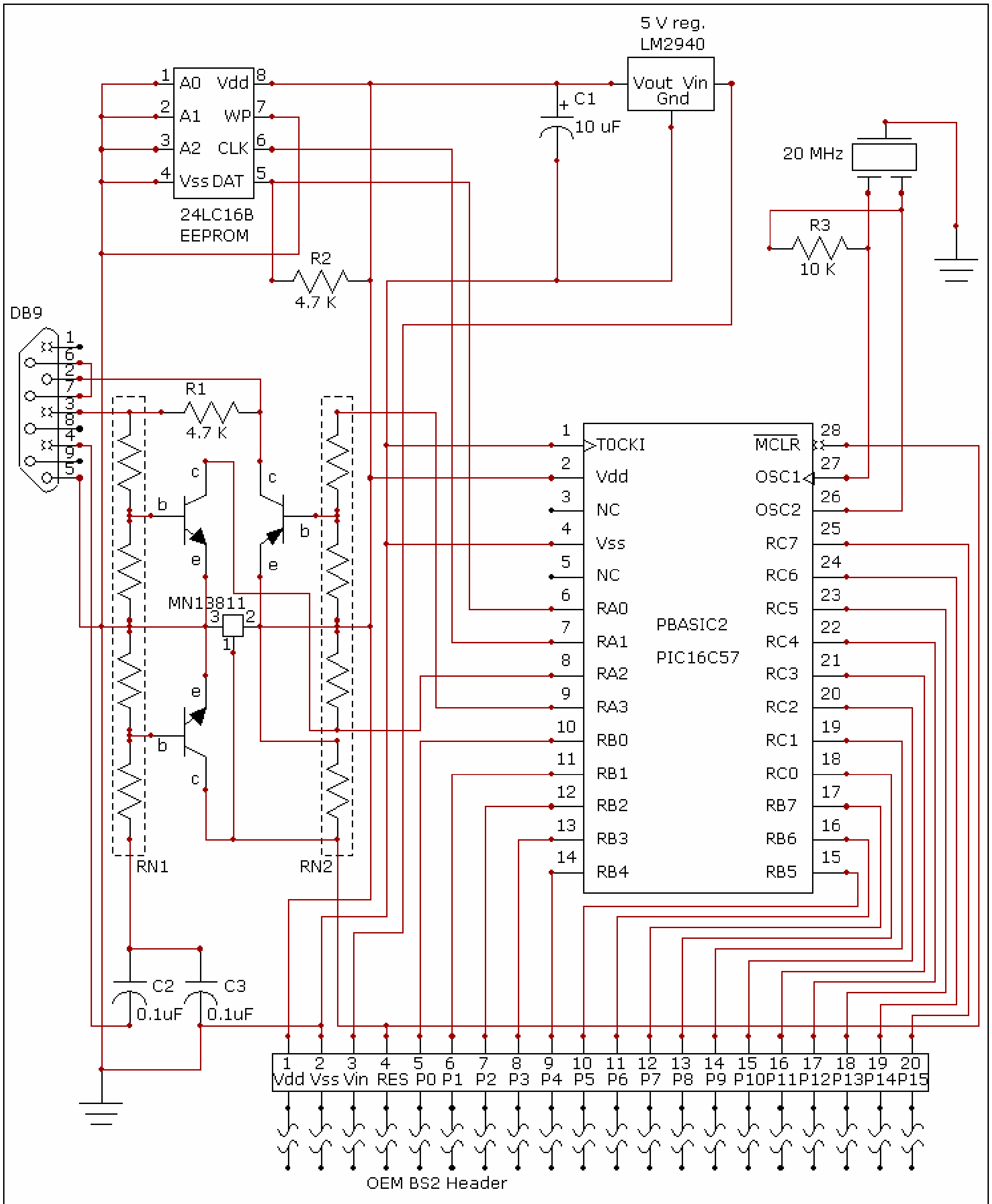


Notes:

1. R5 serves as a load-i.e. a current path-if the output is connected to a mosfet gate, capacitor, high Z output or some other device that doesn't allow sufficient collector current to flow.
2. This circuit switches voltage levels. A +5V signal on the input causes the output to be switched to ground. If the device connected to ground causes a large current flow, then the 2nd (switching) NPN transistor should be a power type.
3. In some cases, this could all be replaced by a one-transistor (NPN) basic inverter circuit. The reason for two transistors is in case the +5 signal on the input is coming from a device that cannot provide much base current. If the switching device had a high output Z then the single transistor inverter might not have enough base current to be driven into saturation.

Electronic switch replacement for the "transmit" button

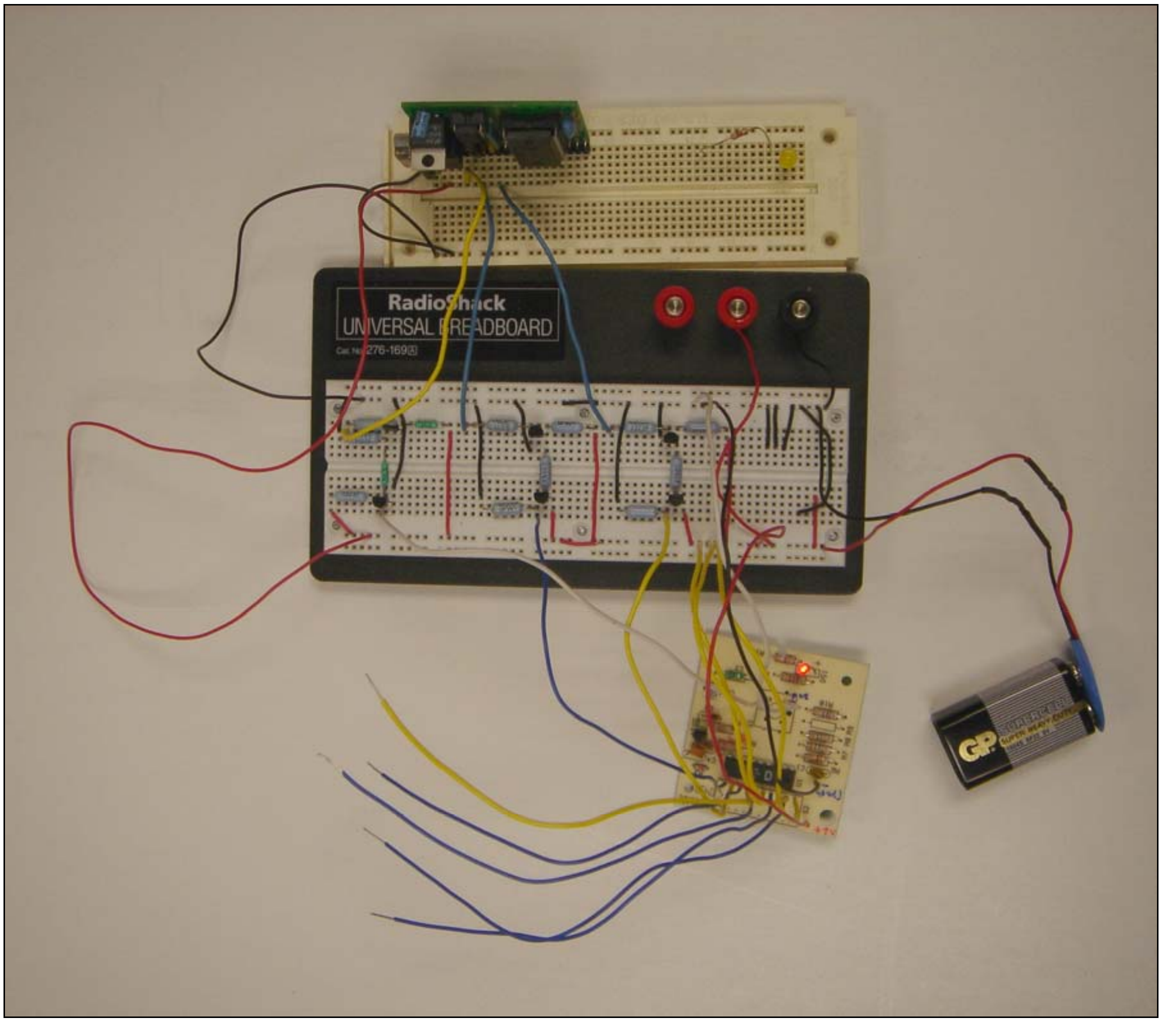
<u>Figure 5</u>



Notes:
1. NPN's are 2N3904.
2. PNP is 2N3906.
3. MN13811 is a "Reset Supervisor".
4. Each resistor in a resistor network is 10 kOhm.

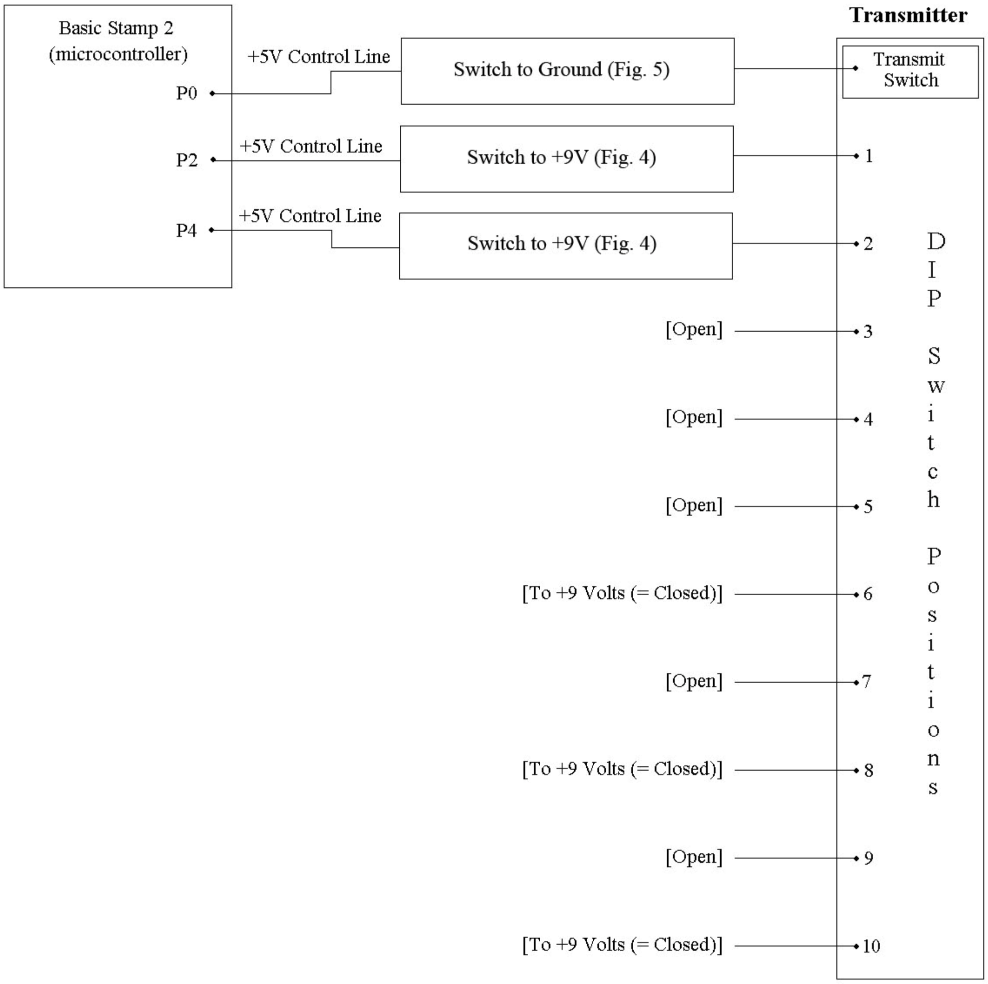
The OEM Basic Stamp 2

Figure 6



Modified transmitter. The small vertically-mounted board at the top is the microcontroller. The central breadboard contains the replacement for the "transmit" button (left portion of board) and the replacement for the two DIP switch individual switches (center & right of board). The actual transmitter (sans case) is the board at the bottom of the picture. The DIP switch has been removed and replaced with wires. The wires not connected to the central board (or anywhere else) represent the "open" positions on the DIP switch.

Figure 7



Block diagram of modified transmitter

Figure 8

2. Results

We tested three lights using a set of LED's to represent each light, and successfully ignited them in perfect synchronization. The useful range, unaided by an RF amplifier, between transmitter and receiver was about 130 feet (unobstructed). If (several) lights were arranged in a roughly circular pattern and the transmitter were coincident with one of the lights then the diameter of the circle could be 130 feet and the system would work without an RF boost. On the other hand, if the transmitter were at the center of such a circle and not coincident with one of the lights, then the effective diameter would be twice this or roughly 260 feet. Putting aside questions of FCC compliance (i.e. interference with garage doors near a work zone) and the higher voltage used by the receivers, this system *could be used as presently constituted to drive up to* $2^{10} = 1,024$ *lights.* Such a large number would seem to cover most contingencies. Furthermore, FCC compliance is a regulatory hurdle and not a technical one. One possibility would be to change the frequency that is used while keeping everything else the same.

3. Discussion

A simple (and therefore relatively inexpensive and robust) system for firing work zone lights in synchrony has been demonstrated. If questions of FCC compliance are laid aside, the system could be adopted as it stands with only minor changes. But even given the need to comply with FCC regulations to avoid interference, the solutions could well be very straightforward (such as changing the frequency used). This could also allow the range of the system discussed here to be increased by the simple expedient of connecting an off-of-the-shelf RF amplifier.

Future experiments may demonstrate that even greater benefit could be achieved by *sequential* ignition of WZ lights in order to produce the appearance of a moving light to delineate the WZ boundary. The problem of sequential firing of lights without external labeling and a priori physical arrangement of the lights requires that the system of lights be "*self-organizing*" as to their firing order. Unlike our present "broadcast" model, such a system requires two-way communication between each individual light and the "master controller". It also requires a lot more. There are three main difficulties:

- Determining signal/light location
- Duplex (or at least two-way) communication
- Pattern generation

The first problem is determining the location of each light. The simplest and most straightforward way of doing this would seem to be GPS. The problem with GPS, or at least *cheap* GPS, is positional accuracy (an expensive solution won't be adopted). Any further developments of this system along this line would require a demonstration that affordable GPS will yield sufficiently accurate position information to be able to distinguish light locations. Fortunately, only *relative* locations are needed and sufficient accuracy may be available in this case even if absolute position accuracy is poor.

If accurate positional reporting can be established then the next step would be to find a method for reporting that position to the master control. Probably the simplest method would be to use a different frequency from the one used to fire the lights. The method would work as follows. For concreteness, suppose the lights are labeled A, B, C, D and E; suppose also that they are laid out such that they would need to be fired A, B, E, D, C (repeated) to sweep a circle.

The master controller would fire them *at first* in the sequence A, B, C, D, E (or however the sequence is stored before the master knows the positions). Upon its first firing, light A would both fire and report its position. Then B would fire and report its position and so on. Because firing is sequential, reporting position to the master is sequential *and therefore only one channel is needed for this*. Since the "master" "knows" which "pupil" has just been called upon, it can now associate a position in space with a label ("A" is here. "B" is over there. …). Consequently, the ***correct*** firing order can now be computed. The only downside to this scenario is that the very first round of firings would not be in the right order. But that seems a small price to pay for keeping the scheme simple. All subsequent firings would be in the right pattern.

It has occurred to us that one needs to consider cost issues in the context of real world work zone signaling. In that context, investing each light in the zone with expensive capabilities such as GPS could be economically impractical, at least for the present. Thus we are also considering a mixed strategy wherein key signals such as Emergency Warning Lights affixed to vehicles would operate using the sequential strategy, and lesser signals (a flashing signal on a barrier) near to such key signals would be slaved to, and thus synchronous with, the nearest fixed signal. A subsequent phase of our research could point to a test of such a mixed strategy.

A second chore for any development of this system would be to do the technical work to take the GPS readings found at a given light and reduce them to a simple form and transmit them to the master control in a form it can use over the second channel. Development work could use a PC for this but a fielded system would have to use something much less expensive like a microcontroller. The final task, if these lines of development are followed, would be to find a way to have the master controller implement the correct firing order given the reported positions of each light. This consists of finding an algorithmic solution (e.g. computer code for a controller) to an essentially topological problem (deducing relative position given coordinates). The difficulty arises because the lights can be laid out in any order and in a pattern that only vaguely resembles a circle. There is no guarantee for example that the light spacing between nearest neighbors couldn't vary wildly or that the boundary formed by the lights would even be convex. Very few simplifying assumptions could be made. The most straightforward implementation would have the master controller *not* reside near one of the lights but instead be interior to the geometric pattern formed by the lights and have the master controller "know" its own GPS coordinates.

III. CONCLUDING REMARKS

The results of these experiments are encouraging, in that the results reveal a trend that, while not statistically significant, is consistent with our hypothesis that the deviation between the actual and desired vehicle trajectory, under conditions where synchronously flashing lights delineate the work zone, is less than when the lights flash asynchronously, while the deviation is least when no work zone is present. Moreover, we were able to demonstrate this hierarchy in all three classes of experiments we conducted: daytime, nighttime, and extended nighttime simulated conditions. However, we were unable, within the scope of these experiments, to demonstrate statistical significance of these results, and thus a confirmation of our hypothesis will require additional research. Based on the promising results we did achieve, however, we anticipate that our goal can be reached, and our hypothesis verified, given a more realistic simulation. Ideally, we would like to continue this research and perform the following experiments:

1. Implement a laboratory experiment involving actual discrete light sources arranged in a true three-dimensional array. Each source would be independently addressable, and separate experiments for asynchronous and synchronous firing would be performed. Moreover, this apparatus would allow us to extend our experiments so as to include an additional condition where work zone lights are flashed sequentially. In this situation, the appearance of the boundary would be enhanced by the perception of motion along the boundary. This apparent motion effect could also be elicited to possibly even greater effect by maintaining the work zone boundary lights on by default, with a sequential temporary extinguishing of lights. Finally, synchronous flashing could be combined with sequential extinguishing to provide the best features of both paradigms.
2. Devise additional computer simulations which are enhanced by use of a stereoscopic display and associated 3D goggles. This would allow greater fidelity with the actual road application, as well as greater flexibility in developing the simulation. The experiments described in this report would be repeated using this enhanced simulation.
3. A follow-up to our demonstration of the feasibility of using wireless technology to enable physically separate lights fire synchronously. In a new demonstration, we would devise means by which separate lights can be made to fire sequentially, as described above, also using wireless technology and incorporating position sensing, possibly by use of GPS technology. This would allow workers to place any individual WZ light without regard to its location relative to the other WZ lights, an easier and less time-consuming task than having to place lights physically in sequence according to their individual codes in order to achieve sequential ignition (see previous Discussion section).

The proposed extension of research from this project, as described above, is of significant importance for work zone safety. If one can enhance the signature of a work zone by coordinating warning lights therein, and if that contributes to driver accuracy and lane-keeping while passing by the work zone, there should be a meaningful reduction of adverse events such as collisions and work zone personnel should benefit for increased safety. The promise of these potential achievements needs testing, and fortunately, the testing will be relatively inexpensive. We plan to pursue avenues, particularly those within Caltrans, to obtain funding for these extended tests.

APPENDIX I

PSYCHOPHYSICAL TEST DETAIL

Table 1 Detail

	TS1							
	None		Constant		Asynchronous		Synchronous	
File	**mean**	**std error**	**mean**	**std error**	**mean**	**std error**	**mean**	**std error**
TS1 01	23	16	28	23	34	27	35	28
TS1 02	21	14	20	15	25	21	29	25
TS1 03	22	15	22	19	26	21	26	23
TS1 04	22	15	17	13	18	15	18	13
TS1 05	22	15	14	11	19	15	20	15
TS1 06	23	16	17	13	19	16	18	16
TS1 07	23	15	18	16	21	16	21	16
TS1 08	22	15	17	13	22	17	20	15
TS1 09	23	17	29	19	33	23	32	23
TS1 10	20	15	17	14	21	15	20	15
TS1 11	20	15	17	14	20	16	19	16
TS1 12	21	15	15	11	18	13	20	14
TS1 13	22	15	14	11	20	17	17	13
TS1 14	20	14	15	11	20	15	20	14
TS1 15	21	16	20	15	23	17	23	17
TS1 16	22	15	17	12	18	13	21	16
TS1 17	22	15	18	14	22	15	21	15
TS1 18	22	15	20	15	19	12	18	13
TS1 19	21	14	17	14	16	13	20	15
TS1 20	22	15	15	12	20	14	22	17
Overall	**21.7**	**14.3**	**18.4**	**13.4**	**21.7**	**15.5**	**22.0**	**15.8**

TS1	mean	std error
None-Constant:	**3.4**	**4.4**
None-Asynchronous:	**0.0**	**4.7**
None-Synchronous:	**-0.3**	**4.8**
Constant-Asynchronous:	**-3.4**	**4.6**
Constant-Synchronous:	**-3.7**	**4.6**
Asynchronous-Synchronous:	**-0.3**	**5.0**

	TS2							
	None		Constant		Asynchronous		Synchronous	
File	**mean**	**std error**	**mean**	**std error**	**mean**	**std error**	**mean**	**std error**
TS2 01	21	16	21	17	24	18	18	17
TS2 02	20	16	23	17	22	20	20	18
TS2 03	22	17	26	21	29	25	25	26
TS2 04	23	18	27	23	31	26	26	18
TS2 05	20	16	24	20	27	21	21	17
TS2 06	22	17	25	25	27	21	21	23
TS2 07	19	15	27	20	32	26	26	20
TS2 08	19	14	24	20	31	26	26	18
TS2 09	18	14	25	21	26	20	20	21
TS2 10	18	14	26	20	31	24	24	23
TS2 11	17	13	31	22	33	23	23	23
TS2 12	17	14	29	22	34	25	25	23
TS2 13	18	13	28	21	32	24	24	19
TS2 14	16	12	29	20	35	24	24	21
TS2 15	17	12	32	23	36	27	27	26
TS2 16	18	12	29	22	33	25	25	23
Overall	**19.1**	**14.7**	**26.6**	**21.0**	**30.2**	**23.6**	**23.4**	**21.2**

TS2	mean	std error
None-Constant:	**-7.6**	**6.4**
None-Asynchronous:	**-11.1**	**6.9**
None-Synchronous:	**-4.4**	**6.4**
Constant-Asynchronous:	**-3.6**	**7.9**
Constant-Synchronous:	**3.2**	**7.5**
Asynchronous-Synchronous:	**6.8**	**7.9**

	TS3							
	None		Constant		Asynchronous		Synchronous	
File	**mean**	**std error**	**mean**	**std error**	**mean**	**std error**	**mean**	**std error**
TS3 01	22	17	18	14	23	15	24	15
TS3 02	23	17	18	12	21	14	21	15
TS3 03	22	16	19	14	21	15	23	15
TS3 04	22	16	18	13	21	15	19	14
TS3 05	22	19	19	14	19	14	21	15
TS3 06	23	20	19	13	23	16	22	16
TS3 07	22	17	19	13	22	14	22	14
TS3 08	21	17	18	13	22	14	22	14
TS3 09	23	18	20	16	19	14	21	15
TS3 10	22	18	18	12	19	15	20	16
TS3 11	21	16	19	12	22	14	19	13
TS3 12	23	16	19	12	22	16	21	14
TS3 13	20	17	20	13	22	16	22	15
TS3 14	21	15	20	13	22	14	21	14
TS3 15	22	17	20	13	22	14	21	13
Overall	**21.9**	**17.1**	**18.9**	**13.2**	**21.3**	**14.7**	**21.3**	**14.6**

TS3	mean	std error
None-Constant:	**3.0**	**5.6**
None-Asynchronous:	**0.6**	**5.8**
None-Synchronous:	**0.7**	**5.8**
Constant-Asynchronous:	**-2.4**	**5.1**
Constant-Synchronous:	**-2.3**	**5.1**
Asynchronous-Synchronous:	**0.1**	**5.3**

Overall	**20.9**	**16.4**	**21.1**	**17.4**	**24.3**	**19.7**	**22.2**	**18.9**

Overall	mean	std error
None-Constant:	**-0.2**	**3.3**
None-Asynchronous:	**-3.3**	**3.6**
None-Synchronous:	**-1.3**	**3.5**
Constant-Asynchronous:	**-3.1**	**3.7**
Constant-Synchronous:	**-1.1**	**3.6**
Asynchronous-Synchronous:	**2.0**	**3.8**

Table 2 Detail

				TS1				
	None		Constant		Asynchronous		Synchronous	
File	**mean**	**std error**	**mean**	**std error**	**mean**	**std error**	**mean**	**std error**
TS1 01	24	15	21	15	20	15	19	16
TS1 02	20	13	16	14	16	11	17	12
TS1 03	23	15	19	14	17	12	17	13
TS1 04	23	16	18	15	20	16	19	13
TS1 05	23	16	19	13	19	14	20	15
TS1 06	22	15	16	12	18	12	20	14
TS1 07	24	16	22	13	24	17	21	14
TS1 08	23	15	18	12	19	13	22	16
TS1 09	22	15	19	15	21	16	21	15
TS1 10	22	15	18	14	20	16	19	14
TS1 11	22	16	18	14	20	15	20	14
TS1 12	22	16	16	13	19	14	18	14
TS1 13	23	16	20	14	20	14	23	15
TS1 14	21	14	20	14	18	12	22	16
TS1 15	23	16	19	13	21	14	21	15
TS1 16	21	15	17	13	19	13	19	15
TS1 17	22	15	19	15	19	13	19	14
Overall	**22.4**	**15.3**	**18.5**	**13.7**	**19.4**	**14.0**	**19.8**	**14.5**

TS1	mean	std error
None-Constant:	3.8	5.0
None-Asynchronous:	2.9	5.0
None-Synchronous:	2.5	5.1
Constant-Asynchronous:	-0.9	4.8
Constant-Synchronous:	-1.3	4.8
Asynchronous-Synchronous:	-0.4	4.9

				TS2				
	None		Constant		Asynchronous		Synchronous	
File	**mean**	**std error**	**mean**	**std error**	**mean**	**std error**	**mean**	**std error**
TS2 01	18	13	26	18	26	18	26	19
TS2 02	16	12	24	20	28	23	28	20
TS2 03	16	12	31	22	29	19	32	23
TS2 04	16	11	34	24	43	27	40	25
TS2 05	17	12	35	23	37	25	35	24
TS2 06	16	12	34	22	42	28	41	26
TS2 07	15	11	43	24	41	26	41	25
TS2 08	14	11	42	19	45	25	42	25
TS2 09	14	11	46	27	47	25	42	23
TS2 10	15	11	43	27	45	25	45	26
TS2 11	14	11	46	23	36	21	40	24
TS2 12	15	12	46	24	47	24	50	26
TS2 13	14	11	51	26	52	26	48	22
TS2 14	15	12	56	34	58	33	58	37
TS2 15	13	11	50	27	51	30	52	32
TS2 16	13	10	43	25	47	28	50	34
TS2 17	15	12	79	64	71	50	66	50
Overall	**15.1**	**11.5**	**42.9**	**28.3**	**43.8**	**27.5**	**43.3**	**28.1**

TS2	mean	std error
None-Constant:	-27.8	7.4
None-Asynchronous:	-28.8	7.2
None-Synchronous:	-28.2	7.4
Constant-Asynchronous:	-0.9	9.6
Constant-Synchronous:	-0.4	9.7
Asynchronous-Synchronous:	0.5	9.5

				TS3				
	None		Constant		Asynchronous		Synchronous	
File	**mean**	**std error**	**mean**	**std error**	**mean**	**std error**	**mean**	**std error**
TS3 01	20	15	20	13	21	13	21	14
TS3 02	21	16	19	13	19	13	20	14
TS3 03	23	18	20	14	22	16	19	14
TS3 04	27	22	21	16	23	19	22	16
TS3 05	20	16	19	12	19	13	19	13
TS3 06	21	16	19	14	19	13	18	12
TS3 07	20	17	18	13	18	15	18	14
TS3 08	22	16	19	12	22	13	19	12
TS3 09	21	16	19	12	19	12	19	12
TS3 10	20	16	18	12	19	12	19	12
TS3 11	22	16	19	12	20	12	20	13
TS3 12	21	16	19	14	21	13	19	14
Overall	**21.5**	**16.8**	**19.2**	**13.1**	**20.2**	**13.8**	**19.4**	**13.4**

TS3	mean	std error
None-Constant:	2.3	6.1
None-Asynchronous:	1.3	6.3
None-Synchronous:	2.1	6.2
Constant-Asynchronous:	-1.0	5.5
Constant-Synchronous:	-0.3	5.4
Asynchronous-Synchronous:	0.8	5.6

Overall	**19.4**	**14.4**	**27.7**	**20.2**	**28.6**	**20.1**	**28.4**	**20.4**

Overall	mean	std error
None-Constant:	-8.3	3.7
None-Asynchronous:	-9.2	3.6
None-Synchronous:	-9.0	3.7
Constant-Asynchronous:	-0.9	4.2
Constant-Synchronous:	-0.7	4.2
Asynchronous-Synchronous:	0.2	4.2

Table 3 Detail

	TS2							
	None		Constant		Asynchronous		Synchronous	
File	mean	std error	mean	std error	mean	std error	mean	std error
TS2 01	16.5	14.0	25.6	19.6	30.0	20.0	29.4	22.5
TS2 02	17.5	14.9	25.2	19.5	27.8	20.4	27.2	20.0
TS2 03	17.0	13.5	26.4	20.6	30.0	22.8	28.3	22.0
TS2 04	16.0	12.2	24.8	17.3	26.4	20.4	28.9	24.5
TS2 05	16.7	13.4	23.6	17.7	25.8	20.2	27.3	20.7
TS2 06	17.4	14.9	20.4	15.5	24.7	17.9	24.0	18.2
TS2 07	16.2	13.2	18.3	13.1	24.1	17.6	22.9	17.5
TS2 08	17.0	14.7	21.5	16.6	23.3	16.5	24.2	18.8
TS2 09	17.6	14.4	19.9	14.4	24.4	18.2	22.4	16.4
TS2 10	19.0	15.7	19.1	13.8	20.5	15.7	20.6	14.9
TS2 11	16.2	14.1	19.3	12.3	18.6	13.8	20.9	14.9
TS2 12	17.9	14.7	17.7	14.1	22.2	17.0	19.1	13.9
TS2 13	17.1	13.8	18.8	13.8	19.6	15.3	19.4	14.4
TS2 14	17.1	13.9	17.6	13.6	19.1	14.9	20.3	16.1
TS2 15	17.3	14.5	17.0	12.9	21.1	15.7	21.1	14.3
Overall	**17.1**	**14.2**	**21.0**	**15.9**	**23.8**	**17.9**	**23.7**	**18.2**

TS2	mean	std error
None-Constant:	-3.9	5.5
None-Asynchronous:	-6.7	5.9
None-Synchronous:	-6.6	6.0
Constant-Asynchronous:	-2.8	6.2
Constant-Synchronous:	-2.7	6.2
Asynchronous-Synchronous:	0.1	6.6

	TS4							
	None		Constant		Asynchronous		Synchronous	
File	mean	std error	mean	std error	mean	std error	mean	std error
TS4 01	38.0	31.0	40.3	31.0	43.3	33.3	41.6	33.2
TS4 02	39.1	31.6	31.9	25.4	46.1	38.4	39.5	30.7
TS4 03	41.9	34.2	31.9	24.8	43.1	35.5	32.7	35.4
TS4 04	45.8	35.0	36.1	26.7	45.5	35.2	42.8	35.8
TS4 05	48.7	35.4	43.1	29.8	48.0	32.5	47.0	31.7
TS4 06	63.9	40.1	51.0	31.4	54.1	37.5	55.8	38.1
TS4 07	58.4	38.9	50.6	34.7	56.6	40.8	60.7	36.4
Overall	**48.0**	**35.3**	**40.7**	**29.3**	**48.1**	**36.3**	**45.7**	**34.6**

TS4	mean	std error
None-Constant:	7.3	17.3
None-Asynchronous:	-0.1	19.1
None-Synchronous:	2.2	18.7
Constant-Asynchronous:	-7.4	17.6
Constant-Synchronous:	-5.0	17.1
Asynchronous-Synchronous:	2.4	18.9

Overall	**26.9**	**23.1**	**27.3**	**21.1**	**31.6**	**25.3**	**30.7**	**24.6**

Overall	mean	std error
None-Constant:	-0.4	6.7
None-Asynchronous:	-4.6	7.3
None-Synchronous:	-3.8	7.2
Constant-Asynchronous:	-4.3	7.0
Constant-Synchronous:	-3.5	6.9
Asynchronous-Synchronous:	0.8	7.5