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Workzone Safety Improvements through Enhanced Warning Signal Devices

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California PATH Research Report
UCB-ITS-PRR-2008-3

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation, and the United States Department of Transportation, Federal Highway Administration.

Final Report for Task Orders 5205/6205

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Final Report

Workzone Safety Improvements through Enhanced Warning Signal Devices

Prepared for

California PATH

TO#5205/6205

by

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Workzone Safety Improvements through Enhanced Warning Signal Devices
California PATH Task Order 5205/6205
Final Report

I. Abstract

The high incidence of accidents associated with work zones suggests that current warning lights and signals have been in need of improvement. In this project we have developed and tested an improved emergency warning light intended specifically for Caltrans work zone vehicles, and an enhanced rear warning light for shadow trucks, both intended to improve visibility and conspicuity, and to reduce reaction times for drivers approaching the work zone.

Keywords:

work zone, emergency warning light, shadow truck, visibility, conspicuity, reaction time, vision

II. Executive Summary

Increasing collision rates in and near work zones suggest that Emergency Warning Lights (EWLs) that sit atop work vehicles, and rear warning lights on shadow truck vehicles, are in need of improvement. In this project, the Visual Detection Laboratory (VDL) at UC Berkeley sought to design, fabricate and test an EWL that would offer improved visibility and conspicuity, and that would uniquely identify Caltrans maintenance vehicles and thereby convey to the public the special hazardous nature of the portion of the highway where they are seen. VDL also sought to design, fabricate, and test a new rear warning light for shadow trucks that would offer increased attention-getting qualities over existing designs, and in turn elicit a faster reaction time from drivers approaching the rear of a shadow truck and work convoy.

Rather than increase the brightness of warning lights which, while increasing visibility, can have the undesirable effect of increased and even disabling glare, VDL was motivated to obviate the need for high brightness by replacing the extra visibility that it provides with visibility that arises from the temporal and spatial structure of the signal. A growing body of knowledge concerning the structure and function of the visual nervous system supplied guideposts to reaching this goal. By giving a signal the ability to appear to move we can replace visibility due to intensity with visibility due to “movement”. We call devices that incorporate this technique Motion Enhanced Warning Signals (MEWS). Previous research has demonstrated the superiority of MEWS devices.

We also sought to design devices that offer increased energy efficiency in comparison to those incorporating incandescent lamps and motors for rotation. We decided to use light emitting diodes (LEDs) exclusively, which have the property of high efficiency (thus saving energy), very fast ignition and extinction times (which better stimulate the humal visual system), and higher reliability (thus reducing maintenance costs). Also, warning signals that incorporate multiple LEDs can be programmed to provide the patterns seen in MEWS devices.

To make an EWL that could be uniquely identified with Caltrans vehicles we decided on a conical design that resembles a standard work zone cone. LEDs arranged in longitudinal stripes were programmed to provide the appearance of a rotating beacon light. A color of LED was chosen to be reminiscent of the orange color typical of Caltrans vehicles.

We fabricated an EWL that allowed great flexibility in the timing of patterns so that we could perform laboratory experiments in order to optimize the apparent rotation rate and the apparent width of the longitudinal stripes. On the basis of an extensive series of reaction time experiments with human observers, we established an optimal set of parameters.

For the shadow truck light bar, we designed and fabricated a large, rectangular display incorporating several thousand individual LEDs. The LEDs were functionally grouped into a series of four nested rectangles, each of which could be individually ignited or extinguished. The idea was to create a gradually expanding bar of light which would convey the impression to a driver in a vehicle approaching the rear of a shadow truck, that he/she was closing in at a high rate of speed and needed to slow down rapidly to avoid a collision. An onboard computer allowed us to program the timing parameters of the display so as to optimize the pattern for minimum reaction time in a series of laboratory experiments with human observers. Having established the optimal pattern and timing of the display, we then demonstrated the device in the field by mounting it on the back of a work vehicle and using a radar device to detect a vehicle approaching from the rear to fire the display. The radar device also served to measure the trajectory of the approaching vehicle, which we did with different warning signal firing patterns in order to confirm the results of our laboratory experiments.

In summary, the prototype EWL and shadow truck light bar fully met our expectations as unique signaling devices that improved upon earlier designs.. They proved to be visually effective and conspicuous while at the same time avoiding the problems of excessively high levels of illumination that plague their forerunners. In addition, the unique shape and appearance of the EWL would serve well to identify it uniquely with Caltrans work vehicles, and to distinguish it from other warning signal devices, thus providing an additional margin of safety in Caltrans work zones.

III. Table of Contents

This project consists of two independent studies:

(1) Improved Emergency Warning Light for Maintenance Vehicles
(2) Protecting the Protector: An ITS Shadow Truck Warning Signal

Accordingly, we present the final report for the project in two independent sections.

Improved Emergency Warning Light for Maintenance Vehicles

Protecting the Protector: An ITS Shadow Truck Warning Signal

Note on Figures

Many of the figures in this report contain important color information which is not reproduced in the printed version of this document. Please see the PDF format available online, to view the figures in color.

Improved Emergency Warning Light for Maintenance Vehicles

I. Introduction

The high frequency of accidents associated with roadway work zones suggests that current warning lights and signals are in need of improvement. In one part of a two-part project, the Visual Detection Laboratory (VDL) has worked on developing and testing improved emergency warning lights for work zone vehicles with the objective of improving visibility, conspicuity and reducing the reaction time of drivers approaching the work zone.

Increasing collision rates in and near work zones are suggestive that emergency warning lights (EWL) on work zone vehicles do not suffice. This is surprising considering the recent increase in intensity of light sources used and the resulting warning signals' high visibility. One part of the problem may be pervasiveness: too many other vehicles employ a flashing amber signal similar to the usual EWL. In this project the Visual Detection Laboratory sought to design, fabricate and test an emergency warning light that would uniquely identify Caltrans maintenance vehicles and thereby convey to the public the special hazardous nature of the portion of the highway where they are seen.

A major step in meeting this challenge consists of better understanding the fundamental nature of the problem by noting what does ***not*** work. As mentioned in the companion report on the *Shadow Truck Warning Signal* the trend toward increasing signal intensity may be doing more harm than good. Ultra-bright signal lights can be discerned at great distances and can clearly attract attention in an ocean of distracting sights. But a problem arises when an observer is close to the signal. Approaching a work zone or a maintenance vehicle one discovers that extremely bright signals defeat their own purpose. The same fixtures that are easy to see at a great distance are too bright to look at up close. *The nearby observer cannot look at the vehicles or structures that bear these lights for long enough to "compute" the nature of the hazard she faces.* While evidence of this is mostly anecdotal, Benekohal and Shim[1] have stated that Illinois truckers surveyed about work zone safety specifically cited arrow boards as too bright.

While a very intense light certainly signals presence, it can degrade *computability*, the ability of a signal to convey information to the eye and then to the brain. In this case the information to be conveyed (beyond mere presence) is the distance from the observer to the signal and the nature of the message.[2] In other words, the observer (driver) has to "read" the signal at a glance, which is not likely if she has been blinded or dazzled by overly bright warning lights (that are presently in use).

Thus VDL was motivated to obviate the need for high brightness by replacing the extra visibility that it provides with visibility that springs from the temporal and spatial structure of the signal. Fortunately, a growing body of knowledge concerning the structure and function of the visual nervous system supplied guideposts to reaching this goal.

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[1] Benekohal, R.F. and Shim, E. (1999), *Multivariate Analysis of Truck Drivers' Assessment of Work Zone Safety* in **Journal of Transportation Engineering** 125, 398-406.

[2] In this case the message would be "this is a *Caltrans* maintenance vehicle in a work zone adjust your driving accordingly" with the message having been acquired by repeated exposure during highway driving to this (presumably) unique signal.

By giving a signal the ability to *appear* to move we can replace visibility due to intensity with visibility due to "movement". This notion of Motion Enhanced Warning Signals (MEWS[3]) was first described at the 1995 ITS International Congress.[4] What movement does, we now know, is to stimulate elements of the visual nervous system that are more sensitive than those whose job is to process fine detail and color. Beyond their additional sensitivity (less light gets an equal response) these neurons are faster. The message arrives faster at those parts of the brain where conscious perception resides.

Having decided that using MEWS was the only reasonable approach and having rejected variants of commercial off-the-shelf devices on the basis that they represent the wrong technology trajectory (namely increased visibility at the expense of blinding the motorist), the question then became what type of specific implementation to use. What colors should the EWL use and what type of lighting technology?

The choice of colors is limited; the 'good' colors are taken. Red and blue are forbidden except on fire and police vehicles. Green sends a message opposite to the intended one. Purple (combination of red and blue) would be a possibility except that it is located at relatively insensitive portions of the visual sensitivity spectrum (the luminosity function) thereby making it inefficient—large energy usage for modest visibility. Also a red-blind (protanopic) observer would see it as blue. Orange was a strong possibility but the very similar amber was ultimately chosen because amber light sources are more generally available. Thus VDL decided that the signal would be made amber despite the proliferation of amber beacons (e.g. on contractor vehicles).

The specific choice of lighting technology then comes in to play. One way to mitigate the effect of high intensities is to use strobe devices, that is gas-discharge tubes. These ignite *very* briefly, for millionths of a second. They are on *so* briefly however that the observer cannot recover information as to where they are located.[5] Trying to mitigate this with more frequent flashing just brings back the original problem of being very distracting and overly bright.

Incandescent lights are energy inefficient and have significant (in terms of reaction times) ramp-up times due to the thermal inertia of the filaments. LEDs on the other hand have no such problems; they have quick ignition and extinction, and are highly energy-efficient. Furthermore, the perception of motion can be produced through sequential firing of adjacent sets of LEDs. Thus MEWS can be created without any moving parts (e.g. rotating mirrors). Therefore VDL decided on making the EWL from amber LEDs using electronic control to provide the appearance of motion. LEDs also provide opportunity for a uniquely shaped signal as opposed to incandescent lights which are more limited in their flexibility of design.

The size and shape of the EWL are discussed in the next section.

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[3] See also the companion report for the other part of this project: *Shadow Truck Warning Light Report.*

[4] Cohn, T.E. (1995) *Engineered Visibility Warning Signals* in **Proceedings of the Second World Congress on Intelligent Transportation Systems, Yokohama,** Vol. 1, 452-457. Along this same line the reader is referred to two patents: Cohn, T.E., U.S. Patent No. 5,499,010 *Braking Light System for a Vehicle* (issued Mar. 12, 1996) and Cohn, T.E., U.S. Patent No. 5,710,560 *Method and Apparatus for Enhancing Visual Perception of Display Lights, Warning Lights and the like, and of Stimuli Used in Testing for Ocular Disease* (issued Jan. 20, 1998).

[5] Tests have shown that a brief strobe can appear anywhere within a few degrees of where its location was before the eyes move to a few degrees around the location where they come to rest and anywhere in between. See Greenhouse, D. and Cohn, T.E. (1991) *Saccadic Suppression and Stimulus Uncertainty* in **J. Opt. Soc. Am. A** 8: 587-595.

II. EWL Design and Signal Pattern Choices

VDL’s initial conception for the EWL is shown in Figure 1.

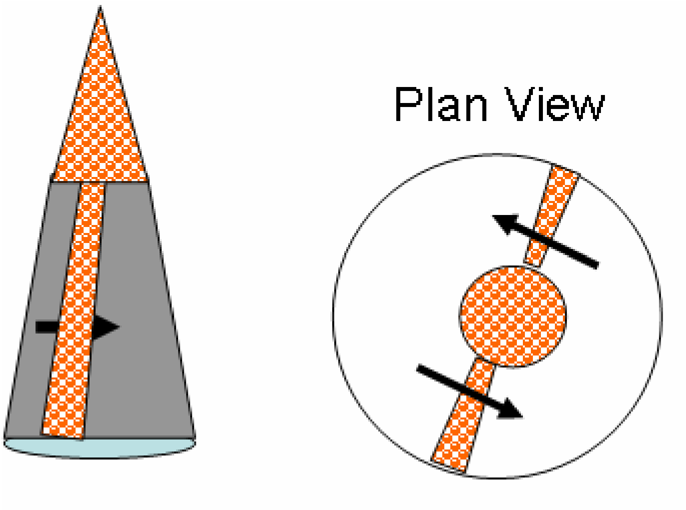

Figure 1: The initial conception of the EWL was literally an orange cone made up of LEDs, albeit with only a portion lit at any given time. The lit portion in ‘motion’ consists of two opposing strips rotating around the vertical axis of the cone.

As is quite clear from the picture, the EWL was meant to be evocative of a traffic cone and follow the “cone zone” motif. Upon discussion with the vendor[6] this conception was modified slightly. The final specifications given to the vendor were as follows.

- <u>General design</u>: The cone will be divided into upper and lower sections (see drawing[7]). The surface of the upper (smaller) section will consist of LEDs mounted with uniform density. The surface of the lower, larger section will contain eight equally-spaced vertical stripes, numbered 1 to 8 sequentially. Each of these eight stripes will consist of two closely-spaced adjacent columns of LEDs. The separation between the two columns will be as small as possible at the top, and increase lower in the columns as the diameter of the cone increases (in order to keep each column “vertical” along the surface of the cone). The upper section can be cylindrical rather than conical. (In fact, it is cylindrical in the final product).
- <u>LEDs</u>: The LEDs in both sections of the cone should be amber, wide angle and high brightness. In the upper section, they should be mounted as densely as is practical to allow the brightest possible display. In the lower section, they should be mounted as described above.

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[6] *Electro-Tech’s*, 1875 Sampson Avenue, Corona, CA. 92879-6009

[7] This section is taken directly from the specifications to the vendor. The drawing referred to is substantially similar to Figure 1.

- Electronic controls: The electronic controls for the unit must be remote from the EWL, and the electrical cable connecting them must be able to withstand being closed between the door and frame of a vehicle.
- Upper section driver and controls: For the upper section of the cone, the electronic controls should be able adjust the strobe rate and intensity of the LEDs. The strobe rate should be adjustable from 60 to 120 flashes per minute. The LED intensity should be variable from off to maximum brightness. The controls should ignite all the LEDs of the upper cone simultaneously and with less than 10 milliseconds delay to half-intensity.
- Lower section driver and controls: For the lower section, the intensity of the LEDs should also be variable from completely off to maximum intensity. The controls should illuminate opposite pairs of the LED "stripes" sequentially, in a counter clockwise direction as viewed from above. Thus when stripe 1 is illuminated, panel 5 should be turned on simultaneously[8]. The illumination pattern should be 1 & 5, then 2 & 6, then 3 & 7, then 4 & 8 etc. The electronic controls should be able to independently vary the rate of procession and "dwell" (duration on) time of the stripes. The frequency of procession, or perceived rate of rotation, should be variable from 30 to 60 revolutions per minute. The dwell time, or time each panel remains illuminated, should be able to be varied from short (such that at the highest procession frequency, there is a short period where no stripes are on) to long (such that, at the lowest rate of procession, two adjacent bars are on at the same time briefly). The rise times of the LED ignition would be essentially instantaneous, as described above. As stated above in the original spec, we want independent control of the rate of "rotation" and the duration the stripes remain on. The latter should be variable from near zero (meaning stripes flash on briefly and there are intervals where no LEDs are illuminated) to long enough such that at the slowest rate of rotation (30 per minute), all the LEDs actually remain on at all times (by lowering the duration from this value, we would thus be allowed to create a rotating "black stripe" which flashes "on" only very briefly.[9] We don't want separate controls for individual stripes or pairs of stripes, rather we need a single control (or set of switches) that controls the on-time of all stripes simultaneously. Thus there would simply be two controls that pertain to timing, one for rotation rate and the other for duration.
- Viewing angle: The optical axis of the individual LED emitters should be parallel to the ground, or perpendicular to the longitudinal axis of the EWL. Two possible methods to achieve this are (1) to mount the LEDs on the substrate at an angle to the substrate, or (2) to make the cone out of multiple cylinders of differing size. Other methods to achieve the viewing angle requirement would be considered but should be discussed with the University.
- Cover: The LEDs should be behind a translucent cover, not a diffuser. The color of the cover is at the discretion of the vendor. (In the final product the cover was transparent—see Figures below.)
- Environmental Rating: The EWL will eventually be mounted on a Caltrans vehicle for testing and so should be designed so as to later configure it to be weather

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[8] As mentioned in the previous footnote Figure 1 is substantially the same as the drawing (not shown) referred to here. Where it differs is in the lack of numbering stripes. Clearly with eight stripes enumerated sequentially, stripes 1 and 5, 2 and 6, etc. are opposite each other on the cone. Thus the 'plan view' of Figure 1 would be showing stripes 3 and 7 (say).

[9] This refers to the "inverted" mode which is explained below.

resistant. A subsequent EWL should be constructed so as to meet the NEMA 3 environmental rating. Proof of meeting the NEMA 3 rating is not required. The EWL must also be capable of working between -32 and +49 degrees Celsius and not be damaged by these extreme temperatures.

- Color appearance: The perceived color of the EWL should be amber/orange. Ideally the color would be as close to red as possible but still be classifiable as amber by the C.I.E. The color of the LED substrate and the space between the illuminated panels should be black or dark colored, so that the EWL is minimally visible when not activated, and so that there is maximum contrast within the display.
- Mounting: The EWL should have provisions to be mounted magnetically to a vehicle. (The final product has a magnetic base.)
- Viewing angle: The optical axis of the LEDs should be parallel to the ground, or perpendicular to the longitudinal axis of the EWL. Two possible methods to achieve this are to mount the LEDs on the substrate at an angle to the substrate, or to make the cone out of 4 or more cylinders of differing size. (The final product has the LEDs mounted at an angle to their circuit boards so that the LEDs point horizontally, the symmetry axis of the cone being vertical.)

The final, delivered product from the vendor matched up very well to what was envisioned and is shown in Figure 2. Figures 3 and 4 show the dimensions of the EWL. A full schematic for the EWL and its associated electronic control circuitry is shown in Appendix 2.

Figure 2: The final EWL prototype is shown unlit on the left and running in "inverted" mode (see text) on the right. Note the horizontal projection of the LEDs on the leftmost stripe of the unlit EWL and the amber/orange color of the LEDs in the lit view. The cone is held solidly to the metal file cabinet by its magnetic base.

Figure 3: The truncated cone (lower portion) rests on a squat base cylinder that rises 4 centimeters. The "stripes", two rows of LEDs on a trapezoidal circuit board, are 26 centimeters long. The overall height is 36 centimeters and the top cylinder has a 'square' profile—7 centimeters in height by 7 centimeters in diameter.

Figure 4: The base is 22 centimeters in diameter. There are 8 LEDs in a vertical column on the upper cylinder. There are 24 such columns ringing the cylinder. On the very top there are 36 LEDs forming a disk. Each line of LEDs on the truncated cone consists of 40 LEDs. Two such lines form a "stripe" on a trapezoidal board. There are 8 such stripes (or boards). The cord supplying power/control is seen in the background.

The cylinder at the top of the EWL (hereafter the *upper* section) and the truncated cone (hereafter the *lower* section) are independently controllable. The upper section can be operated in a flashing or strobe mode. It can also be off while the lower section is on. The lower section, as was previously discussed, can run in normal mode (*"light"*) which consists of two opposing stripes circling the cone in a counterclockwise motion (i.e. Figure 1). This mode is shown in the next picture.

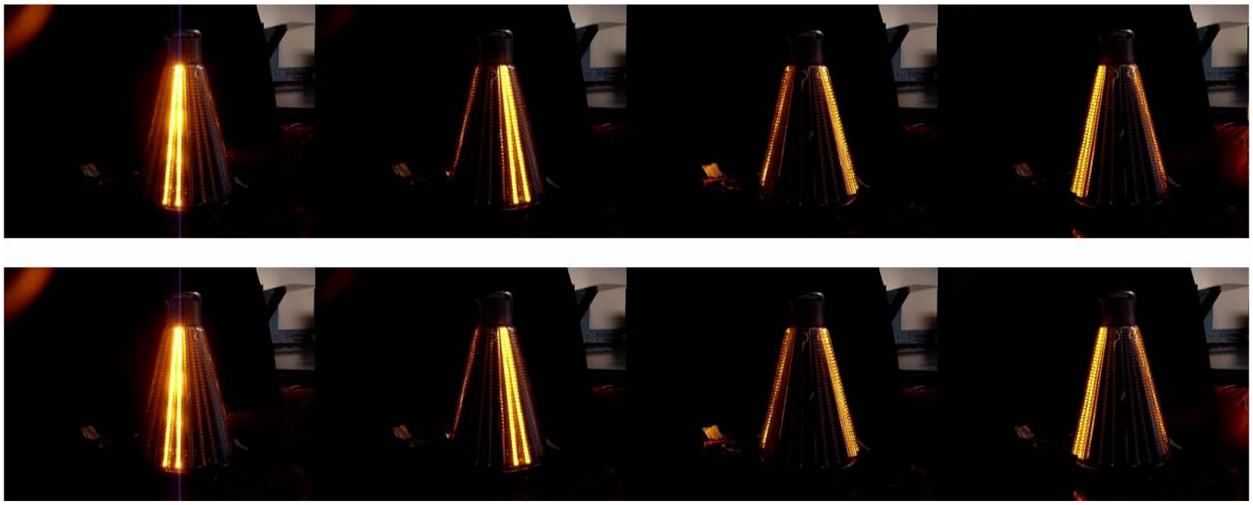

Figure 5: Two cycles of the normal (or light) mode are shown in a darkened room. The time sequence on each strip is left to right.

The lower section can also run in the so-called dark or *inverted* mode. This is literally the inversion of the normal/light mode—every stripe that was dark becomes light and every stripe that was light becomes dark. Thus in inverted mode there are two "dark" stripes (i.e. turned off) that are diametrically opposed and they chase each other around the lower section in a counterclockwise manner when viewed from above (Figure 6).

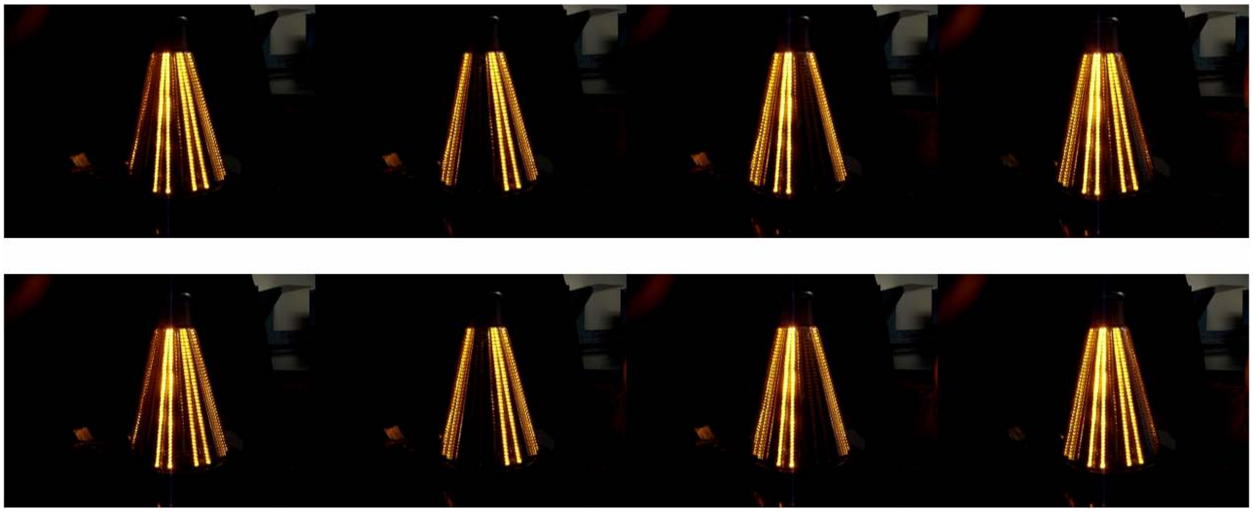

Figure 6: Two cycles of the inverted (or dark) mode are shown. The sequence on each strip is left to right. Despite the nomenclature the dark mode puts out more light than the light mode.

Although the sequence of frames in Figures 5 and 6 is ordered properly, they are not serial frames. These pictures were extracted from a movie and the frame rate was too great to show any significant change with only a few adjacent (in time) frames. Thus these snapshots represent something like every 5th frame, allowing a proper depiction of the cycle with only a few pictures.

What is left out by such a depiction however, is the transition behavior. In Figure 5 for instance there is a brief instant where one stripe is going out as the adjacent one is coming on and they are both lit simultaneously. Similarly, in the inverted behavior there is a brief instant where two adjacent stripes are both dark (or very dim). This transition occurs so fast that it is only noticeable at the slowest rotation settings.

If the EWL is turned on then the lower section is always active in either light or dark modes. The upper section can be turned off however.[10] As was already stated, it can also be put into a flash or strobe mode. The picture below shows the flashing mode combined with the inverted mode in the lower section.

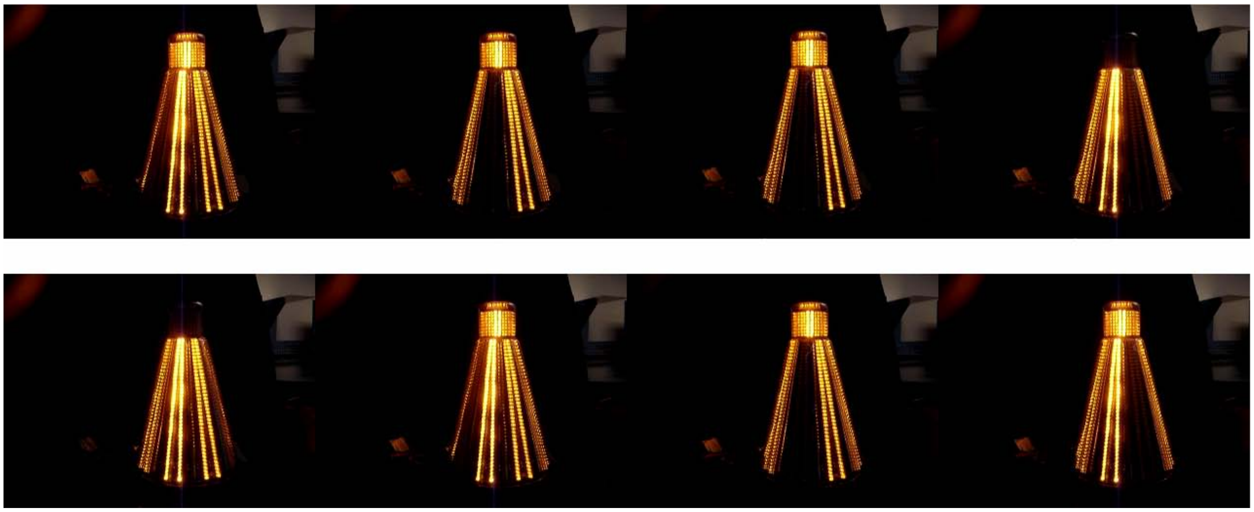

Figure 7: Inverted/dark mode in the lower section combined with flashing in the upper section. The same caveat mentioned above applies to this picture: the frames are ordered properly in time but they represent every 4th or 5th frame because of the high frame rate in the movie from which they were extracted.

The control box supplied by the vendor was superbly engineered for ease of use. It was designed to be very intuitive as can be seen below. In the upper left quadrant of the box is an elliptical ring of LEDs with an LED in the center. This is a miniature or mock-up of the actual EWL. As the stripes rotate on the EWL so too do the lit LEDs on the control box. When the upper section flashes, the center diode on the control box keeps lit in synchrony. Thus the operator could look at the box rather than the very bright lights on the EWL itself to see if it was operating in the manner intended. He didn't even have to be in the same room thanks to the long cord connecting the control box to the EWL.

As can be seen in Figure 8, there is a power switch on the right. The middle section of the box controls the upper section of the EWL. The toggle switch has three settings: flash, off and strobe. The intensity of the EWL's upper section is set by the brightness control. The other knob in that section ('strobe') just sets the frequency for the strobe/flash.

The lower left part of the box controls the lower section of the EWL. The toggle switch is set to either *light* (normal mode) or *dark* (inverted mode). The knob on the right of that section sets the brightness of the stripes. The middle knob sets the duty cycle as it were, that is how long the stripes are on. The leftmost knob, with its label partially obscured by VDL's addition of masking tape with numbers written on, controls the rotation rate or period.

This latter knob was relatively sensitive and VDL wanted reproducibility while trying various rotation rates.[11] Thus VDL personnel made a small modification to the control box. The two wires coming out of the bottom of the box in Figure 8 go to a jack. A frequency counter was

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[10] This is obvious in the Figures 5 and 6. Another way of stating this is that the upper section cannot be on by itself.

[11] The duty cycle knob was not as sensitive in comparison and the brightness knob could be turned up all the way and integral numbers of plastic sheets providing attenuation could be put in front of the EWL to get the needed reproducibility as far as light intensity was concerned.

then plugged into the jack in order to get an accurate reading of the rotation rate or period. Masking tape was then used to provide a scale around the knob. The other minor modification that can be seen is that the power plug was taped over and the power wires brought out so that they could be connected up to the computerized testing equipment for triggering (see next section).

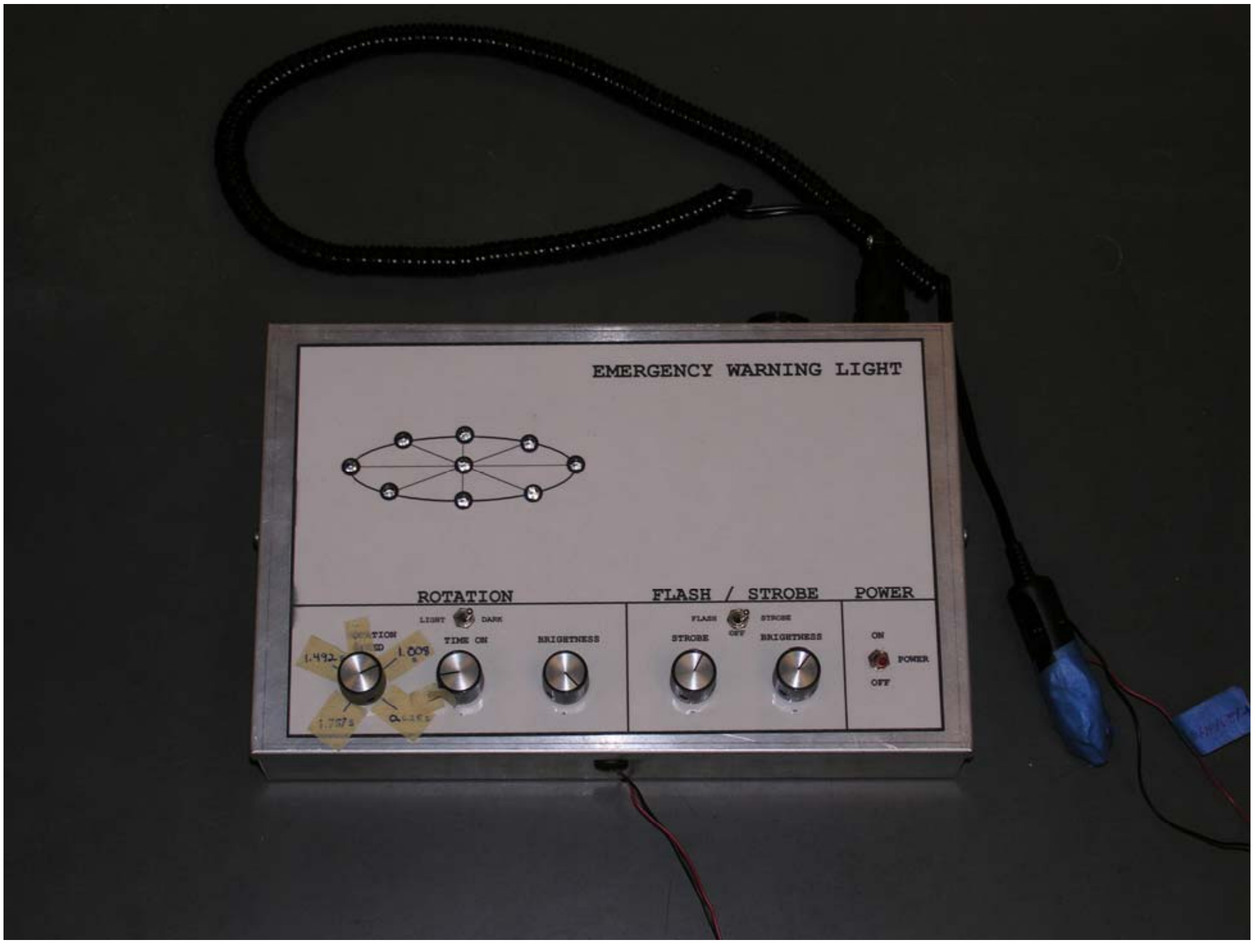

Figure 8: The control (& power) box for the EWL.

The choices in control settings allow for a large number of variations in signal pattern.

The rotation rate was quantified in terms of its period, the time between successive illuminations of a given stripe in the case of *light* mode or the time between successive darkening of a given stripe in *inverted* mode. Note that a rotation of the pattern by 180° results in exactly the same pattern. Thus a ‘period’ here is the time for the stripes to “rotate” by 180° rather than by 360°. The period thus defined ranged from 0.628 seconds to 1.787 seconds.

The duration of any given stripe can be varied, independent of rotation rate, by the second knob from the left (Figure 8) between approximately 0.1 second and 0.75 second. Depending on the rotation rate and duration chosen, this allows the possibility that successive stripes may be illuminated simultaneously for brief periods (for combinations of relatively long durations and slow rotation rates).

The brightness was not measured, only qualitatively observed because of the method of testing detailed in the next section. It was quite bright and noticeable however to the casual observer at even the middle of the range brightness settings.

The flash/strobe unit at the top of the EWL was electrically independent from the cone and could be operated in two modes (as well as being off altogether). In "flash" mode, the unit could be flashed at rates between 1 and 2 Hertz, with 50% duty cycle (equal on and off times). "Strobe" mode was similar to "flash" mode except that instead of the LEDs remaining continuously lit during the "on" portion of the duty cycle, they were flashed on and off eight times. A second control could vary the brightness of the flash/strobe unit.

The configuration choice for testing was therefore quite broad: a continuous range of rotation rate and duty cycle, normal or inverted modes, a continuous range of brightness for both the upper and lower sections and a choice of off, flash or strobe for the upper section. The configurations used during testing had to be limited to a reasonable number because of the large number of trials necessary for a given configuration. Therefore, in order not to fatigue our observers, the possibilities had to be limited to the most important ones.

VDL decided that three rotation rates, normal and inverted modes and two duty cycles would be tested in all combinations with the upper unit off in all cases; this seemed to provide reasonable coverage of the possibilities without overburdening the subjects. Details are given in the next section.

III. Laboratory Testing Configuration and Methodology

Laboratory testing consisted of presenting the EWL to six observers a selection of twelve of its possible configurations (patterns). There were fifty trials for every configuration for every subject. The configurations consisted of three possible rotation rates, two possible duty cycles and normal/inverted operation ($3 \times 2 \times 2 = 12$). The rotation rates were denoted as slowest (period = 1.79 sec.), medium (period = 1.21 sec.) and fastest (period = 0.63 sec.). The individual stripe duration on times (or duty cycles) were denoted by T1 (0.37 sec) and T2 (0.75 sec). Normal and inverted operation was explained above. For all tests the upper section was held off, the reason being that effects from the flash/strobe could confound the data. Also, adding an additional combination (e.g. flash on/off) would likely fatigue our observers. Another consideration was that many sets of warning signals already use a flashing light. VDL was interested in the reaction to the 'new' (MEWS) portion of the EWL (the lower portion).

For each trial the observer was instructed to hit a response button as soon as he saw light from the device, which was blanked off (completely dark) between trials. The interval between when the EWL fired and when the observer hit the response button constituted the observer's reaction time. The data for this experiment then consisted of the set of reaction times categorized by observer and EWL pattern.

In order for the EWL to be properly tested, the light output needed to be attenuated to near-threshold regions. The reason for this is that the response (difference in reaction time) to variation in pattern can be overwhelmed by the response to the high light intensity, which might be expected to elicit short reaction times independent of pattern. It was necessary to conduct the tests under "degraded" (worst case) conditions where the visual response (reaction time) might vary significantly with different patterns.

We selected a magnitude of attenuation that represented the best compromise across subjects and patterns. The light from the EWL was attenuated with six heavy neutral-color filters and one less dense filter. These filters consisted of dark plastic sheeting held in cardboard frames.[12] The EWL was also surrounded on three sides and the top by a box made of heavy black cardboard. This box and the dark surface that the EWL was sitting on ensured that light was not reflected in any significant way off of other surfaces but only reached the viewer directly along his line of sight to the EWL. The filters covered the front.

The experiment was conducted with shades drawn; there was one light on in the room. This provided a small, consistent amount of light so that the room was not completely dark every time the EWL was not activated. This reproducible ambient illumination was approximately equivalent to twilight or early evening, times when external visual clues are diminished during driving.

Each observer stood 25 feet or 7.62 meters from the EWL. A marker was placed on the ground to ensure that each observer stood at the same place during every trial. The observers pushed a response button when they noticed the firing of the EWL. The observers kept their eyes on a mark about one meter from the EWL. This was done so that the participants would detect the EWL with their peripheral vision.

Six participants performed twelve runs each, with fifty trials per run (a grand total of 600 trials for each observer). Each experiment was done in two sessions. In other words, each observer did six runs, while taking five-minute breaks between each run. This was done in order to keep the participants fresh and free from fatigue.

The electronic control system for measuring reaction times is shown in Figures 9 and 10. The setup is similar to that used for the *Shadow Truck* portion of this project (to be described later). The main difference from that operation is that here the mosfet circuitry is used.[13] Unlike the *Shadow Truck*, the EWL was not supplied from the vendor with a +5V 'trigger' wire. Thus the power cord for the device was used directly as a computer-controlled on/off switch. This necessitated the mosfet circuitry to act as a "+5 volt logic to +12 volt power" interface. Referring to the "mosfet board" section in Figure 10, a +5 volt signal on the gate of the N-type FET (the source of which is discussed below) causes current flow in the 100 kΩ resistor which drops the voltage at the gate of the P-type FET switching it on and providing power to the EWL. Both five and twelve volt power was conveniently provided by the computer power supply. The power is 'teed' off with a Y cable and routed to a small gray box which acts as a power junction (Figure 9). The front of the box supplies the +5 volts and the back supplies +12 volts. *All* grounds are tied together.

The rest of the electronic instrumentation is largely as it was for the companion *Shadow Truck*, using the National Instruments card. A *National Instruments Data Acquisition Card* (Nidaq)—

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[12] See Figures 9 and 10 of the companion report for this project, *Shadow Truck Light Bar*, for an example of the plastic sheeting attenuation used.

[13] Compare Figure 10 here with Figure 13 from the companion report on the *Shadow Truck Light Bar*. Here the EWL can be supplied (via the FET circuitry) with sufficient power from the computer's power supply. In the case of the *Shadow Truck Light Bar* too much power is required and an external supply is used for the +12 volts.

model 6024E—is a programmable, electronic circuit card that has 8 digital input/output ports, 16 channels of analog input, and 2 channels of analog output along with various timing and gating functions. This card plugs into a standard PCI slot in a PC (Figure 9). Its functions can be programmed in the C language (along with using the supplied Nidaq library functions). The use of this card is far superior in timing, accuracy and control in comparison to trying to program the standard serial or parallel outputs on a PC to perform the functions needed for this experiment.

A ribbon cable takes the inputs and outputs of this card to a connector. From there the board pins are wired to the logic and mosfet driving circuitry (Figure 9: physical, Figure 10: schematic).

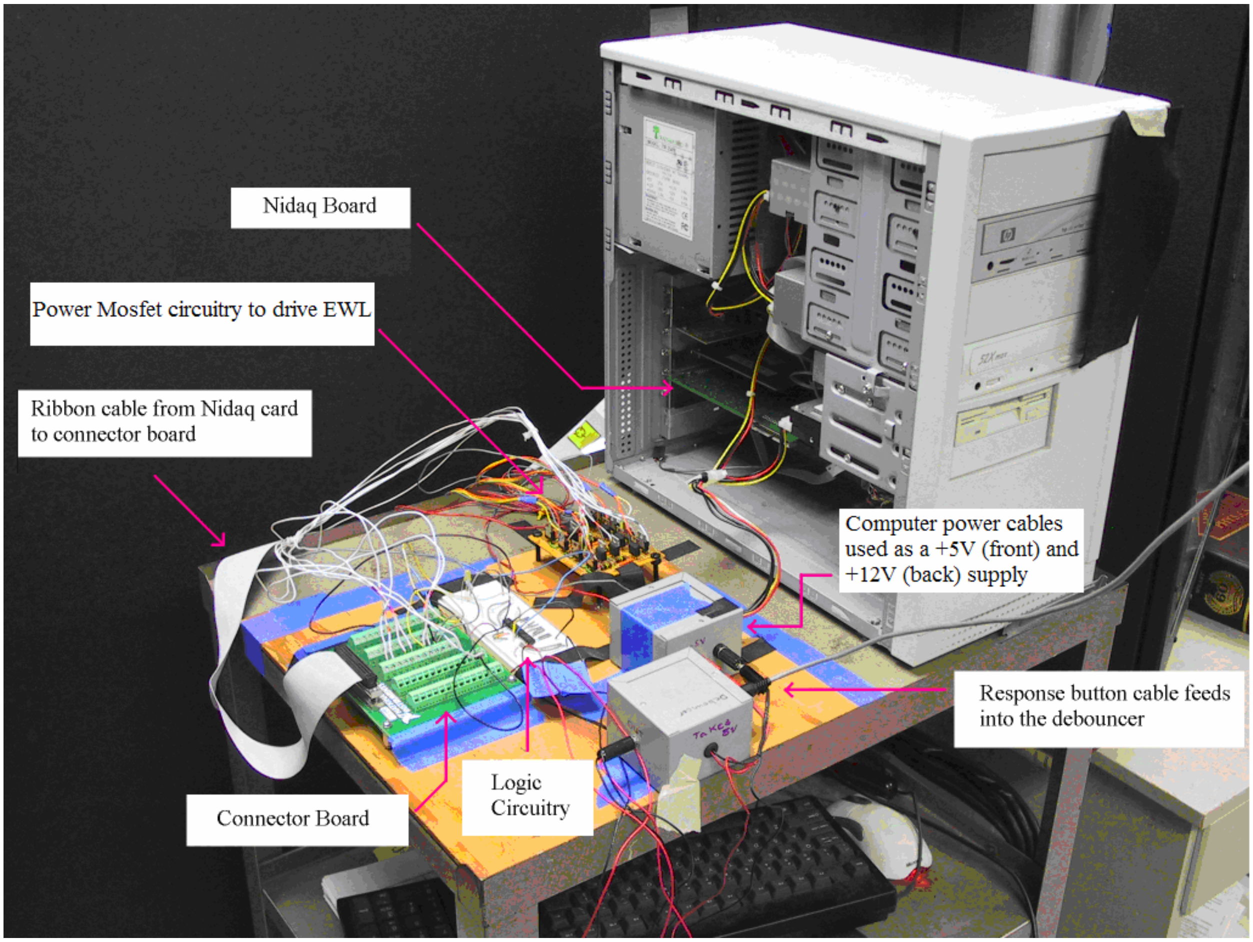

Figure 9: Electronic control system for the reaction time experiment

There is also a debouncer that takes the input from the response button (a noisy signal from a mechanical switch) and provides a “clean” version to the logic circuitry.

An outline of the theory of operation is as follows. EWL firing occurs when the Nidaq board issues a +5 volt signal to the digital outputs. The power from the Nidaq board is insufficient to directly operate the EWL (which require +12 volts). Therefore the digital outputs trigger an external circuit (the mosfets discussed above) that in turn drives the EWL. This is shown in Figure 10. The Nidaq digital I/O #6 corresponds to pin 16 on the connector board. This turns on the mosfet circuitry (dashed box), which turns on the EWL.

The C programming language was used, along with the Nidaq supplied library, to program the Nidaq card. The standard pseudo-random number generator in C was used to provide a time delay between pattern firings. A random delay is needed because the observer can "learn" what the time delay is and anticipate (perhaps without realizing it) the firing rather than reacting to it.

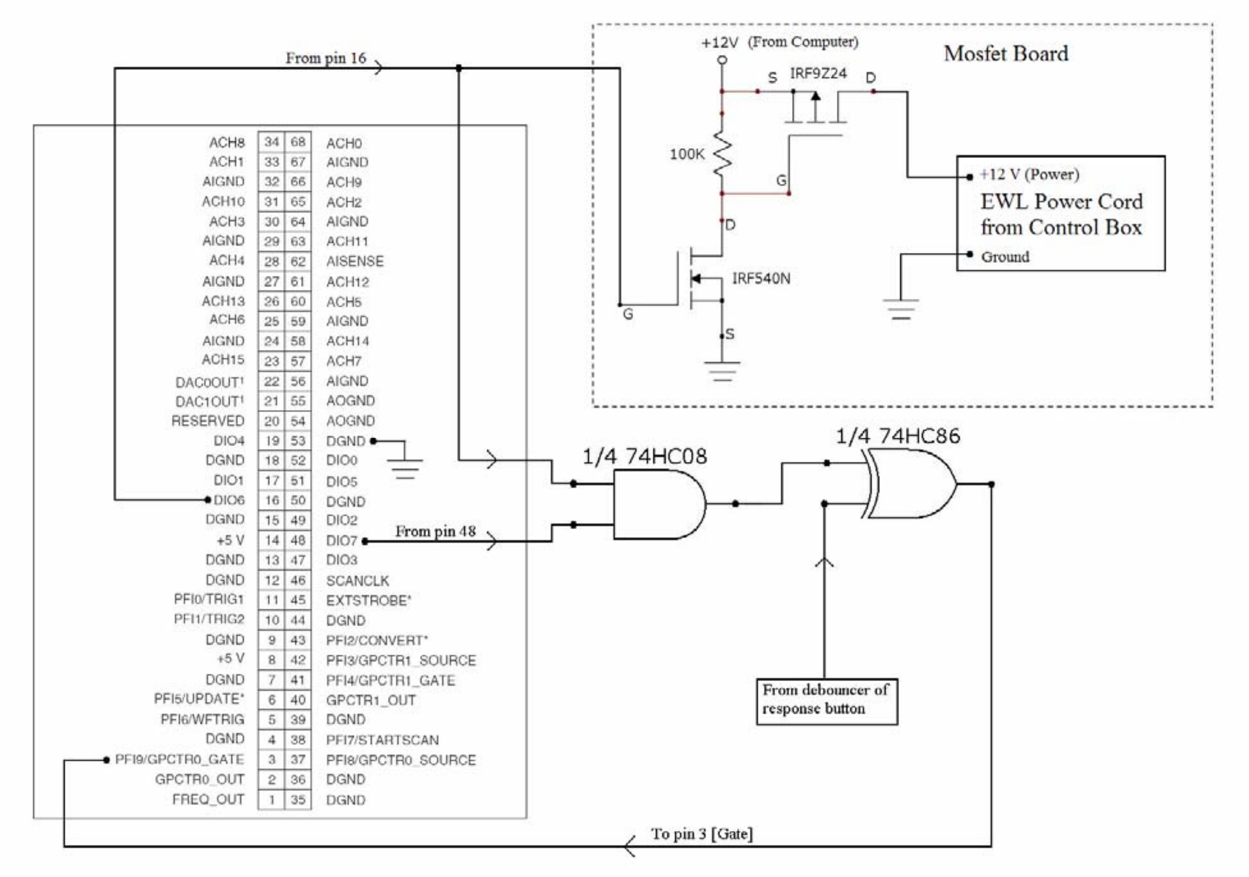

Figure 10: Connector board pinout, driving circuit and control logic.

However, this precaution does not completely obviate the possibility of a premature response. The counter in the Nidaq card, which measures the reaction time, works off of two gate signals—a start signal and a stop signal. It measures the time between these two signals. The start signal is the firing of the EWL (indirectly) from pin 16 (digital I/O #6). The stop signal is from the response button of the subject (via the debouncer which introduces a negligible delay).

These two gate signals both need to go to the Nidaq timing gate at pin 3, but they cannot both be electrically connected directly at pin 3 or the two signals would interfere with each other's circuitry. Therefore the two signals need to be buffered. Even if this weren't the case, a problem would arise should the subject accidentally hit the response button before the firing actually occurs. The two signals would reverse their roles and the response button could signal a start to the counter and the light firing could signal an end to it. This is why the logic circuitry in Figure 10 is used, along with a software safeguard. The digital I/O #7 (pin 48) is used as an "arming" mechanism for the counter gate signals. When pin 48 goes high the output of pin 16 can be passed (through the AND gate) to the "exclusive or" (XOR) which has its output linked to the timing gate at pin 3. If pin 48 is low, pin 16 has no effect on the AND gate.

The timing gate (pin 3) is not "activated" by the software until just before the light is to fire. *Thus a response button push before this time has no effect*. Pin 48 goes high just before the light goes on for the first time in a given pattern. It goes low 5 ms after the EWL comes on for the first time. This first firing in a pattern constitutes the start signal. Since 5 milliseconds is far below a typical reaction time, the chances of someone hitting a response button during that interval is effectively nil. Of course after a response is recorded, everything is reset.
Unlike the *Shadow Truck Light Bar* there was no provision for computer control of the configuration (pattern) being tested. Thus after every run of fifty trials the pattern was changed manually at the control box for the next set of trials. Needless to say this prevented the randomization of the order of presentation of patterns to the subjects—a very desirable feature but one simply not possible here.

The Nidaq card's 100 kHz internal timebase is used for the timing. Thus the accuracy is to the hundredth of a millisecond, far greater than what is needed for this kind of experiment. The reaction time data is held in active memory until the sequence of trials is done and then it is all written to disk, thereby preventing any disk operations from interfering with timing measurements.

IV. Data Analysis and Laboratory Test Results

After collecting the data the fifty reaction times for every pattern/configuration were averaged. The summary of results is shown in the next six Tables.

Subject #1:

Runs	Rotation Speed	Time	Normal/Inverted Lights	Reaction Time (ms)	STD	Std Error
1	slowest	T1	Normal	284.2	76.0	10.7
2	slowest	T1	Inverted	549.3	300.4	42.4
3	slowest	T2	Normal	315.0	124.9	17.6
4	slowest	T2	Inverted	451.7	327.4	46.3
5	medium	T1	Normal	268.9	77.5	10.9
6	medium	T1	Inverted	427.4	214.1	30.2
7	medium	T2	Normal	334.8	208.4	29.4
8	medium	T2	Inverted	593.9	241.1	34.0
9	fast	T1	Normal	304.7	117.6	16.6
10	fast	T1	Inverted	434.2	122.1	17.2
11	fast	T2	Normal	315.0	99.6	14.0
12	fast	T2	Inverted	342.7	146.9	20.7

Table 1 - Subject 1 results

Subject #2:

Runs	Rotation Speed	Time	Normal/Inverted Lights	Reaction Time (ms)	STD	Std Error
1	slowest	T1	Normal	339.2	149.9	21.1
2	slowest	T1	Inverted	353.4	177.7	25.1
3	slowest	T2	Normal	363.4	136.1	19.2
4	slowest	T2	Inverted	321.5	93.9	13.2
5	medium	T1	Normal	300.4	63.1	8.9
6	medium	T1	Inverted	306.4	49.4	6.9
7	medium	T2	Normal	345.6	112.7	15.9
8	medium	T2	Inverted	310.3	69.0	9.7
9	fast	T1	Normal	380.6	116.1	16.4
10	fast	T1	Inverted	378.3	186.7	26.4
11	fast	T2	Normal	424.6	146.9	20.7
12	fast	T2	Inverted	372.0	136.1	19.2

Table 2 - Subject 2 results

Subject #3:

Runs	Rotation Speed	Time	Normal/Inverted Lights	Reaction Time (ms)	STD	Std Error
1	slowest	T1	Normal	251.3	43.4	6.1
2	slowest	T1	Inverted	246.3	57.9	8.1
3	slowest	T2	Normal	238.2	59.5	8.4
4	slowest	T2	Inverted	237.1	40.8	5.7
5	medium	T1	Normal	237.8	34.5	4.8
6	medium	T1	Inverted	239.0	38.0	5.3
7	medium	T2	Normal	228.9	25.6	3.6
8	medium	T2	Inverted	231.9	39.5	5.5
9	fast	T1	Normal	208.1	65.4	9.2
10	fast	T1	Inverted	223.7	19.0	2.6
11	fast	T2	Normal	230.2	36.8	5.2
12	fast	T2	Inverted	232.8	24.2	3.4

Table 3 - Subject 3 results

Subject #4:

Runs	Rotation Speed	Time	Normal/Inverted Lights	Reaction Time (ms)	STD	Std Error
1	slowest	T1	Normal	370.7	180.7	25.5
2	slowest	T1	Inverted	430.4	281.6	39.8
3	slowest	T2	Normal	462.5	253.2	35.8
4	slowest	T2	Inverted	432.9	270.6	38.2
5	medium	T1	Normal	364.6	127.1	17.9
6	medium	T1	Inverted	489.1	238.5	33.7
7	medium	T2	Normal	369.7	118.5	16.7
8	medium	T2	Inverted	403.5	177.8	25.1
9	fast	T1	Normal	332.3	133.3	18.8
10	fast	T1	Inverted	408.4	196.5	27.7
11	fast	T2	Normal	359.4	176.1	24.9
12	fast	T2	Inverted	502.9	308.9	43.6

Table 4 - Subject 4 results

Subject #5:

Runs	Rotation Speed	Time	Normal/Inverted Lights	Reaction Time (ms)	STD	Std Error
1	slowest	T1	Normal	282.2	62.8	8.8
2	slowest	T1	Inverted	606.1	273.5	38.6
3	slowest	T2	Normal	267.9	64.0	9.0
4	slowest	T2	Inverted	278.5	78.0	11.0
5	medium	T1	Normal	239.2	55.4	7.8
6	medium	T1	Inverted	358.6	146.6	20.7
7	medium	T2	Normal	267.3	46.0	6.5
8	medium	T2	Inverted	416.6	160.3	22.6
9	fast	T1	Normal	289.2	150.4	21.2
10	fast	T1	Inverted	440.0	90.46	12.7
11	fast	T2	Normal	264.8	73.5	10.3
12	fast	T2	Inverted	467.7	141.9	20.0

Table 5 - Subject 5 results

Subject #6:

Runs	Rotation Speed	Time	Normal/Inverted Lights	Reaction Time (ms)	STD	Std Error
1	slowest	T1	Normal	277.2	56.7	8.0
2	slowest	T1	Inverted	975.5	58.7	8.3
3	slowest	T2	Normal	320.1	121.1	17.1
4	slowest	T2	Inverted	800.1	241.2	34.1
5	medium	T1	Normal	260.6	42.1	5.9
6	medium	T1	Inverted	817.9	273.2	38.6
7	medium	T2	Normal	377.8	277.6	39.2
8	medium	T2	Inverted	850.7	155.6	22.0
9	fast	T1	Normal	279.7	70.7	9.9
10	fast	T1	Inverted	514.9	79.7	11.2
11	fast	T2	Normal	341.0	161.7	22.8
12	fast	T2	Inverted	662.9	100.2	14.1

Table 6 - Subject 6 results

With twelve configurations to analyze, *analysis of variance* (ANOVA) was clearly called for; the large number of patterns also meant that an analysis "by hand" was likely to let error creep in. Fortunately VDL staff had access to the use of SAS[14] (which once stood for "S*tatistical Analysis Software*"). The relevant program, data and output file are shown in Appendix 1.

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[14] http://www.sas.com/

The ANOVA was run as a four factor[15] F-test with no interactions. There seemed no good rationale for doing a more complicated test. The p-values were as shown in Table 7.

Factor	**p-value**
Subject	0.0001
Rotation (slowest, med., fastest)	0.6115
Time (T1/T2)	0.7728
Normal/Inverted	0.0001

Table 7: P-values from the ANOVA on the EWL taken from Appendix 1.

The strong variation among subjects, as evidenced in Table 7, is no surprise. It is invariably the case that individual differences in reaction time are quite marked; in fact, if this well-known fact is **not** taken into account the results of a statistical analysis are quite likely to be *wrong*.

More surprisingly however, the *rotation rate seems to have made no difference*. The same can be said for the duty cycle (i.e. the null hypothesis of no difference in reaction time due to these factors cannot be rejected).

The interesting factor seems to be normal vs. inverted operation. The data from Tables 1 through 7 can be recast as looking only at the normal (light) or inverted (dark) and of course (as per the warning above) subject. Table 8 is obtained by first taking the average of each run in Table 1 labeled "Inverted" and the average of each run labeled "Normal" in Table 1 and putting them into the first row with numerical entries (1st two columns). This represents subject one. The process is repeated for Table 2 representing the second subject and so on. Since all six of each run for "Normal" for a given subject have fifty trials this averaging is equally weighted. The same is obviously true for the "Inverted" condition. Since rotation and time seemed to produce no differences there is unlikely to be any interaction term (between these and normal/inverted) affecting this procedure. The third column is just the difference of the first two columns.

Inverted Pattern (ms)	Normal Pattern (ms)	Difference (Inv. - Norm.)
466.5	303.8	162.7
340.3	358.9	-18.6
235.1	232.4	2.7
444.5	376.5	68.0
427.9	268.4	159.5
770.3	309.4	460.9
	Average of Differences:	139.2

Table 8: Table of reaction times between the normal (*light*) pattern and the inverted (*dark*) pattern and the differences. Subject number orders the rows.

Table 8 suggests a t-test (paired two-sample for the mean). For the paired t-test between the normal pattern and the inverted pattern, Table 8 gives us the sample variance:

$$s^2 = \frac{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}{n-1} = \frac{153057.8}{5} = 30611.6\,,$$

---

[15] The four factors were subject, rotation speed, duty cycle and normal/inverted.

where the individual time *differences* are denoted by x_i and the average by $\overline{x}$, along with the number of subjects by n (= 6). From these we can easily get the t statistic:

$$t = \frac{\overline{x}\sqrt{n}}{s} = \frac{139.2\sqrt{6}}{175.0} = 1.95 .$$

The associated critical (one-tail) value[16] for five degrees of freedom (= n – 1) is 2.02 at the 95th percentile. Hence,

$$t_{paired\ diff.} = 1.95 < t_{crit.0.95} = 2.02$$

barely showing that a rejection of the null hypothesis of equal means for the reaction times of the two configurations is **not** warranted. The associated p-value is 0.054, falling just above the five percent cutoff.

While this outcome falls just short of statistical significance, there are some tantalizing clues in the data tables that there may actually be an effect, at least for some individuals. The reader is referred to Table 6 (subject 6). Note that in ***every*** configuration his reaction time to the inverted pattern is ***substantially*** longer than his reaction time to the normal pattern. Qualitatively it seems that at least a portion of the population may be affected by the difference in the normal vs. inverted patterns. Additional testing with a larger number of observers (beyond the scope of the present project) would be necessary to generalize this trend.

V. Conclusions

On a qualitative basis the EWL was a success. The vendor supplied a product very near what was originally envisioned. The device can fairly be judged to look unique (Figures 5-7) as per our original goal.

The reaction time testing also illuminated the variability in the response to the range of parameters. Contrary to what we might have expected, neither the rotation rate nor the duty cycle elicited a significant difference in reaction time.[17]

The more interesting result from the reaction time testing was with the comparison of normal vs. inverted pattern, in which the normal pattern elicited the shorter reaction time. While this result just failed to reach statistical significance at the 95% level (i.e. $\alpha = 0.05$), experience suggests that it may affect at least a portion of the population and that this might have shown up in the statistics with a larger pool of subjects.

The reason this result is particularly interesting has to do with the amount of light. As mentioned briefly above, the inverted (or *dark*) mode actually has more light than the normal (or *light*) mode despite the name. A comparison of Figures 5 and 6 shows this clearly. Figure 5 shows

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[16] Appendix D of *Probability and Statistics (2nd Ed.)*, by Murray R. Spiegel in *Schaum's Outline Series* [McGraw-Hill Book Company].

[17] At least it made no difference within the quite reasonable bounds tested of 0.628 seconds to 1.787 seconds for a period. Nothing in the data would lead one to suspect that increasing the frequency alone (i.e. with a new, modified EWL) would give any different result.

that, in the half of the EWL visible at any one time, an observer will see one lit stripe in normal mode.[18] From Figure 6, we note that he'll see (approximately—see footnote 18) three lit stripes. Thus inverted mode provides roughly three times the light signal of the normal mode.

This is important because, other things being held equal, a greater intensity of stimulus will produce a greater response or faster reaction time (up to a limit); thus more light would lead one to expect a faster reaction. In fact, the opposite happened, although the result falls just short of statistical significance. If the inverted mode yields a longer reaction time than the normal mode despite three times the light signal, how to explain it? Apparently, total brightness is not necessarily the most important factor in determining which pattern elicits the fastest reaction time. Provided there is a certain minimum brightness, it seems to be the case that the conspicuity of the moving stripe in the apparent motion stimulus may determine which pattern is the most effective. One can easily imagine that with the prototype EWL, the narrow stripe against a dark background has greater conspicuity than a 'dark' stripe against a background that is normally on, due to any number optical or visual factors that could reduce the effective contrast between the stripe and the background. For example, a slight defocus of the eyes would cause the almost solidly lit background portion of the EWL to spill over into the dark stripe region. The same effect would result in the field under foggy conditions. Also, since the target was viewed peripherally in the lab, as would most often be the case initially in the field (depending on the driver's direction of gaze when the EWL first came into the field of view), the resolution of the visual system in the part of the retina that is being stimulated might be insufficient to produce the maximum possible contrast between the dark stripe and bright background of an inverted display, particularly at long viewing distances (which produce small image size on the retina).

In other words, the movement of a light stripe against a dark background might provide visually greater contrast, due either to eye defocus, poor resolution in the visual periphery, or environmental conditions, than does the movement of a dark stripe against a light background. The resulting improved detection of movement could more than compensate for the reduced time-averaged quantity of illumination.

Additional testing with a large pool of observers could serve to further refine the optimal settings of rotation speed of the apparent movement stimulus, duty cycle of the individual stripes, and normal vs. inverted mode. Future testing could also explore use of the flash/strobe unit in the upper section, which was outside the scope of the present project. Observational field testing of the EWL would be anticipated to be of substantial value in serving to refine the timing parameters of the device and to compare its overall effectiveness with that of traditional devices.

In summary, the prototype EWL fully met our expectations as a unique signaling device. It proved to be visually effective and conspicuous while at the same time avoiding the problems of excessively high levels of illumination that plague its forerunners. Its unique shape and appearance would serve well to identify it uniquely with Caltrans work vehicles in the perception of drivers, and to distinguish it from other warning signal devices, thus providing an additional margin of safety in Caltrans work zones.

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[18] This is just meant to be an estimate. Of course an observer can also see pieces of both stripes at a certain point, one coming into view, one passing out. "One stripe" is just meant to be a rough average over time.

Appendix 1 – SAS Input, Data and Output Files

The input program for the *Statistical Applications Software* was as follows:

```
/* Four-factor ANOVA on EWL data -- NO INTERACTION MODEL */

title 'Four-factor ANOVA for EWL - NO INTERACTION';

options nocenter ls=80 ps=60; /* Formatting. */

data EWLnoint;
/* Take data from external file. */

infile 'C:\SAS\sasprog\Kent_data\EWLinput.txt';

input subj 1 rot 9 time 17 N_I 25 RT 33-37;

proc glm;
class subj rot time N_I;
model RT=subj rot time N_I;
run;
quit;
```

The data file consisted (as can be seen in the *class* line above) of the subject number (1 through 6), rotation rate (1 through 3), duty cycle (time—1 through 2) and whether it was normal or inverted (N_I—1 through 2) all on a line with the last number on the line being the average reaction time response in milliseconds for that subject and configuration. Each number is tab separated from the next. The number of lines represents all the subject/configuration combinations tested; fortunately this is short enough that it can be reproduced in its entirety here after the legend (key):

Legend for SAS input: subject rotation time norm/inv RT (no STD included)
subject # - (alphabetical by last name)
Rotation Speed --> slow is 1,

med is 2, fast is 3
Time --> T1 is 1, T2 is 2
Normal/Inverted --> Normal is 1, Inverted is 2
Reaction Time (RT) in ms to 1 decimal place

1	1	1	1	284.2
1	1	1	2	549.3
1	1	2	1	315.0
1	1	2	2	451.7
1	2	1	1	268.9
1	2	1	2	427.4
1	2	2	1	334.8
1	2	2	2	593.9
1	3	1	1	304.7
1	3	1	2	434.2
1	3	2	1	315.0
1	3	2	2	342.7
2	1	1	1	339.2
2	1	1	2	353.4
2	1	2	1	363.4
2	1	2	2	321.5
2	2	1	1	300.4
2	2	1	2	306.4
2	2	2	1	345.6
2	2	2	2	310.3
2	3	1	1	380.6
2	3	1	2	378.3
2	3	2	1	424.6
2	3	2	2	372.0
3	1	1	1	251.3
3	1	1	2	246.3
3	1	2	1	238.2
3	1	2	2	237.1
3	2	1	1	237.8
3	2	1	2	239.0
3	2	2	1	228.9
3	2	2	2	231.9
3	3	1	1	208.1
3	3	1	2	223.7
3	3	2	1	230.2
3	3	2	2	232.8
4	1	1	1	370.7
4	1	1	2	430.4
4	1	2	1	462.5

4	1	2	2	432.9
4	2	1	1	364.6
4	2	1	2	489.1
4	2	2	1	369.7
4	2	2	2	403.5
4	3	1	1	332.3
4	3	1	2	408.4
4	3	2	1	359.4
4	3	2	2	502.9
5	1	1	1	282.2
5	1	1	2	606.1
5	1	2	1	267.9
5	1	2	2	278.5
5	2	1	1	239.2
5	2	1	2	358.6
5	2	2	1	267.3
5	2	2	2	416.6
5	3	1	1	289.2
5	3	1	2	440.0
5	3	2	1	264.8
5	3	2	2	467.7
6	1	1	1	277.2
6	1	1	2	975.5
6	1	2	1	320.1
6	1	2	2	800.1
6	2	1	1	260.6
6	2	1	2	817.9
6	2	2	1	377.8
6	2	2	2	850.7
6	3	1	1	279.7
6	3	1	2	514.9
6	3	2	1	341.0
6	3	2	2	662.9

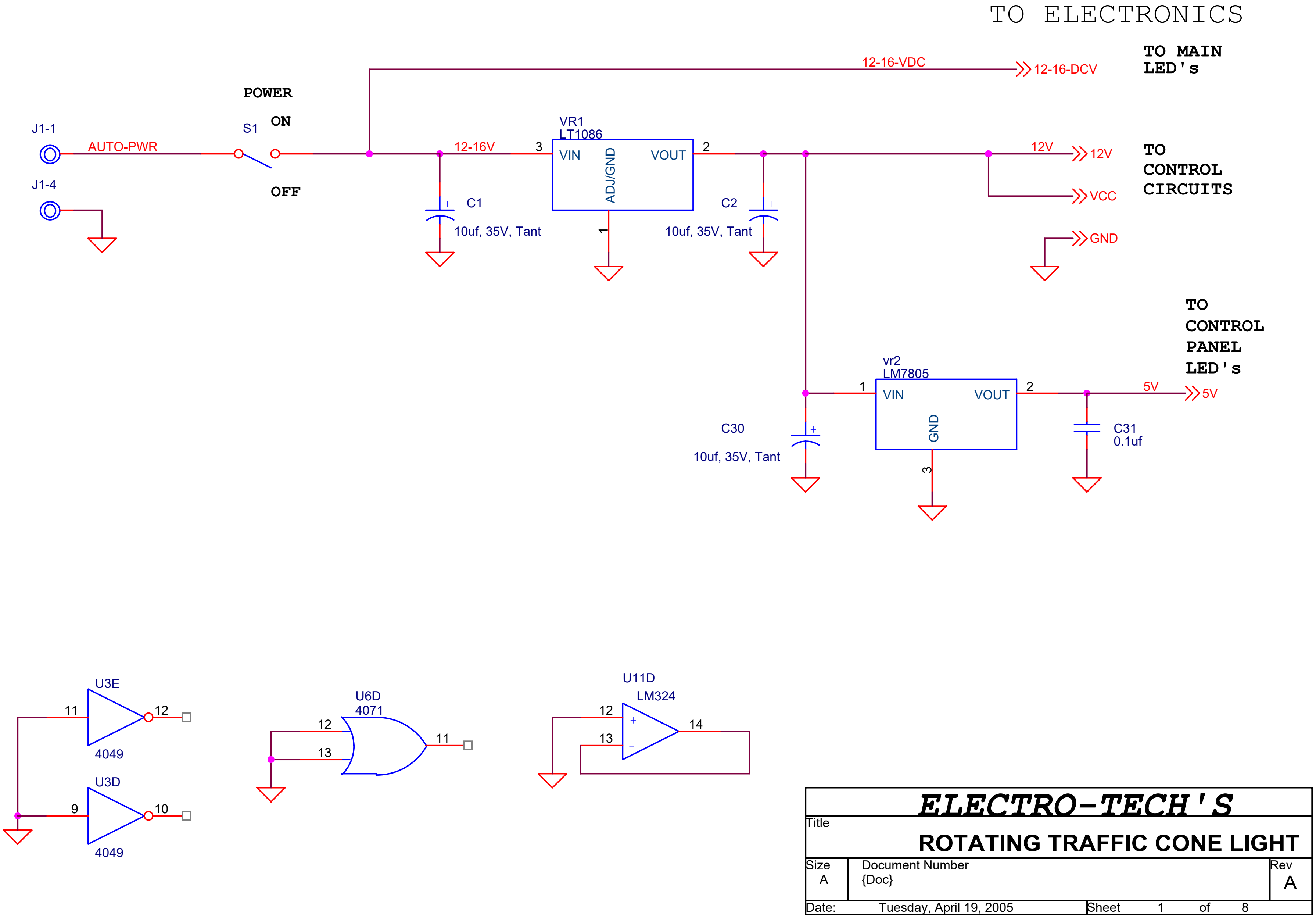
The output file is also short enough to be shown (next page):

```
Four-factor ANOVA for EWL - NO INTERACTION    22:33 Friday, February 17, 2006   1

General Linear Models Procedure
Class Level Information

Class    Levels    Values

SUBJ          6    1 2 3 4 5 6

ROT           3    1 2 3

TIME          2    1 2

N_I           2    1 2


Number of observations in data set = 72


Four-factor ANOVA for EWL - NO INTERACTION    22:33 Friday, February 17, 2006   2

General Linear Models Procedure

Dependent Variable: RT
                                     Sum of            Mean
Source                  DF          Squares          Square   F Value      Pr > F

Model                    9     959060.92931    106562.32548      9.11      0.0001

Error                   62     725239.60722     11697.41302

Corrected Total         71    1684300.53653

                  R-Square             C.V.        Root MSE               RT Mean

                  0.569412         28.62316       108.15458             377.85694


Source                  DF        Type I SS     Mean Square   F Value      Pr > F

SUBJ                     5     597657.73903    119531.54781     10.22      0.0001
ROT                      2      11598.44778      5799.22389      0.50      0.6115
TIME                     1        983.46125       983.46125      0.08      0.7728
N_I                      1     348821.28125    348821.28125     29.82      0.0001

Source                  DF      Type III SS     Mean Square   F Value      Pr > F

SUBJ                     5     597657.73903    119531.54781     10.22      0.0001
ROT                      2      11598.44778      5799.22389      0.50      0.6115
TIME                     1        983.46125       983.46125      0.08      0.7728
N_I                      1     348821.28125    348821.28125     29.82      0.0001
```

Appendix 2 – EWL Schematic

(see following pages)

TRAFFIC CONE LIGHT



ELECTRO-TECH'S

Title
ROTATING TRAFFIC CONE LIGHT

Size A
Document Number {Doc}
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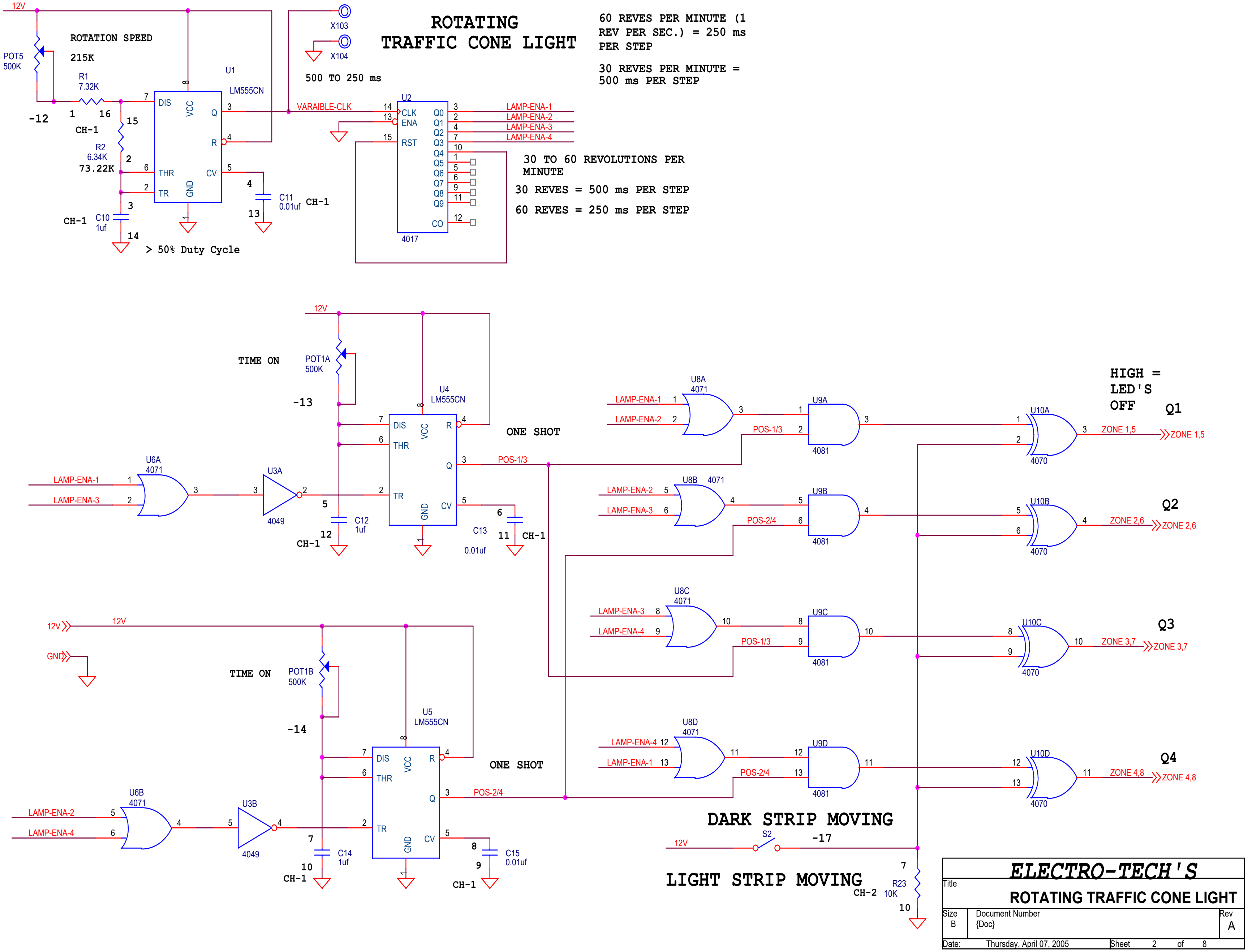

ELECTRO-TECH'S

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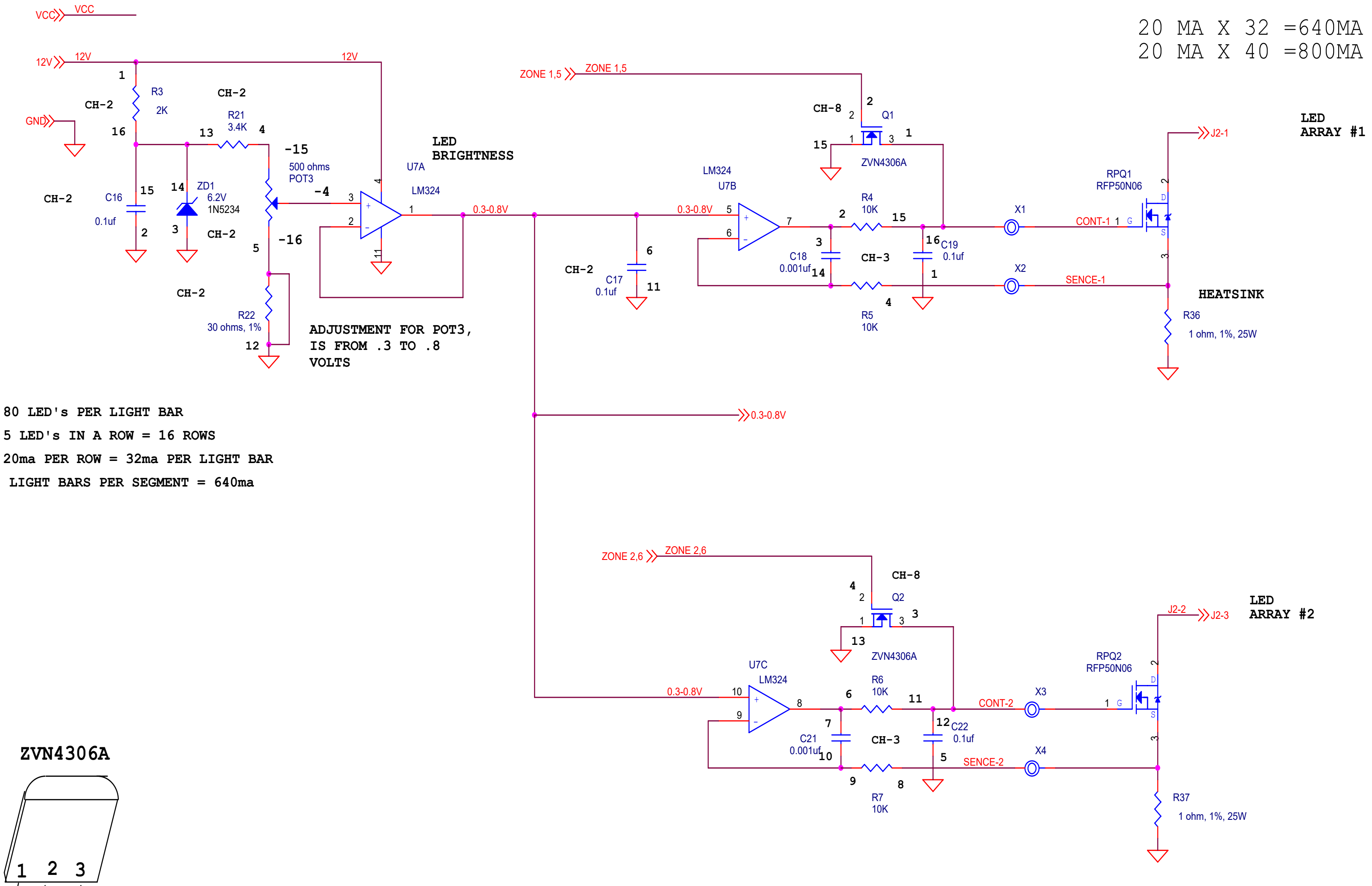
160 LED'S   40 OR 32

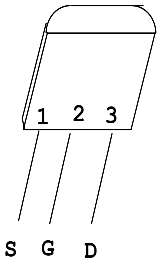
20 MA X 32 =640MA
20 MA X 40 =800MA



ADJUSTMENT FOR POT3,
IS FROM .3 TO .8
VOLTS

80 LED's PER LIGHT BAR
5 LED's IN A ROW = 16 ROWS
20ma PER ROW = 32ma PER LIGHT BAR
2 LIGHT BARS PER SEGMENT = 640ma

ZVN4306A



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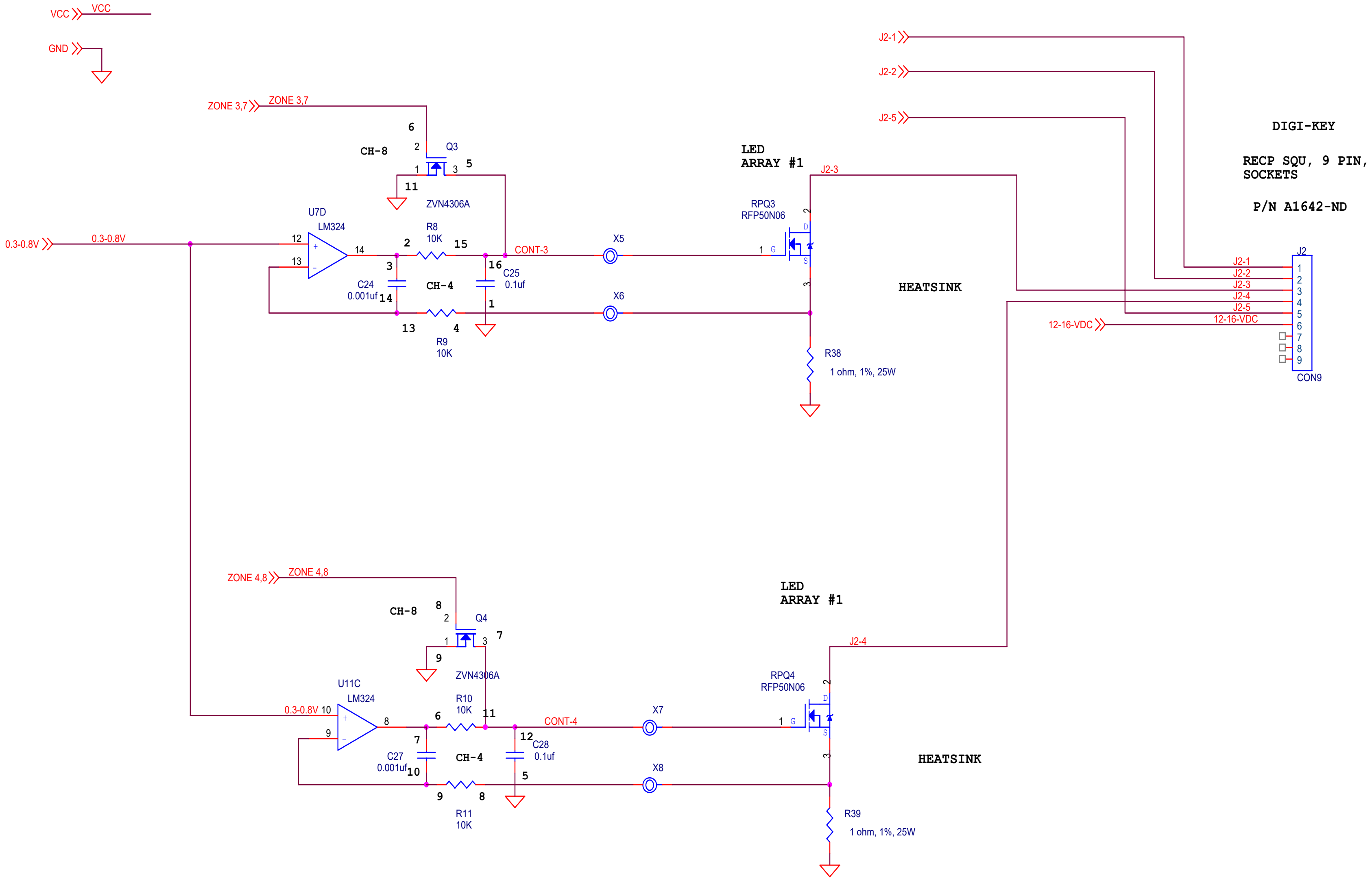

ELECTRO-TECH'S

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ROTATING TRAFFIC CONE LIGHT

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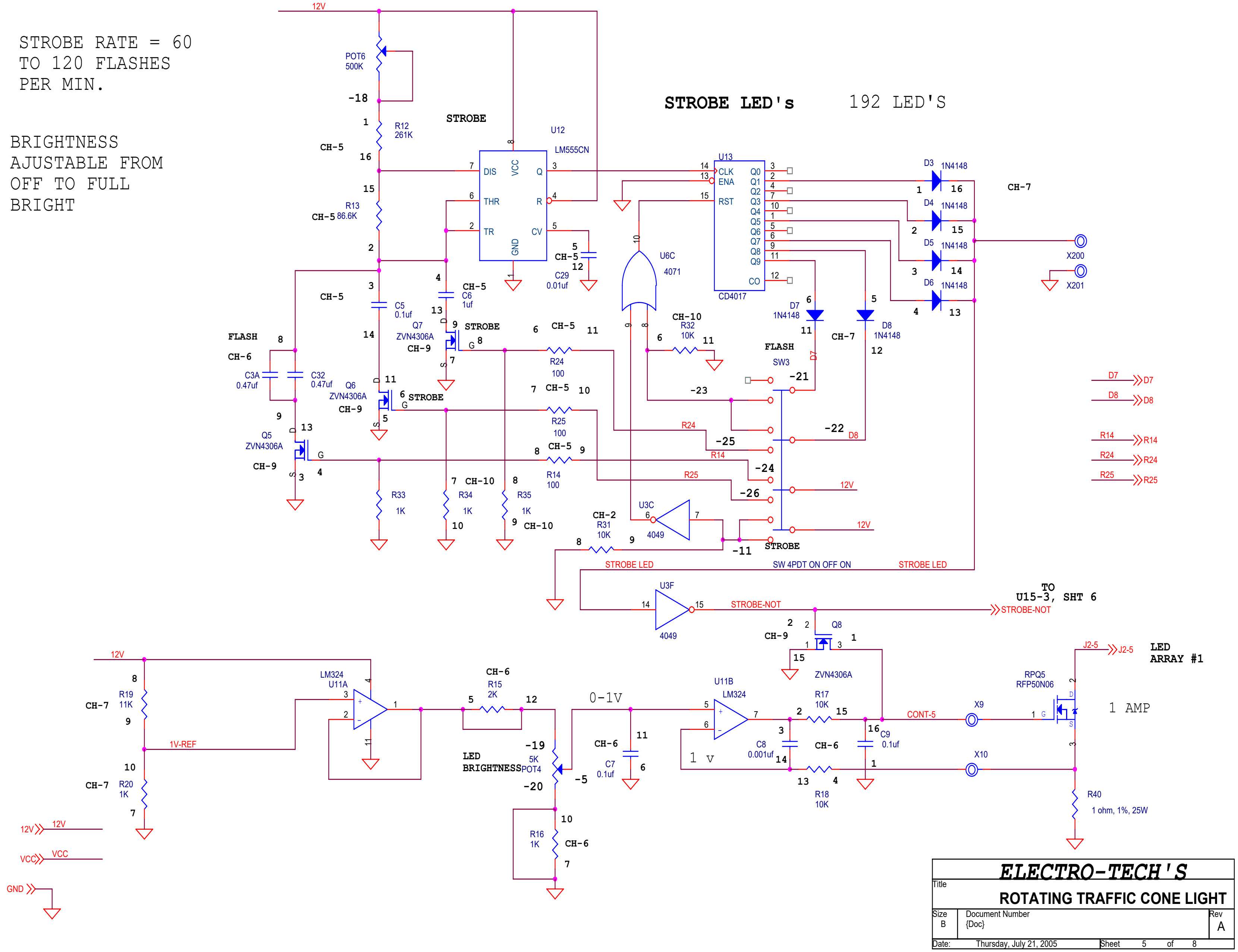

STROBE RATE = 60
TO 120 FLASHES
PER MIN.

BRIGHTNESS
AJUSTABLE FROM
OFF TO FULL
BRIGHT

ELECTRO-TECH'S

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ROTATING TRAFFIC CONE LIGHT

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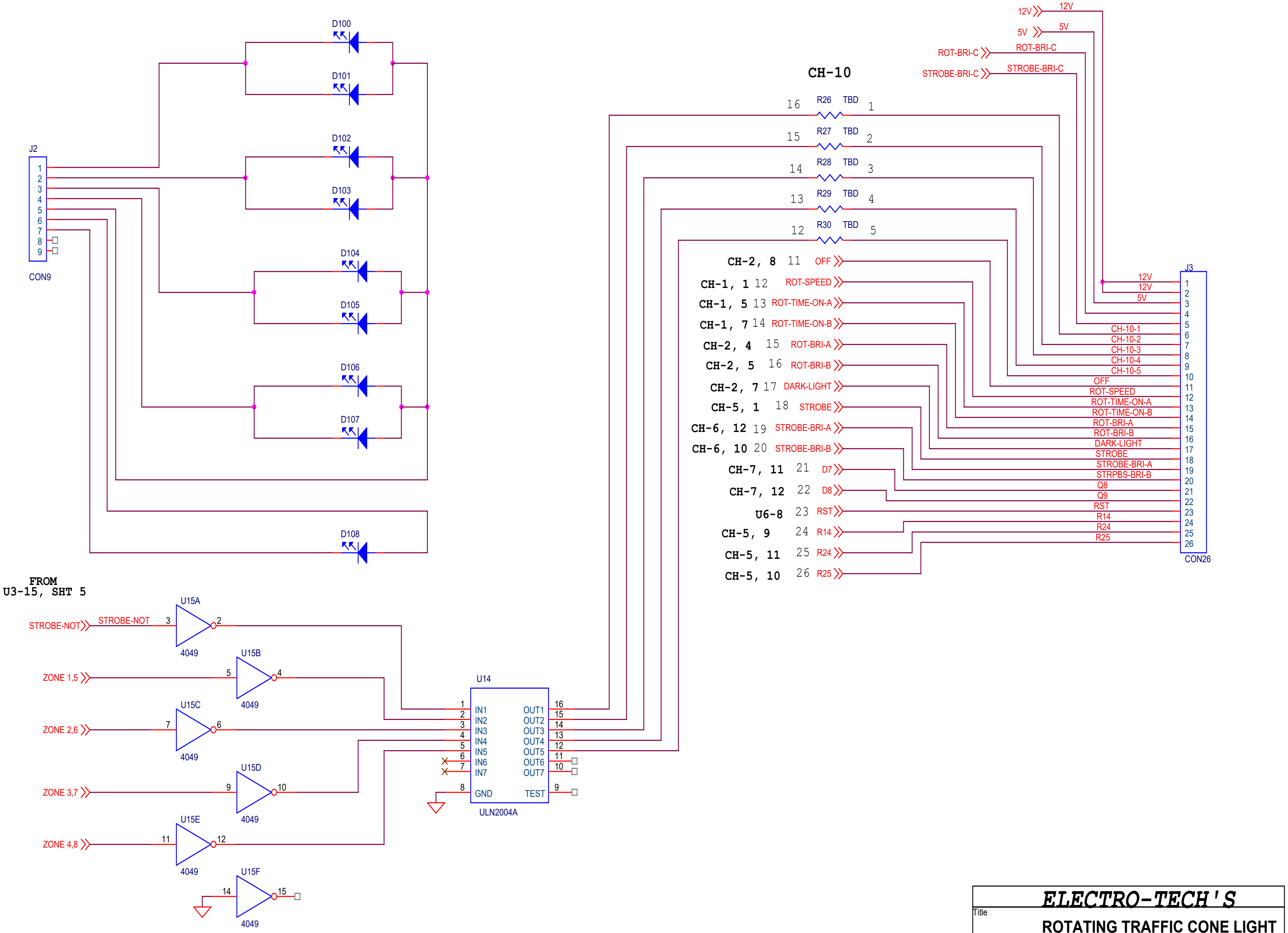

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Title ROTATING TRAFFIC CONE LIGHT	
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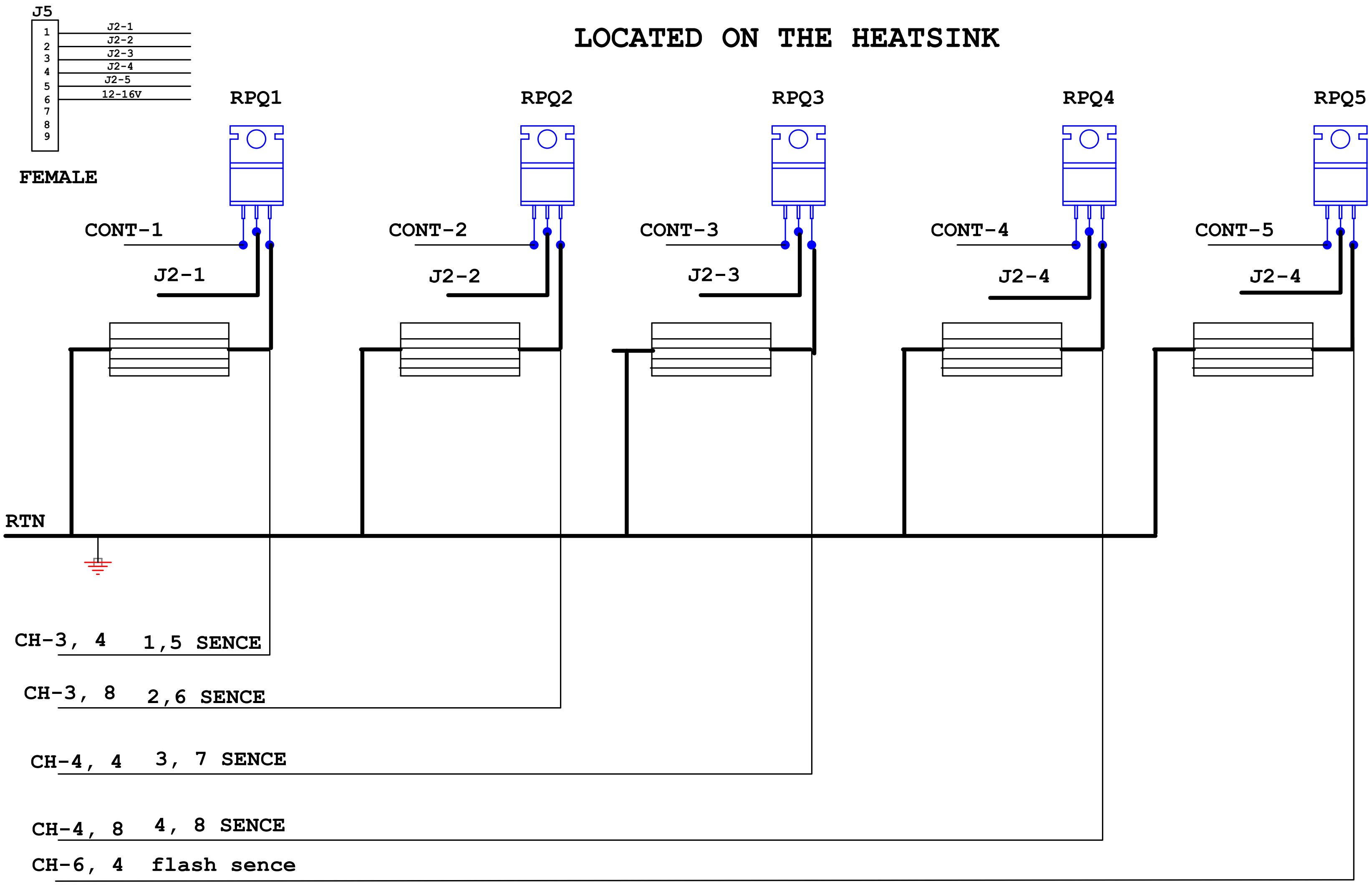

ELECTRO-TECH'S

Title

ROTATING TRAFFIC CONE LIGHT

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CH-1

1	7.32K	16	R1
2	6.34K	15	R2
3	1uf	14	C10
4	0.01uf	13	C11
5	1uf	12	C12
6	0.01uf	11	C13
7	1uf	10	C14
8	0.01uf	9	C15

CH-2

1	2K	16	R3
2	0.1uf	15	C16
3	ZD1	14	ZD1
4	3.4K	13	R21
5	~~301~~	12	R22
6	0.1uf	11	C17
7	10K	10	R23
8		9	

CH-3

1	0.1uf	16	C19
2	10K	15	R4
3	0.001uf	14	C18
4	10K	13	R5
5	0.1uf	12	C22
6	10K	11	R6
7	0.001uf	10	C21
8	10K	9	R7

CH-4

1	0.1uf	16	C25
2	10K	15	R8
3	0.001uf	14	C24
4	10K	13	R9
5	0.1uf	12	C28
6	10K	11	R10
7	0.001uf	10	C27
8	10K	9	R11

CH-5

1	261k	16	R12
2	86.6k	15	R13
3	0.1uf	14	C5
4	1uf	13	C6
5	0.01uf	12	C29
6	100	11	R24
7	100	10	R25
8	100	9	R14

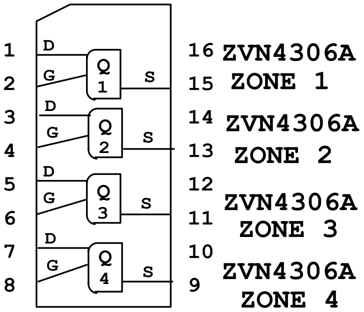
CH-6

1	0.1uf	16	C9
2	10K	15	R17
3	0.001uf	14	C8
4	10K	13	R18
5	~~2K~~	12	R15
6	0.1uf	11	C7
7	~~3K~~	10	R16
8	TBD	9	C23

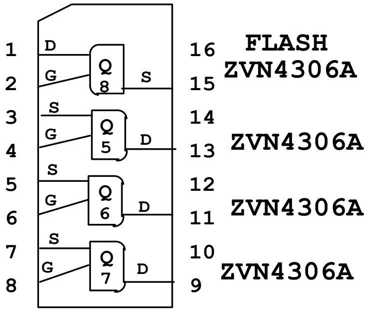
CH-7

1	1N4148	16	D3
2	1N4148	15	D4
3	1N4148	14	D5
4	1N4148	13	D6
5	1N4148	12	D7
6	1N4148	11	D8
7	20K	10	R20
8	20K	9	R19

CH-8

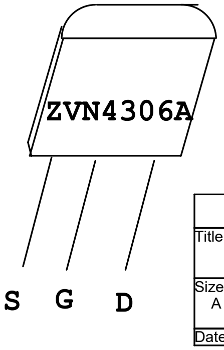


CH-9



CH-10

1	300	16	R26
2	300	15	R27
3	300	14	R28
4	300	13	R29
5	300	12	R30
6	10K	11	R32
7	1K	10	R34
8	1K	9	R35



ELECTRO-TECH'S

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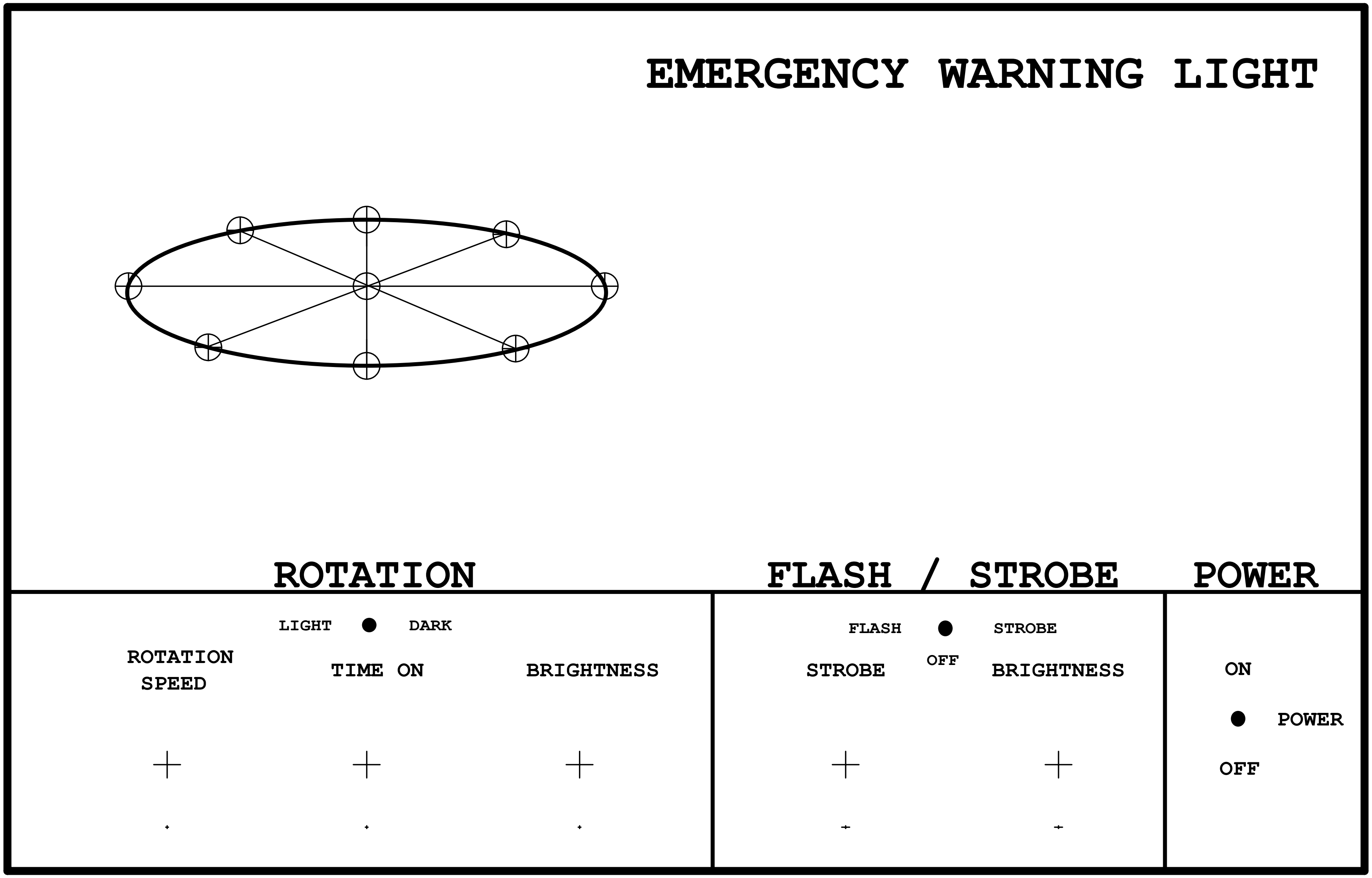
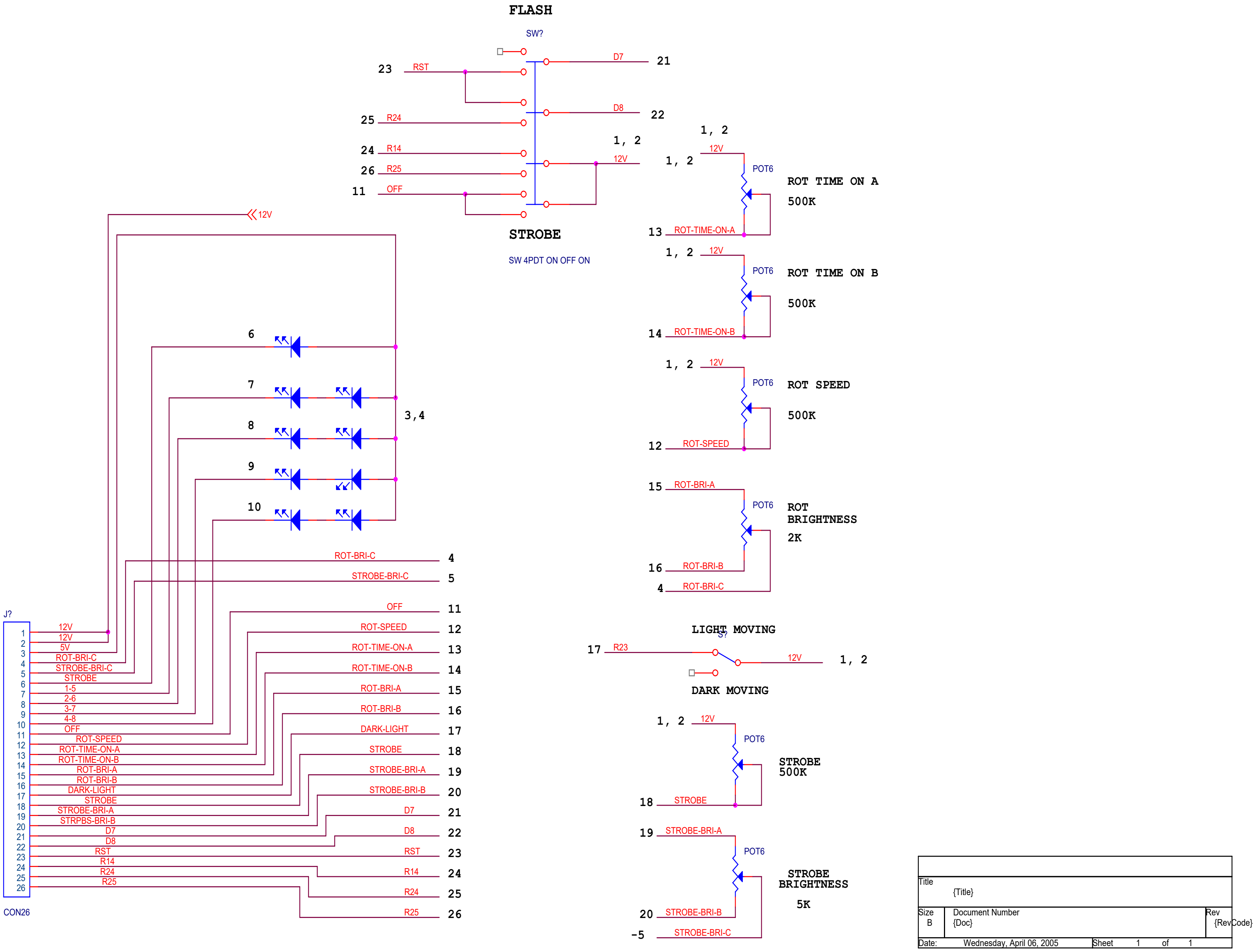
CONTROL PANEL


EMERGENCY WARNING LIGHT
ROTATION
FLASH / STROBE
POWER
LIGHT
DARK
ROTATION SPEED
TIME ON
BRIGHTNESS
FLASH
STROBE
OFF
STROBE
BRIGHTNESS
ON
POWER
OFF


FLASH
SW?
23 RST
D7 21
D8 22
25 R24
24 R14
26 R25
11 OFF
1, 2
12V
STROBE
SW 4PDT ON OFF ON
12V
1, 2
12V
POT6
ROT TIME ON A
500K
13 ROT-TIME-ON-A
1, 2 12V
POT6
ROT TIME ON B
500K
14 ROT-TIME-ON-B
1, 2 12V
POT6
ROT SPEED
500K
12 ROT-SPEED
15 ROT-BRI-A
POT6
ROT BRIGHTNESS
2K
16 ROT-BRI-B
4 ROT-BRI-C
6
7
8
9
10
3,4
ROT-BRI-C 4
STROBE-BRI-C 5
OFF 11
ROT-SPEED 12
ROT-TIME-ON-A 13
ROT-TIME-ON-B 14
ROT-BRI-A 15
ROT-BRI-B 16
DARK-LIGHT 17
STROBE 18
STROBE-BRI-A 19
STROBE-BRI-B 20
D7 21
D8 22
RST 23
R14 24
R24 25
R25 26
J?
1 12V
2 12V
3 5V
4 ROT-BRI-C
5 STROBE-BRI-C
6 STROBE
7 1-5
8 2-6
9 3-7
10 4-8
11 OFF
12 ROT-SPEED
13 ROT-TIME-ON-A
14 ROT-TIME-ON-B
15 ROT-BRI-A
16 ROT-BRI-B
17 DARK-LIGHT
18 STROBE
19 STROBE-BRI-A
20 STRPBS-BRI-B
21 D7
22 D8
23 RST
24 R14
25 R24
26 R25
CON26
LIGHT MOVING
S?
17 R23
12V 1, 2
DARK MOVING
1, 2 12V
POT6
STROBE
500K
18 STROBE
19 STROBE-BRI-A
POT6
STROBE
BRIGHTNESS
5K
20 STROBE-BRI-B
-5 STROBE-BRI-C
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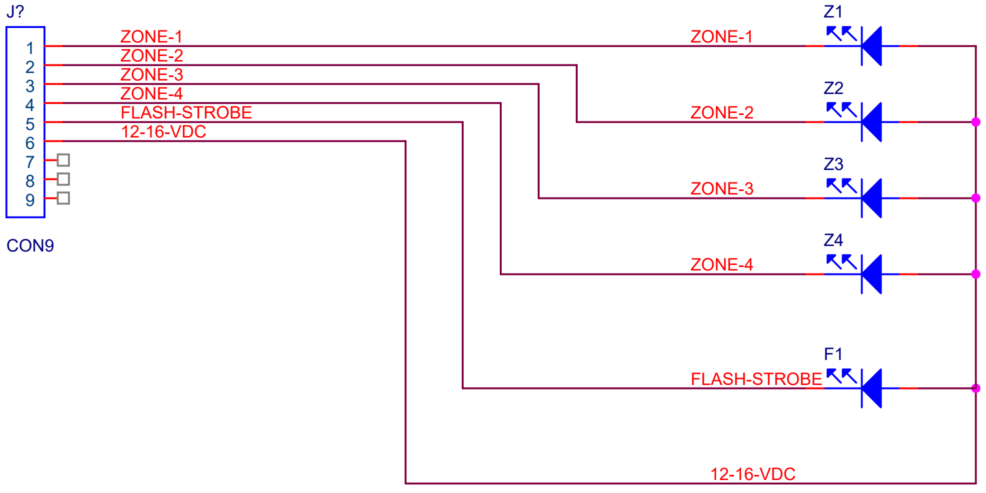
DIGI-KEY P/N

PLUG, 9 PIN, PINS
P/N A1645-ND

BACK SHELL
P/N A1332-ND



12V DC POWER CABLE

DIGI-KEY
P/N ZA5074-ND

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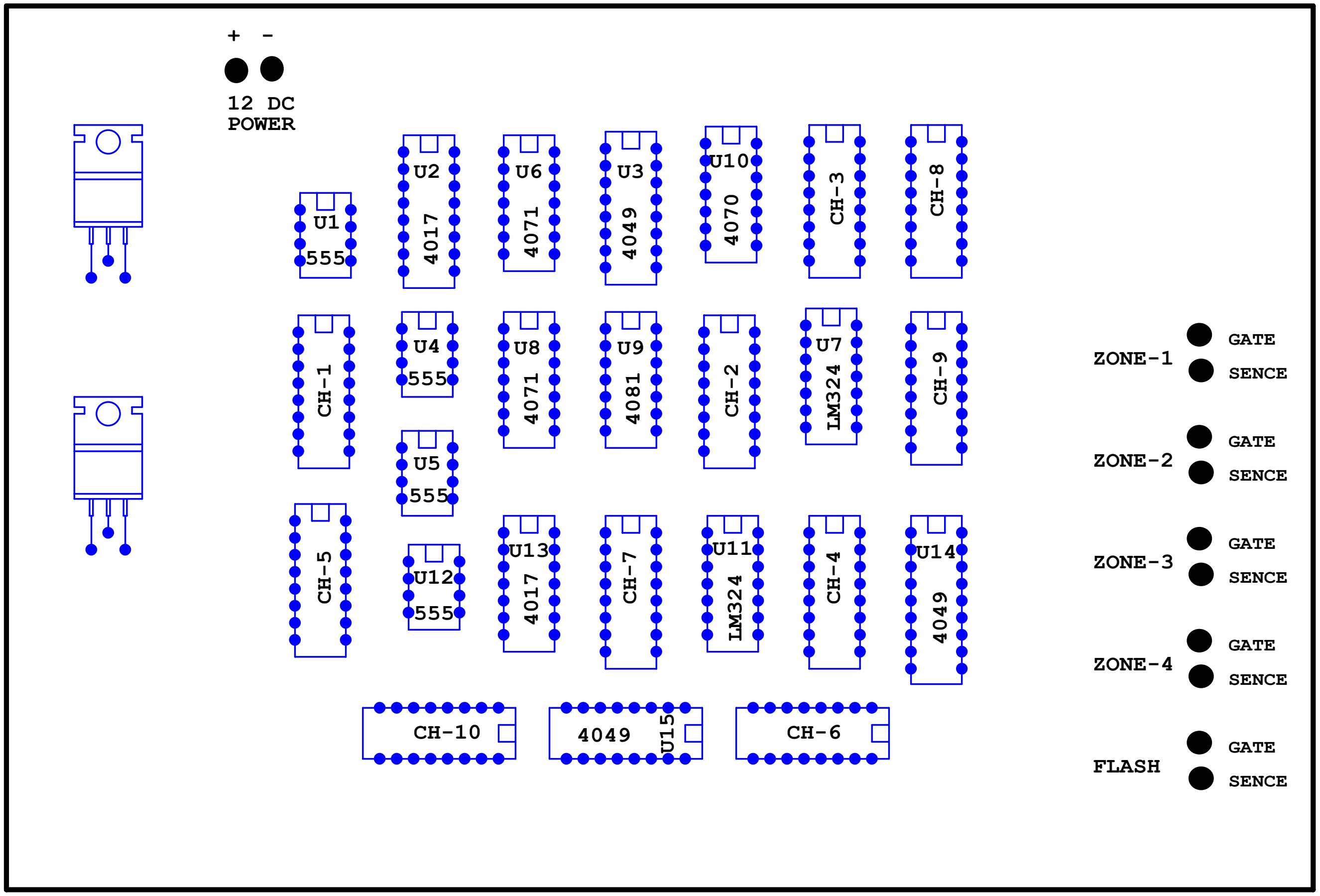

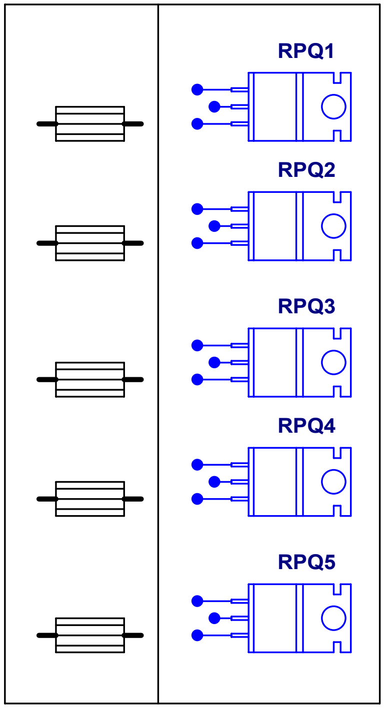

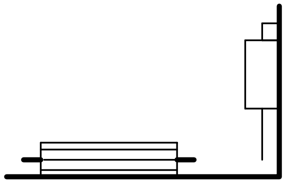

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Part II

Protecting the Protector: An ITS Shadow Truck Warning Signal

Protecting the Protector: An ITS Shadow Truck Warning Signal

I. Introduction

The high incidence of accidents associated with roadway work zones suggests that current warning lights and signals are in need of improvement. In the second part of a two-part project, the Visual Detection Laboratory (VDL) has worked on enhancing the rear warning lights for 'shadow trucks' so as to improve visibility and reduce the reaction time of drivers approaching the work zone.

A 'shadow truck' or barrier vehicle serves as the last in a convoy of slow-moving maintenance or construction vehicles. It may, for example, be protecting a single cone-laying vehicle, a road sweeper or a spraying operation. The shadow truck carries a massive "crash cushion" (a truck mounted attenuator) that serves as a collision damper when hit from behind. Additionally, the truck bears flashing warning lights to announce its presence, and, in theory, to warn away closing traffic from the convoy. The state of the art for warning signal protection is presently a vertical array of flashing amber lights or a light bar (similar to a light stick) across the full vehicle width. Each such device has been measured to have superior visual properties to the flashed or strobed 'point' signals that it replaces.

The goal of the present research was to improve the effectiveness of the warning signal even further. Before discussing the approach that VDL took toward this task, it is perhaps worthwhile to look at the approach that should **not** be taken.

There is a recent tendency to make warning signals more intense and more attention-getting by using strobe flashing or rotating mirror elements and by using multiple illuminated elements. Our first-hand experience with these devices leads to a seeming paradox: while this type of signal is more detectable, it is less easy to look at. A moment's thought provides the resolution; the very high intensity signals used on emergency vehicles or on the shadow truck and other maintenance vehicles present more light to the eye of the observer than can easily be used. The result is that the observer, *especially the nearby observer*, must avert his or her eyes to avoid being blinded by the excess illumination of modern signals. *Averting the eyes, of course, makes it very difficult to compute the range of the vehicle bearing the signal*. We have concluded that present-day technology is moving in the wrong direction. While modern signals can be seen from very far away, *they cannot be looked at up-close, and up-close is the range at which a collision is possible.* Thus such ultra-bright signals can defeat their own purpose.

VDL believes that there is a better way to design signals—Motion Enhanced Warning Signal (MEWS)[1]. This is simply a technique that takes advantage of a signal's *spatial*

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[1] Cohn, T. E. (1995), *Engineered Visibility Warning Signals* in **Proceedings of the Second World Congress on Intelligent Transportation Systems**, Yokohama, Vol. 1, p. 452-457.

extent in *combination* with its *time* course so as to provide the *appearance of movement*. This replaces visibility due to intensity with visibility due to (apparent) movement.

Since humans (and indeed virtually all animals with any significant visual system) have evolved to detect motion because they are both predator and prey, this technique utilizes another ‘pathway’ in the brain’s visual system to elicit the driver’s attention. Indeed, VDL has shown this technique to be directly applicable and effective in the case of bus bars—a series of lights on a bar on the back of a bus that warn away drivers approaching from behind.[2]

In fact, the shadow truck is very similar to a bus as it presents itself to drivers—large, wide and (typically) slow moving. Thus the VDL staff thought that the same MEWS techniques applied successfully in the case of the bus bar could be brought to bear in the case of the shadow truck warning light. The specific design we used to do this is discussed in the next section.

II. Light Bar Description and Signal Pattern Choices

The heart of the concepts behind the shadow truck warning signal is shown in Figure 1 below. There are four concentric rectangular bars each consisting of a grid of uniformly spaced light emitting diodes (LEDs). The bars increase in size as one moves toward the perimeter of the device[3]. Lighting each rectangle in sequence would provide a “looming” effect, similar to the way a freeway sign or billboard occupies a larger fraction of a driver’s field of vision as he approaches it. The “natural” looming as a vehicle approaches a constant size, statically lit rectangle on the back of a shadow truck would thereby be “amplified” by this technique. Hopefully the expanding pattern would not only attract the driver’s attention more quickly because of the apparent motion of the lights, but that ‘motion’ would signal the driver that he is approaching too quickly.

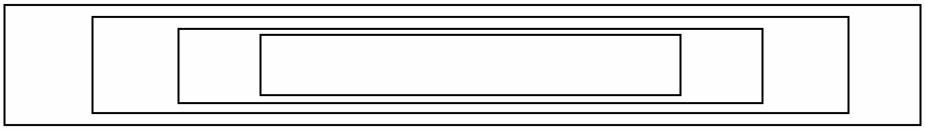

Figure 11: Schematic conception of the shadow truck light bar

In order to achieve maximum flexibility though, VDL designed the warning signal to be programmable. The four rectangles could be lit in any order for (essentially) any amount of time. This meant that a great variety of patterns could be considered. In fact, given the practical limits of time and subject fatigue there was almost too great a variety of

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[2] Cohn, T. E. and Nguyen, K. (2002), *Tortoise Beats the Hare Again: Turning on Parts of a Warning Signal with Some Delay Makes It Seen Faster,* **Proceedings of the TRB Visibility Meeting**, Iowa City, June 2002.

[3] Initially the signal was conceived as having each half of a rectangle (left/right) be independently controllable—in other words, eight light sections rather than four. This asymmetric capability was not determined to be useful.

choices. This flexibility was essential though since only by testing a number of patterns could we be confident that our final signal pattern choice was near optimal.
This availability of pattern choice was achieved by having the vendor[4] make the light sections controllable by a *Basic Stamp II* (BSII), a microcontroller that can be programmed in the higher-level computer language BASIC (or rather a very close, somewhat simplified derivative version of BASIC). This allows the light patterns to be configured by someone who is acquainted with BASIC programming but who is not necessarily a professional programmer. More importantly, the light patterns can be easily *re*-programmed; a standard serial port on the BSII circuit board allows connection via a standard serial cable to a personal computer, which has the BSII BASIC editor software, making updating the patterns a painless affair.

Beyond the results of this particular project it is worthwhile to briefly note here the great utility of the above-mentioned approach. In future implementation of signals that need pattern flexibility for either the testing and/or the design stages, this method is ideal. Using a microcontroller that can be reprogrammed "on-the-fly", in a very simple language, from an ordinary PC puts the flexibility of pattern changes into software rather than into the circuitry. If the initial choice of patterns is not found to be good, one is not locked into a given set. The patterns can be changed before a final product or design is made. The source code for this project is given in Appendix 3.

The actual look of the prototype is shown below. The separation between individual LEDs is ½ inch or about 1.3 cm, both vertically and horizontally. The overall width of the device is 120 cm and the height is 28.5 cm. The overall dimensions of the LED field are 20.5 x 111 cm. A space (or border) of 5 cm exists on the front panel between the edges of the signal box and the field of LEDs. Fifteen millimeters of this consists of the metal lip or flange that runs around the edge of the front panel.

In Figure 3, the electronic controls are shown on the raised, light green board. On the right of that are two silver RS-232 type connectors, one male and one female. The female connector is for reprogramming the BSII; the male is for connection to an external PC that can choose which (pre-programmed) pattern to display. (This is discussed further in the methodology section below. See also Appendix 4.) The dark green board near the bottom of the light green one is the BSII. About halfway along the bottom is a switch (white tape either side) that in one position allows the light bar to be externally controlled by a PC (via the aforementioned RS-232 connection) or, in the other position, has the light bar default to "manual" or internal control[5]. This manual control is just a small, multi-position switch that fixes the light bar into a given pattern. The multi-position switch is the small object between the BSII and the external/internal switch.

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[4] *Electro-Tech's*, 1875 Sampson Avenue, Corona, CA. 92879-6009

[5] The label at this switch position actually reads "Norm" on the white tape.

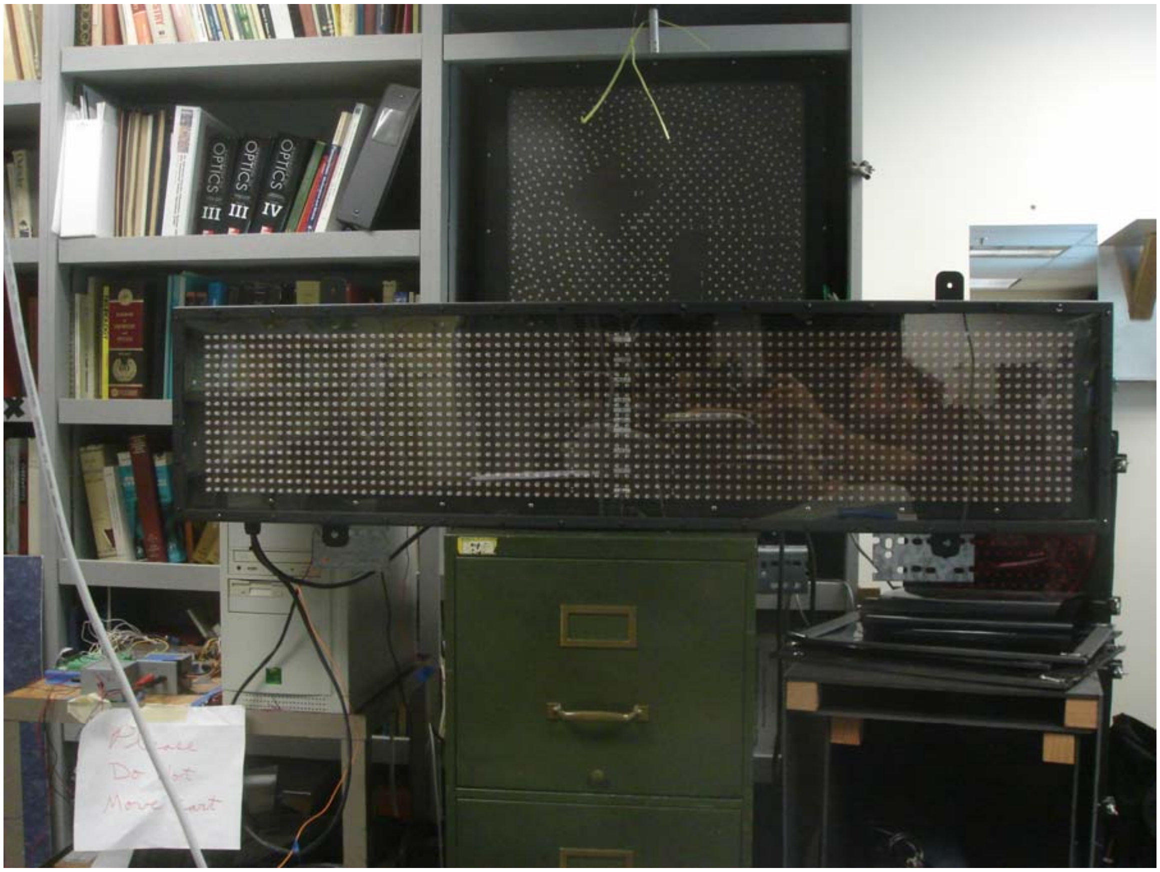

Figure 12: The prototype shadow truck warning light as mounted for testing. The light bar is securely bolted to angle iron framing that is mounted on the file cabinet (the angle iron is just visible on the upper right of the cabinet). The left-hand arrow signal behind the light bar is not relevant to this project.

Figure 13: The rear of the light bar with the access panel removed.

The next four pictures show the lit rectangles discussed above and shown schematically in Figure 1.

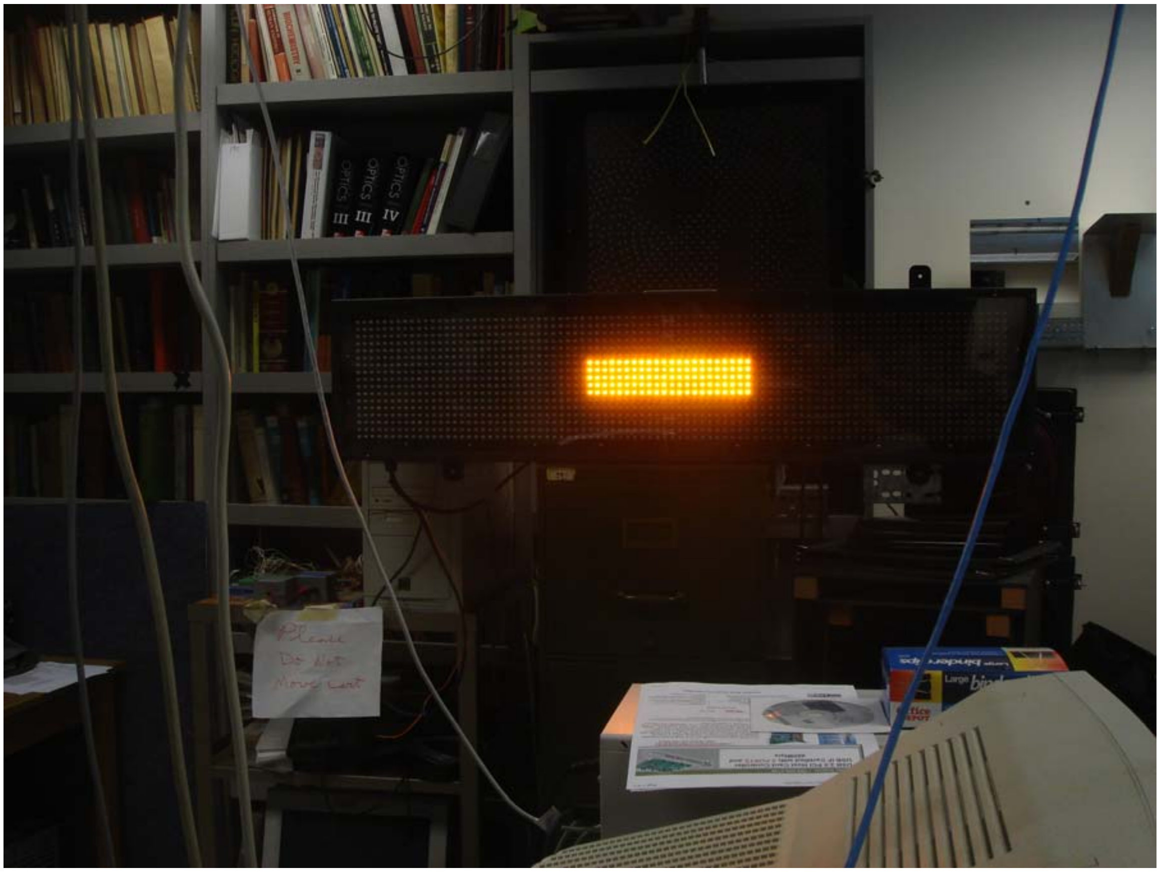

Figure 14: Innermost rectangle shown lit with the room light dimmed. This rectangle consists of 5 rows of 22 LEDs each.

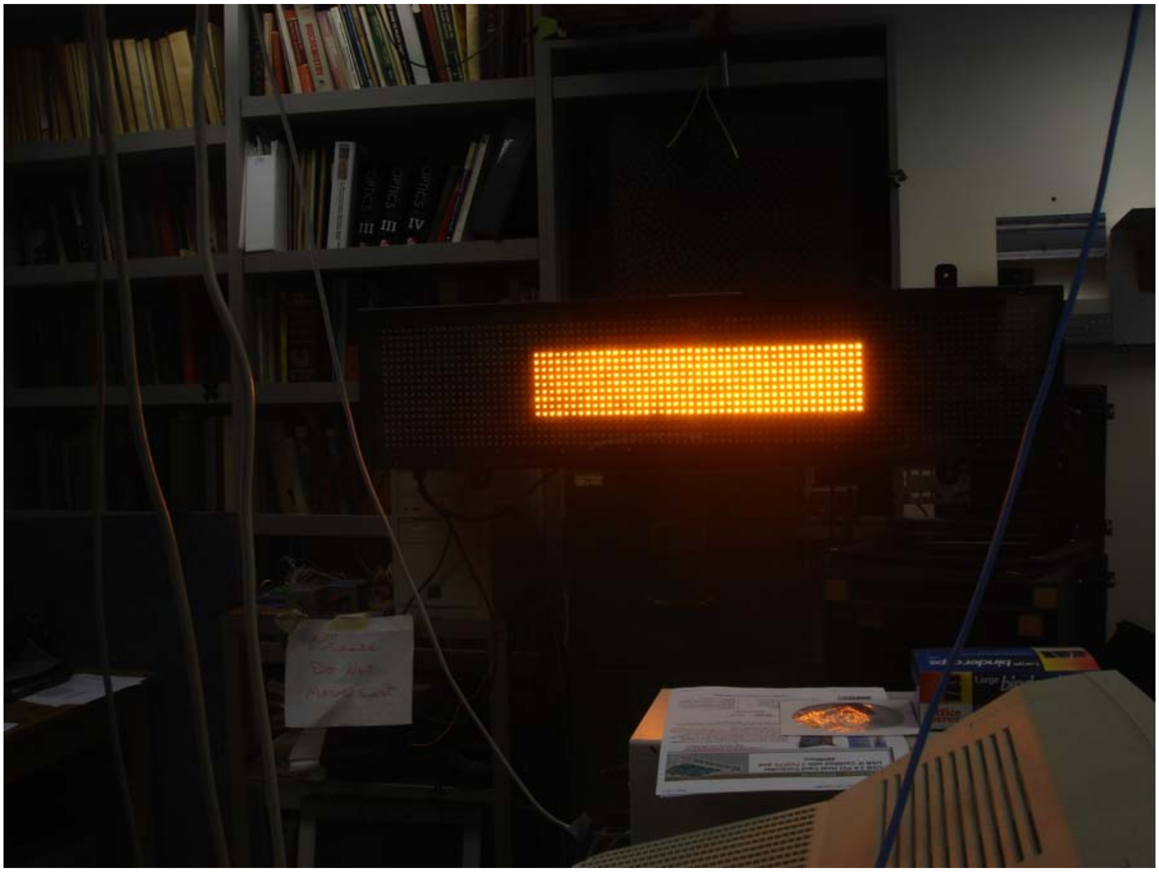

Figure 15: The next larger rectangle is a grid of LEDs 9 x 44. This essentially doubles the dimensions (quadruples the area) of the smallest rectangle.

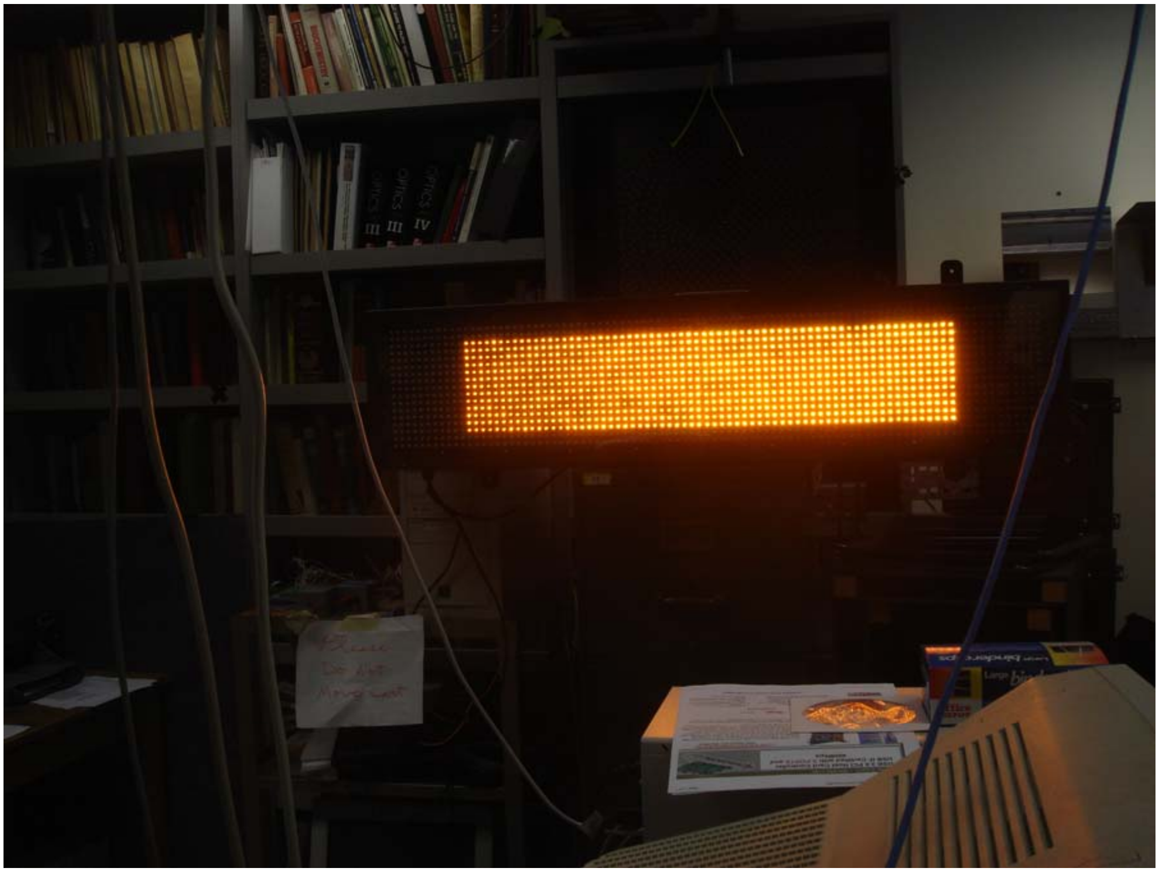

Figure 16: The next to last rectangular block is 13 x 66 LEDs.

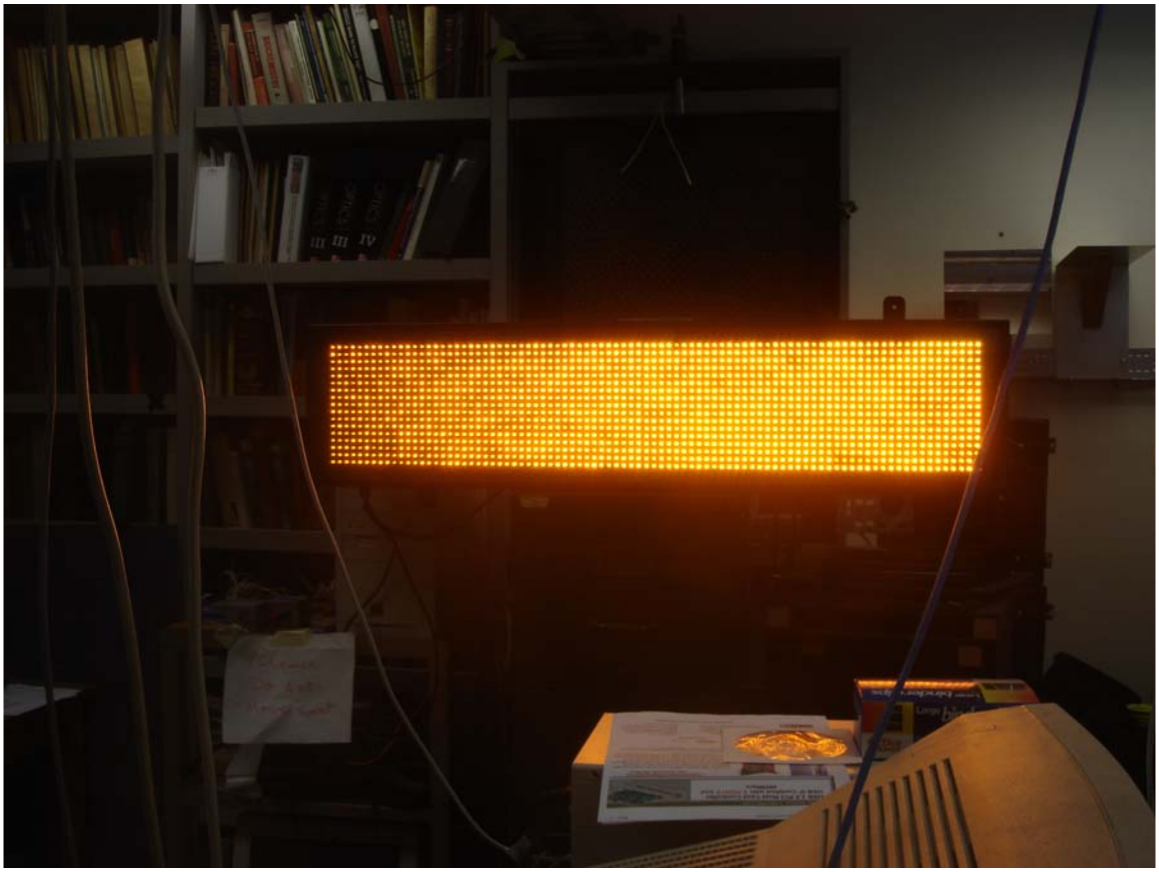

Figure 17: The full bar consists of an array of LEDs that is 17 by 88.

Since the pattern choices were so numerous given the flexibility of reprogramming, VDL had to restrict the final number to something manageable from the large number that we first conceived of (thirteen[6]). We thus did a 'first pass' of reaction time testing using the same methods as described in detail in the next section with the restriction to fewer subjects and fewer trials. Several of the patterns with the longest reaction times were dropped from further consideration, along with a few rejected because that they did not differ significantly from standard flashing.

What follows is a description of the final set of five patterns chosen for testing. They are denoted by the corresponding position of the manual multi-position switch mentioned earlier. Since that switch is labeled in hexadecimal, that is 0 through F, the five patterns turn out to be 3, 4, 5, 7 and D. Of course they could be relabeled sequentially as one

---

[6] In fact, the warning signal was designed and made with a "doubling" wire. By putting 5 volts on the doubling wire, any pattern's time course could be run at twice the frequency, the only exception being the "all on" static pattern. Thus there were potentially 13 + 12 = 25 patterns. After some investigation we decided the doubling wire wasn't needed at all despite our initial expectations.

through five but rather than risk a transcription error across the numerous computer files that constitute the data, we found it simpler to keep the original designations.

Figure 8 in conjunction with Table 1 shows the basis for all the patterns tested. At first there are no segments lit. Then the smallest rectangle (Figure 4) lights up for a time interval v (measured in milliseconds). The second smallest rectangle (Figure 5—9 by 44 LEDs) then lights up for a time w. The next largest rectangle (Figure 6) follows this for a time of x milliseconds. Finally the full light bar (Figure 7) comes on for a time interval y. This is followed by a blanking interval (all lights off) of z. The entire cycle then repeats.

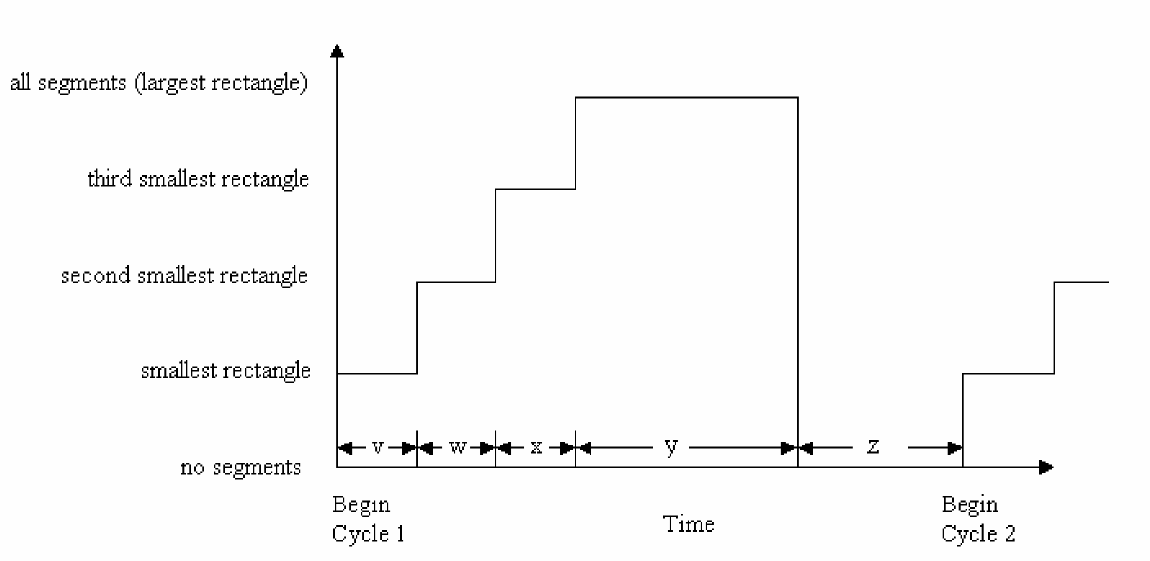

Figure 18: Schematic graph defining pattern intervals.

Pattern #	v	w	x	y	z
3	25	25	25	125	100
4	62	63	62	163	100
5	250	250	250	350	100
7	62	63	62	63	100
D	228	76	38	114	200

Table 9: Time intervals (all in milliseconds) as shown in Figure 8.

Patterns 3, 4 and 5 are (with the exception of some modification of the ‘y’ interval) scaled versions of each other. Pattern 7 deviates from pattern 4 only in the much abbreviated time that all the lights are on (interval y).

Pattern D was an attempt to actually mimic the looming effect of a fixed size rectangle (e.g. the back of a slow-moving shadow truck or bus) as it is approached rapidly by the observer (i.e. a driver). While all the patterns with the type of time profile sketched in Figure 8 show apparent motion, and mimic the looming effect somewhat, pattern D was an attempt to very closely follow what might be seen in the real world. The origin of pattern D is explained in detail in Appendix 1.

Thus all patterns undergoing final testing were variations of a similar theme—a MEWS type “looming” effect. The operational idea being that not only would apparent motion attract the driver’s attention more swiftly, but that the looming effect might add (under field conditions) a perception that the driver is approaching the light bar even faster than he actually is. Some of those that didn’t make the cut were of a different type: a straight flashing of all lights (largest rectangle only) or a static display of all lights coming on and staying on (at least for a lot longer than most human reaction times).

III. Laboratory Testing Configuration and Methodology

The shadow truck warning light is, of necessity, very bright. A very bright light will result in very fast reaction times and can overwhelm reaction time differences that would otherwise be uncovered with a light that is less intense, and therefore more difficult to see. The laboratory testing therefore, in an effort to isolate the reaction time response due to pattern type, required attenuating the signal.

In an actual deployment of course the shadow truck warning light would not be directly attenuated, although as noted earlier, the trend of increasing intensity for signal lights may actually make them less effective. But in fog, or at a distance or at a slightly oblique angle, or with high intensity lights nearby (such as at work zone) the lights would appear much less intense than they would sitting directly opposite you twenty feet away inside a dimly lit laboratory. In any event, to mask the influence of the lights’ intensity and to elicit an observer response dependent on pattern instead of on brightness, the light bar was dimmed using several layers of neutral density plastic sheeting placed over it. This reduced the intensity to a level where the LEDs of the light bar were just barely perceived.

Figure 9 gives an idea of how strongly the light was attenuated. Here the attenuator, consisting of a cardboard frame holding the dark plastic sheeting, is being put into place while the full extent of the light bar is lit.

Figure 10 shows the attenuator in its final position as it was used for the testing. The LEDs of the light bar only become just visible with the room lights dimmed.

The experiment was conducted with black cardboard covering the windows and all room lights off except for a small lamp that provided a dim, diffuse light toward the end of the laboratory where the shadow truck warning signal was situated. This reproducible ambient illumination was approximately equivalent to twilight or early evening, times when external visual clues are diminished during driving.

Figure 19: A demonstration of how effectively the plastic sheeting can attenuate the light.

Figure 20: The configuration of attenuator and light bar as it was used for testing, except for the fact that the lower clips did not have their handles over the viewing surface; instead they pointed away from the surface like the upper and side clips.

The subject sat on a high chair while viewing at a distance of approximately 25 feet from the signal. This prevented any fatigue or restlessness during the test that might have occurred if the subject had been standing, plus it better simulated the driving position. The subject had a handheld box with a pushbutton. He was instructed to push this button upon seeing any light signal whatsoever at the light bar. This part of the setup is shown in Figure 11.

The shadow truck warning light presented a test pattern after a randomly varying interval of inactivity (i.e. all LEDs off) with a uniform probability distribution (to minimize predictability of moment of onset). The minimum delay was 2.5 seconds and the maximum was 6 seconds. The test subject, looking at a fixation point taped to a wall above and behind the light bar, hit a response button when he noticed the lights firing. The computer that was controlling the light bar also recorded the subject's reaction time. The different pattern types were shown to the subjects in a randomized ("shuffled") order. This prevented the subject from getting accustomed to any particular pattern—that is anticipating the type of pattern he would see next. Fifty trials for each of the five patterns were taken and the average reaction time to each pattern was computed.

The electronic control system for reaction time testing is shown in Figures 12 and 13. A *National Instruments Data Acquisition Card* (Nidaq)—model 6024E—is a programmable, electronic circuit card that has 8 digital input/output ports, 16 channels of analog input, and 2 channels of analog output along with various timing and gating functions. This card plugs into a standard PCI slot in a PC (Figure 12). Its functions can be programmed in the C language (along with using the supplied Nidaq library functions). The use of this card is far superior in timing, accuracy and control in comparison to trying to program the standard serial or parallel outputs on a PC to perform the functions needed for this experiment.

A ribbon cable takes the inputs and outputs of this card to a connector. From there the board pins are wired to the logic and light bar enabling circuitry (Figure 12: physical, Figure 13: schematic).

There is also a debouncer that takes the input from the subject's response button (a noisy signal from a mechanical switch) and provides a "clean" version to the logic circuitry. Power is provided to the logic and debouncer circuitry (+5V) by use of an extra power cable from the computer (Figure 12).

Figure 21: The subject's high chair and reaction time response button at the opposite end of the room about 25 feet from the light bar. (The inverted binoculars mounted on a tripod were not used nor present during the test.)

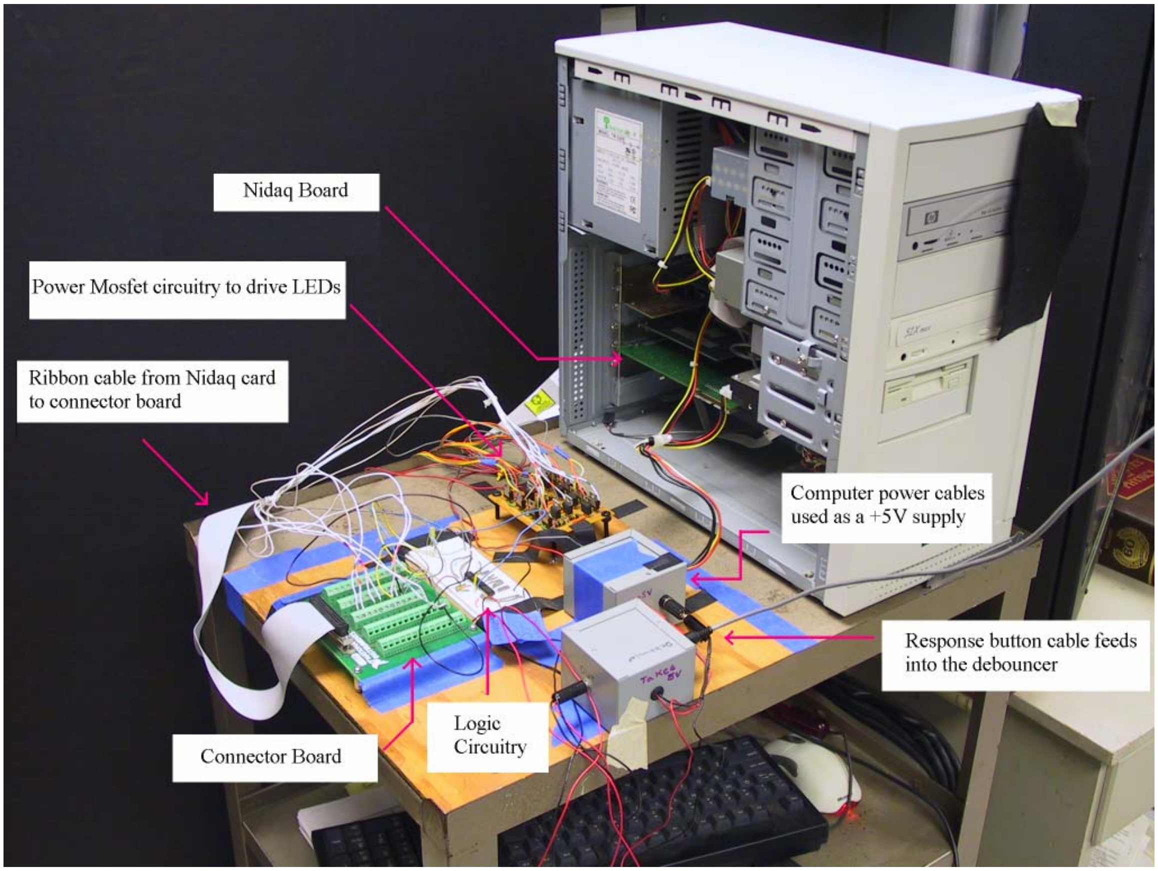

Figure 22: Electronic control system for the reaction time experiment (the power mosfet circuitry was not used in this experiment)

The computer with the Nidaq card also controlled the pattern sent to the shadow truck light bar via the computer's parallel port (LPT1 – at address 0x378).[7] This entailed using a RS-232C cable[8] with a DB25 male connector on one end and a DB9 female connector on the other. The reason for mentioning this seemingly trivial fact is that it clearly means 16 pins (= 25 – 9) on the parallel port have no connection to the light bar's electronic control. Furthermore the numbered pins on the DB25 don't necessarily correspond to the same number on the DB9 (e.g. DB25 pin 8 matches up to DB9 pin 1). Complicating matters <u>still further</u> was the fact that the most significant bit to least significant bit ordering on the DB25 was reversed at the DB9 connector on the control board. *The bottom line is that one had to put in a* ***very*** *carefully checked bit translation table into the software in order to be sure of displaying the right pattern.*

Another difficulty that should be noted is controlling the parallel port directly within some modern operating systems. Unlike *Windows 95* or *98*, where a command (in C say)

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[7] This differed from most previous reaction time experiments done by VDL wherein the Nidaq card was only used for timing and not pattern control as well.

[8] Radio Shack catalog number 26-269. It is not shown in Figure 12.

like "_outp('port', 'databyte')" could send a byte to the parallel port, *Windows XP* (or *Vista* or *2000* or NT) has a so-called *kernel protection mode*. This means more work to send a byte to the parallel port. The workaround is to use a program like "inpout32.dll".[9] This has a library which when linked into the code allows the sending of bytes directly to the parallel port. While this may seem like a minor technical detail, any attempt to program direct control of LPT1 in a standard, platform-independent, high-level language (i.e. no Application Programming Interface) will be doomed to failure in many operating systems without use of a workaround like inpout32. Furthermore, little if any error messages will show up during compilation if this is not used—the program simply fails without it and the inexperienced programmer has no idea why it failed.

The C programming language was used, along with the Nidaq supplied library, to program the Nidaq card. The standard pseudo-random number generator in C was used to provide a time delay between pattern firings as mentioned above. A random delay is needed because otherwise the subject can "learn" what the time delay is and anticipate (perhaps without realizing it) the firing rather than reacting to it.

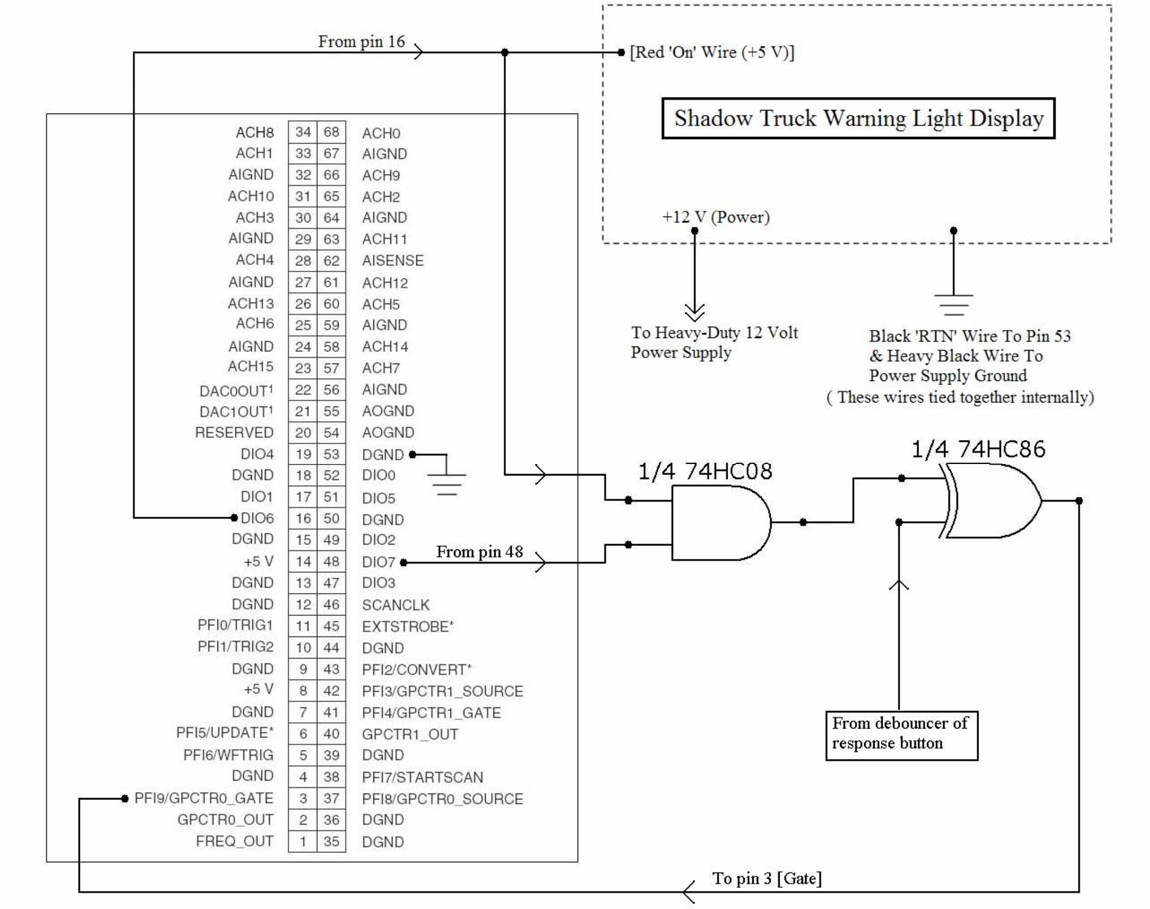

Figure 23: Connector board pinout, shadow truck warning light enabling line and power hookups, and control logic.

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[9] Available at http://www.logix4u.net/inpout32.htm.

However, this precaution does not completely obviate the possibility of a premature response. The counter in the Nidaq card, which measures the reaction time, works off of two gate signals—a start signal and a stop signal. It measures the time between these two signals. The start signal is the "**enable**" signal that comes off of pin 16 (digital I/O #6). When this pin sends +5 volts to the 'On' wire (labeled as such) that comes out of the light bar's external wiring harness, the light bar can produce the pattern that it is sent (or set to).[10] *Without the 'On' wire held at five volts, the display is disabled* (i.e. it shows nothing). As shown in Figure 13, this enable signal is "teed" off to one half of an **AND** gate (74HC08); that becomes the start signal. The stop signal is from the response button of the subject (via the debouncer which introduces a negligible delay) and it is routed to one input of an **XOR** gate (74HC86).

These two gating signals both need to go to the Nidaq timing gate at pin 3, but they cannot both be electrically connected directly at pin 3 or the two signals would interfere with each other's circuitry. Therefore the two signals need to be buffered. Even if this weren't the case, a problem would arise should the subject accidentally hit the response button before the firing actually occurs. The two signals would reverse their roles and the response button could signal a start to the counter and the light firing could signal an end to it. Even if the signals come in the right order, the enabling signal needs to stay high continually while the pattern is running but the actual start signal reaching pin 3 needs to terminate before the stop signal arrives. Thus safeguards are put in place. This is why the logic circuitry in Figure 13 is used, along with a software safeguard. The digital I/O #7 (pin 48) is used as an "arming" mechanism for the counter gate signals. When pin 48 goes high the output of pin 16 can be passed, via the **AND** gate, to the "exclusive or" (**XOR**) which has its output linked to the timing gate at pin 3. If pin 48 is low, pin 16 going high (+5 V) has no effect (on the **XOR** that is).

The timing gate (pin 3) is not "activated" by the software until just before the light is to fire. *Thus a response button push before this time has no effect*. Pin 48 goes high just before the light goes on for the first time in a given pattern. It goes low 5 ms after the light comes on for the first time. Thus the first firing in a pattern constitutes a start signal but all subsequent firings (cycles) do not affect the timing gate. Since 5 milliseconds is very far below a typical reaction time, the chance of someone hitting a response button during that interval is effectively nil. Of course after a response is recorded, everything is reset.

The Nidaq card's 100 kHz internal timebase is used for the timing. Thus the accuracy is to the hundredth of a millisecond, far greater than what is needed for this kind of experiment. The reaction time data is held in active memory until the sequence of trials is done and then it is all written to disk, thereby preventing any disk operations from interfering with timing measurements.

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[10] "Sent" assumes external control as discussed here. "Set to" would mean the light bar is under internal control ("manual" or "Norm"). In either case the +5 V enabling voltage is needed to activate the light bar. The five volts can come from computer control or a fixed power supply. There is one exception where this enabling is not needed but that is the atypical case where pin 1 of the DB9 male connector, J3, is always held low (see Appendix 4). We ignore that case here.

IV. Data Analysis and Laboratory Test Results

As mentioned above, the laboratory portion of the testing involved 8 subjects (observers) each performing 50 reaction-time trials for each of the five patterns. Due to the nature of the experiment, the subject would sometimes anticipate the signal before it had fired (even though the "between trials" interval had been randomized), and push the response button even though it was clear no lights had been fired. As previously mentioned, the arming mechanisms for the counter would usually prevent these "false alarm" responses from registering. But, rarely, these "anticipatory responses" would occur just as the light was firing. The subject's "response" would thus be registered because it technically came after the lights had fired and the counter had been armed, with the resulting "reaction time" obtained in this way being improbably low. A "typical" reaction time can vary quite a bit depending on the individual and the circumstances but in situations like those of this experiment something in the range of a third to three-quarters of a second would be expected. Reaction times below 200 ms occurred but they were rare. Any reaction time below 100 ms was considered an artifact and was stricken from the data[11].

A cutoff on the high side was more problematical, that is more subjective. Since the experiment lasts several minutes and is of necessity repetitive, the subject's attention can easily wander. But this can obviously happen to drivers in a real-life situation too. Thus we decided to leave in reaction times that were much longer than the norm. An upper cutoff of one and a half seconds was chosen based on our previous reaction time measurement experience. Admittedly this is somewhat arbitrary, but anything much longer than this either represents *severe* inattention—being distracted during the test or losing mental focus on the task at hand.

The necessity of an upper cutoff is one reason that fifty trials are done for each pattern. Fewer trials per pattern might seem like it would mean less likelihood of the subject's attention wandering and still allow sufficiently accurate determination of an average[12]. If the testing process was conducted in multiple sessions for each subject or if fewer patterns were examined this conjecture would indeed be true. Other considerations however, precluded this possibility. If subject fatigue weren't a real problem, VDL would have tested even more patterns. Furthermore we had to keep the testing conditions, including possible subject fatigue or inattention, consistent among patterns. Therefore we tested each subject in one sitting and randomized the presentation order of the patterns (subject to the constraint that each pattern was presented 50 times). From experience we know that even with, say, twenty trials per pattern the subsequent total of one hundred trials in one sitting would probably result in at least one observer's having at

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[11] By way of comparison, the world's record holder in the 100-meter sprint, Tim Montgomery ("fastest man alive"), had a reaction time out of the blocks of 104 ms when setting that record in 2002. Source: *USA Track & Field* press release of 9-14-2002, available at http://www.usatf.org/news/showRelease.asp?article=/news/releases/2002-09-14.xml

[12] One way of avoiding this problem of cutoffs is to use medians instead of averages. Since our subsequent statistical analysis (see below) is based (theoretically) on averages, VDL did not take this approach. Such a method may be worth consideration in future projects of this nature.

least one reaction time that is absurdly high—that is not "real" but a result of distraction or the person's attention wandering. Including this number in the average would bias the result too strongly—especially when one is averaging fewer trials! (See below.)

Thus an upper cutoff is needed in any case. The problem is what value to use. By taking more rather than fewer trials the experimenter ironically has a better idea of the upper cutoff despite having a greater chance of more data falling above the cutoff. This is because with more data the trends in an observer's reactions become more apparent. For example, if a subject has no reaction time save one rise above 600 ms and that one exception is 1700 ms then it is highly likely that that exception is "bad" data. On the other hand, if another subject has several times above 800 ms, a few around 900 ms and one or two at 1000 ms then a value of 1250 ms is probably "real". Thus more data reveals the trends necessary to better justify an upper cutoff.

Looking at 250 trials per subject (all patterns) across 8 subjects suggests that 1.5 seconds is a reasonable choice for an upper limit. In previous work of this nature, VDL had used a cutoff of 1 second. In retrospect, with more experience, this value was probably too low (although there is naturally variation with the nature and strength of the signal under test). Of course, taking too high a value for the cutoff has its dangers too. For example, if an average of 450 ms was obtained using 50 trials including a (highest) value for one trial of 1300 ms, then if that last value was an artifact and only the other 49 should have been used, the "true" value is then 433 ms $\left(= \frac{50 \times 450\ ms - 1300\ ms}{49} \right)$. This is a discrepancy of 17 ms $\left(= 450\ ms - 433\ ms \right)$, a quite considerable chunk of 30 ms—a typical minimum pattern reaction differential that might be considered interesting. But note how a higher number of trials help here. If the same situation obtained but with 20 trials instead of 50 then the discrepancy is 45 ms $\left(= 450\ ms - \frac{20 \times 450\ ms - 1300\ ms}{19} \right)$, rounding to the nearest millisecond. More trials dilute the effect of incorrectly including data points on the high end that should have been excluded.

Using these cutoffs, the data in the following table was obtained.

Subject:	Pattern 3	Pattern 4	Pattern 5	Pattern 7	Pattern D
A	398.31	379.26	437.84	377.50	468.77
B	413.80	393.35	398.83	405.98	397.53
C	424.04	443.85	519.04	458.04	509.42
D	432.17	451.98	553.17	453.88	533.48
E	520.46	505.02	536.62	554.06	544.98
F	345.45	344.96	392.97	378.62	410.50
G	326.31	326.67	405.55	320.87	409.64
H	371.74	369.62	419.37	390.74	425.46
Averages	404.04	401.84	457.93	417.46	462.47

Table 10: Averages for reaction times (all in milliseconds).

A mere glance at Table 2 strongly suggests a statistically meaningful difference in reactions to the patterns. The average reaction time for the eight subjects to pattern 4 is 401.84 ms (fastest) while the reaction time average for pattern D is 462.47 ms (slowest). This is a (rounded) difference of 61 ms out of times in the neighborhood of 400 ms—a very large percentage. Furthermore, *every subject had a faster reaction time to pattern 4 in comparison to pattern D.*

Nonetheless, we proceed formally and apply an F test. It should be noted that a *two-factor* F-test is the correct one to apply since *subject variation* is clearly present in Table 2 (e.g. compare the reaction times of subjects E and G for each pattern)[13].

Carrying forward the two-factor (pattern and subject) F-test then, the needed numbers are calculated from the previous table:

$$\begin{aligned}
&\text{grand mean} = 428.75\\
&v = \text{total variation } = 169{,}860.27\\
&v_p = \text{variation between patterns} = 27{,}607.60\\
&v_s = \text{variation between subjects} = 128{,}593.76\\
&v_e = \text{residual (random or error) variation} = 13{,}658.90\,.
\end{aligned}$$

There are a = 5 patterns and b = 8 subjects. The resulting table,

Variation	Degrees of Freedom	(unbiased) Mean Variance	F statistic
$v_p = 27{,}607.60$	$a-1=4$	$\hat{s}_p^2 = \frac{v_p}{a-1} = 6{,}901.90$	$\frac{\hat{s}_p^2}{\hat{s}_e^2} = 14.15$ with $\left(a-1,(a-1)(b-1)\right) = (4,28)$ degrees of freedom
$v_s = 128{,}593.76$	$b-1=7$	$\hat{s}_s^2 = \frac{v_s}{b-1} = 18{,}370.50$	$\frac{\hat{s}_s^2}{\hat{s}_e^2} = 37.66$ with $\left(b-1,(a-1)(b-1)\right) = (7,28)$ degrees of freedom
$v_e = 13{,}658.90$	$(a-1)(b-1) = 28$	$\hat{s}_e^2 = \frac{v_e}{(a-1)(b-1)} = 487.82$	

Table 11: Applying the F-test.

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[13] Even when it is not obvious, a two-factor F-test is *always* called for in comparison to a one-factor F-test in situations like this. Reaction times vary considerably by individual and an application of a one-factor F-test here would almost certainly give the wrong answer.

allows comparison to the critical F values. For *subjects*, the critical F value[14] at the 95th percentile for 7 and 28 degrees of freedom is 2.36. For the 99th percentile the value is 3.36. Therefore since,

$$F_s = 37.66 > F_{\substack{0.95 \\ subjects}} = 2.36$$

and

$$F_s = 37.66 > F_{\substack{0.99 \\ subjects}} = 3.36,$$

the subject variation is, as one would suspect, not consistent with the null hypothesis of equal means. The variation is surely **not** due to chance. This is consistent with the earlier argument (footnote 13) that the two-factor F test had to be used since subject variation could not be ignored. The associated p-value is the astoundingly low $p_s = 1.32 \times 10^{-12}$.

Of course, this significant variation by subject is to be expected. What of the reaction time variation due to the firing *patterns*? Here the answer too is that <u>*the null hypothesis of equal means can easily be rejected at both the 95th and the 99th percentile*</u>. The critical F value at the 95th percentile for 4 and 28 degrees is 2.71; at the 99th percentile it is 4.07. The F statistic from Table 3 easily bests these. Hence,

$$F_p = 14.15 > F_{\substack{0.95 \\ patterns}} = 2.71$$

and

$$F_p = 14.15 > F_{\substack{0.99 \\ patterns}} = 4.07.$$

For reference the p-value is $p_p = 1.96 \times 10^{-6}$. The pattern differences are showing up in the reaction times to a very statistically significant degree.

From Table 2 we can see that the results for patterns 5 and D are fairly close as are the results for patterns 3 and 4. Therefore, it is not particularly useful to perform all ten possible paired t-tests. We merely verify the obvious—that the results of pattern D and pattern 4 differ significantly—and see if the close results between patterns 3 and 4 are statistically significant.

For the paired t-test between pattern 4 and D we have Table 4, which gives us the sample variance:

$$s^2 = \frac{\sum_{i=1}^{n} (x_i - \overline{x})^2}{n-1} = \frac{5454.51}{7} = 779.22,$$

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[14] Appendix F of *Probability and Statistics (2nd Ed.)*, by Murray R. Spiegel in *Schaum's Outline Series* [McGraw-Hill Book Company].

where the individual time differences are denoted by x_i and the average by $\overline{x}$, along with the number of subjects by n (= 8). From these we can easily get the t statistic:

$$t = \frac{\overline{x}\sqrt{n}}{s} = \frac{60.63\sqrt{8}}{27.91} = 6.14 .$$

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
468.77	379.26	89.51
397.53	393.35	4.18
509.42	443.85	65.58
533.48	451.98	81.51
544.98	505.02	39.96
410.50	344.96	65.54
409.64	326.67	82.97
425.46	369.62	55.84
	Average of Differences:	60.63

Table 12: Pattern D vs. Pattern 4 using the paired t-test for differences in sample means.

The associated critical (one-tail) value[15] for seven degrees of freedom (= n – 1) is 1.90 at the 95th percentile and 3.00 at the 99th percentile. Hence,

$$t_{paired\ diff.} = 6.14 > t_{crit.0.95} = 1.90$$

and

$$t_{paired\ diff.} = 6.14 > t_{crit.0.99} = 3.00 ,$$

clearly showing a rejection of the null hypothesis of equal means for the reaction times of patterns D and 4.

On the other hand, using the numbers in Table 5 to proceed in the same manner for pattern 3 vs. pattern 4, we have

$$s^2 = \frac{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}{n-1} = \frac{1770.86}{7} = 252.98$$

and

$$t = \frac{\overline{x}\sqrt{n}}{s} = \frac{2.20\sqrt{8}}{15.91} = 0.39 .$$

Since the number of subjects is the same as in Table 4, the degrees of freedom are the same. Thus the critical t values are unchanged. Very clearly,

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[15] Appendix D of *Probability and Statistics (2nd Ed.)*, by Murray R. Spiegel in *Schaum's Outline Series* [McGraw-Hill Book Company].

$$t_{paired\ diff.} = 0.39 < t_{crit.0.95} = 1.90$$

for this pair, and consequently, *the null hypothesis that patterns 3 and 4 have equal reaction time means* ***cannot*** *be rejected.*

Pattern 3 (ms)	Pattern 4 (ms)	Difference (Patt. 3 – Patt. 4)
398.31	379.26	19.05
413.80	393.35	20.45
424.04	443.85	-19.81
432.17	451.98	-19.81
520.46	505.02	15.45
345.45	344.96	0.49
326.31	326.67	-0.35
371.74	369.62	2.12
		Average of Differences: 2.20

Table 13: Pattern 3 vs. Pattern 4 using the paired t-test.

Interestingly enough the pattern that we tried to make most realistic (see Appendix 1) did the worst among the five patterns that made it to final testing. Looking at Table 1, pattern 3 has the first three time intervals (v, w, x) less than half those of pattern 4 and yet this "rapidity" doesn't seem to make any difference in the speed of the reaction generated. On the other hand, pattern D has the first interval almost four times as long as the first interval in pattern 4 (largely out of necessity—see Appendix 1) and the reaction time rises substantially. The likely cause is that the first interval in pattern D is a substantial fraction of a typical reaction time while patterns three and four have run through the first three rectangles (segments) and are showing "full on" during this same interval. The observer thus sees patterns three and four providing "movement" during the same period that pattern D shows only the smallest rectangle and no "movement" yet.

We also note in passing that pattern 4 resulted in a reaction time 16 ms faster than pattern 7 but that they were *identical* for the first three intervals (refer again to Table 1) and that the real difference lay in the "full on" time. Pattern 7 actually cycled more quickly.

In Table 6 the standard deviations of the individual responses are shown.

Subject:	Pattern 3	Pattern 4	Pattern 5	Pattern 7	Pattern D
A	171.57	75.57	173.95	143.74	188.73
B	224.24	166.86	136.10	203.08	112.02
C	105.27	69.80	151.66	110.28	96.44
D	113.72	100.02	133.61	112.98	125.79
E	189.58	177.03	208.43	224.46	205.68
F	99.21	67.82	163.21	146.45	164.06
G	101.76	107.53	182.92	70.55	232.147
H	146.89	101.78	117.10	110.94	186.85

Table 14: Standard deviations (in ms) for the individual sets of observations. The greatest values for an observer are in orange while the smallest values are in blue.

From the table, it is seen that pattern 4 had three fourths of the least variant values and *none* of the greatest deviations. Pattern 4 thus not only had the fastest reaction time response among the subjects but it had the least deviation (for 6 out of 8 subjects anyway) in that response.

V. Field Evaluation

The field testing was conducted by VDL with the assistance of PATH[16] engineers at the Richmond Field Station (RFS). The shadow truck warning signal was transported to RFS after laboratory testing was completed. There it was secured to the roof of a test vehicle (a Lincoln *Town Car*), which came equipped with a radar unit—the Eaton-Vorad EVT-300 system. This is seen in Figure 14.

Figure 24: Test vehicle with shadow truck warning signal mounted and operational at the Richmond Field Station. The black rectangle (on the rear bumper just above the license plate well) with wires running into the trunk is the transponder for the radar unit.

The radar system equipment is fairly extensive and occupies the trunk as can be seen in Figure 15. In the upper right of that picture is an inverter to supply AC power to the equipment. The computer running the system is in the lower left. The purpose of the frequency generator (next to the power strip) is explained below. The data from the radar system can be sent to a laptop operated from the backseat of the test vehicle (Figure 16).

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[16] PATH—*Partners for Advanced Transit and Highways* was created in 1986. It is administered by the Institute of Transportation Studies (ITS) at UC Berkeley in conjunction with *Caltrans*.

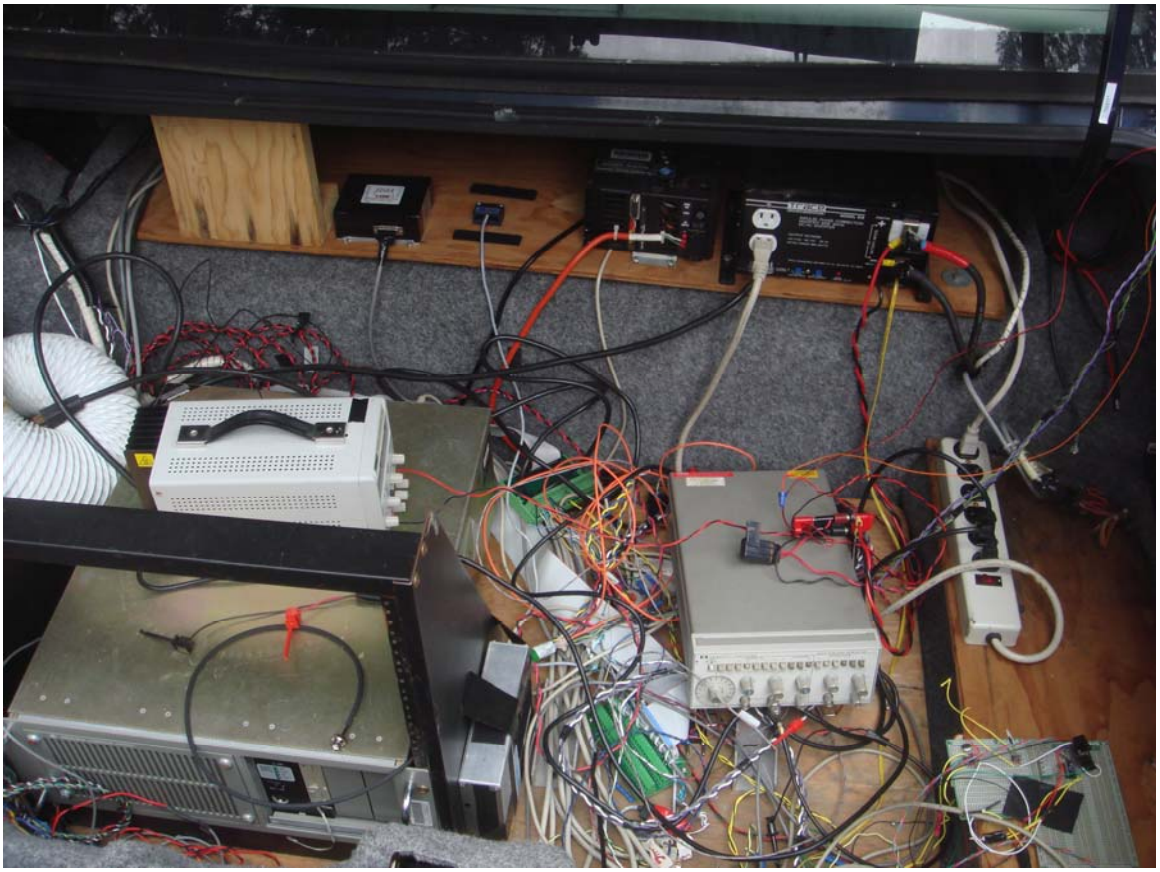

Figure 25: Radar support equipment occupies the trunk of the test vehicle.

We decided to have the radar-equipped vehicle stationary and have laboratory and RFS personnel drive their own vehicles toward the test car. Since subjects would be driving directly toward the car they would have to either brake or swerve in order to avoid hitting it. Despite the low speeds of the test (10 and 25 m.p.h.) and the uniformity in testing that would be gained by use of a single approaching vehicle for all subjects and trials, VDL felt that, in the interest of safety, subjects would be best able to avoid an accident if they were driving a vehicle with which they felt at ease (e.g. their own car). Furthermore, despite subjects knowing that they were to brake (or swerve if there was insufficient braking distance) when they saw the signal become active, VDL wanted to try to keep the test somewhat realistic; this was done by having the driver keep his foot on the accelerator until the signal actually lit up and not having his foot hovering over the brake in anticipation of the signal activating. A driver would be much more confident of doing this safely in his personal vehicle rather than in a car that he has never driven before.

Figure 26: Christina Chow (VDL) and Scott Johnston (PATH) confer during the field evaluation. The mounting for the shadow truck warning signal can be seen just above the doorway. Mr. Johnston is examining the laptop that receives the radar data.

The road used for this test was contained wholly within the RFS facility. It was also largely isolated from buildings, parking lots and what little traffic there is at RFS. This can be seen in the background of Figure 14. The background of Figure 16 shows that there is clearly ample unoccupied space to the right of the parked test car when approaching from the rear. This allows a subject to safely swerve if he decides that the braking distance available is insufficient. In fact the only car showing up in the background of Figure 16 is one of the personal vehicles used for the testing. We should also note that the test vehicle with radar and signal was unoccupied during the actual testing. VDL made every effort to ensure that the field testing was done in a safe manner.

The radar is designed for a vehicle that is normally moving. However, since the test vehicle was stationary, the radar had to be “fooled” into “thinking” that both cars were moving[17]. This was done with the frequency generator mentioned above. By changing the frequency of the generator the “speed” of the stationary test vehicle, *as seen by the radar*, would also change. This in turn changed the closing distance at which the radar system triggered the signal light. Preliminary trials, for which no data was saved, were performed in order to estimate a reasonable signal triggering distance.

The method used in the actual trials is as follows. The subject would be stopped with his vehicle idling at a distance of a few hundred feet away. After checking with lab personnel via a walkie-talkie that all was ready, he would try to drive, along the straight road, at a predetermined speed (either 10 or 25 m.p.h.—indicated by the car’s speedometer) directly toward the rear of the parked test vehicle. In order to be as realistic as possible, the driver would hold his foot steady on the accelerator until he saw the shadow truck warning signal light up. At that point the subject would brake.

Trials were conducted for two signal patterns and two speeds such that each subject completed five trials for every pattern-speed combination. Thus every subject completed a total of twenty trials. As already mentioned, the two speeds were ten and twenty-five miles per hour.

The two patterns compared were numbers 2 and 4. As discussed earlier in this report, pattern 4 is a MEWS pattern with its specific parameters already given in Table 1/Figure 8; it is meant to give the impression of an expanding rectangle. Pattern 2 is a simple flashing pattern (see the “all_flash” section of the program in Appendix 3). All segments, that is the full light bar, come on for one full second and then all lights go dark for one second. The cycle then repeats until the light bar is deactivated.

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[17] More precisely, the algorithm activating the radar had to interpret the closing speed of the two vehicles as different than it actually was. If the radar thought the cars were closing too fast it could trigger the signal at an absurdly early point in the trial allowing so much stopping distance that the scenario was very unrealistic. Conversely, if the algorithm didn’t trigger the signal until there was only the possibility of swerving to avoid collision (i.e. insufficient braking distance) subjects became too nervous to react in a consistent manner.

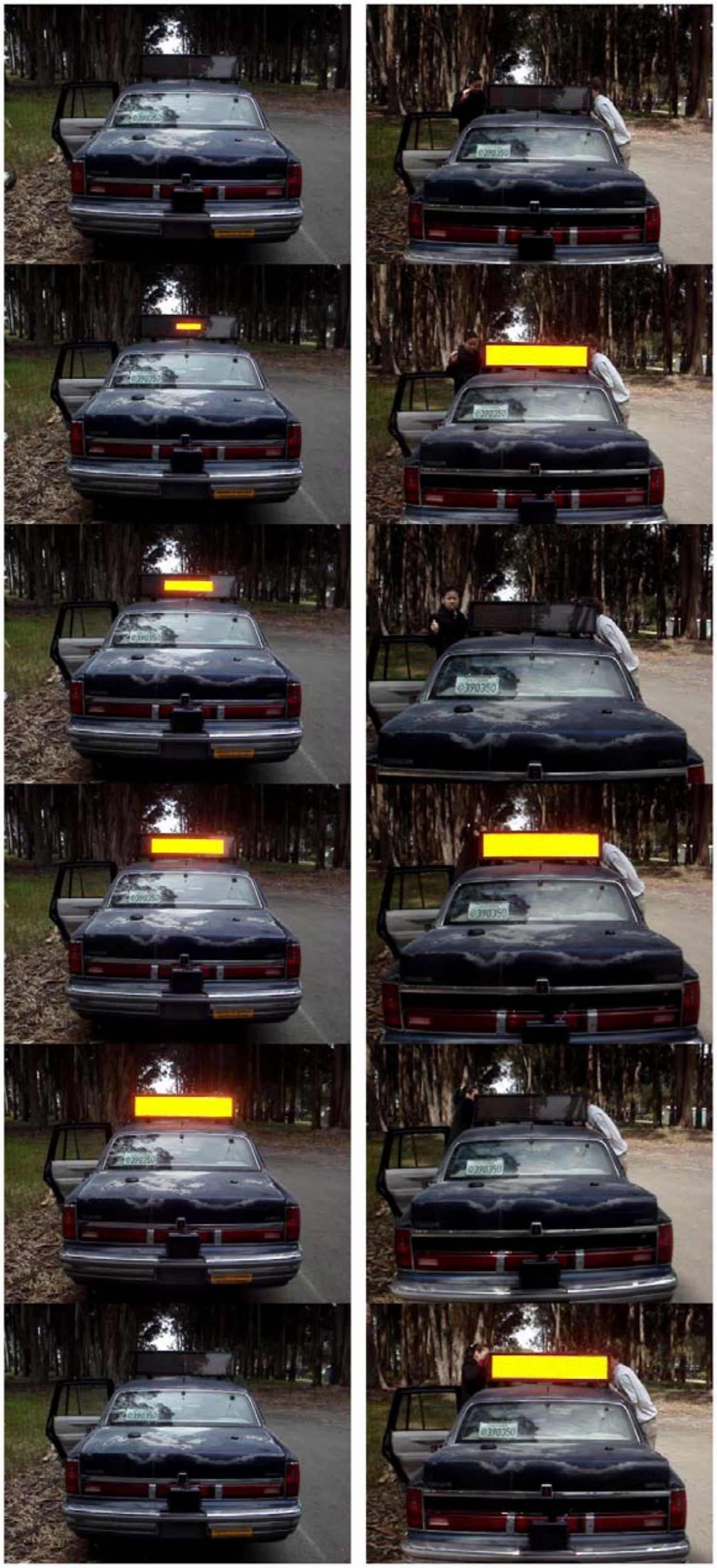

Figure 27: The vertical strip on the left represents pattern 4 and the vertical strip on the right shows pattern 2 (time increasing down the page in both cases).

Pattern two was chosen rather than one of the other patterns tested in the lab because of an unfortunate difficulty that came to the attention of VDL after laboratory testing was complete. The radar unit available to us had a sampling interval of over 65 ms. In practice, this meant a resolution in reaction time not better than 65 ms.[18]

Since the biggest reaction time difference from the laboratory tests was just over 60 ms (see Table 2), *the radar sampling interval was greater than the widest difference in recorded (averaged) reaction times in the laboratory*. Therefore we had to choose a pattern which would have an even bigger discrepancy against pattern 4 (the best result from the lab). Pattern 2 was known to have a wider discrepancy with pattern 4 than did other patterns tested in the laboratory, and thus we elected to include pattern 2 in the field testing. Having settled on the patterns and speeds to be tested, trials were run for three subjects in order to see if sufficient time resolution was being obtained in the data to justify further testing.

The radar data was recorded on the laptop computer mentioned above by RFS personnel and sent to VDL in the form of ASCII files that could be read into Excel for further processing. A key to the data columns in the resulting file was supplied by RFS. The relevant (for this experiment) columns were radar sampling time, vehicle speed (in units of a tenth of a foot per second!), and "DDU messages"; the latter are codes recorded by the radar unit's computer and show the radar's status. The particular code number "230" corresponded to activation of the shadow truck warning signal. By examining the time column entry in the Excel file in the same row as the "230" code for the DDU message the signal activation time could be deduced. The time at which the subject began braking required more effort to figure out.

One might naively think that taking the difference of sequential speed entries (a finite difference approximation to acceleration) would yield the time at which braking started and that the process could therefore be automated. This was not the case and the relevant time for the start of braking had to be found "by hand" for <u>every</u> individual trial. The reasons for this are: 1) the radar can lose track of the vehicle and then reacquire it, resulting in huge, *spurious* "accelerations"; 2) even if the radar had kept perfect track of vehicles, the threshold (de)accelerations (necessary for automating the data extraction process—i.e. with Excel macros) could vary enormously by subject and by trial, making a fixed standard impossible; 3) there is some ambiguity in determining which data point is the beginning of braking. The next few figures illustrate the difficulties.

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[18] *Theoretically* speaking this is not true; a sufficiently large number of trials with a sufficiently large number of subjects could partially overcome this *discretization error* (or *quantization error* as it is known in signal processing). This reduction is possible because the "signal" being quantized is not a continuous deterministic function but rather a continuous distribution of a random variable (the reaction time). The mathematics involved can be complicated. The interested reader is referred to Appendix 2 for a numerical analysis. For our field test "sufficiently large" was deemed impractical.

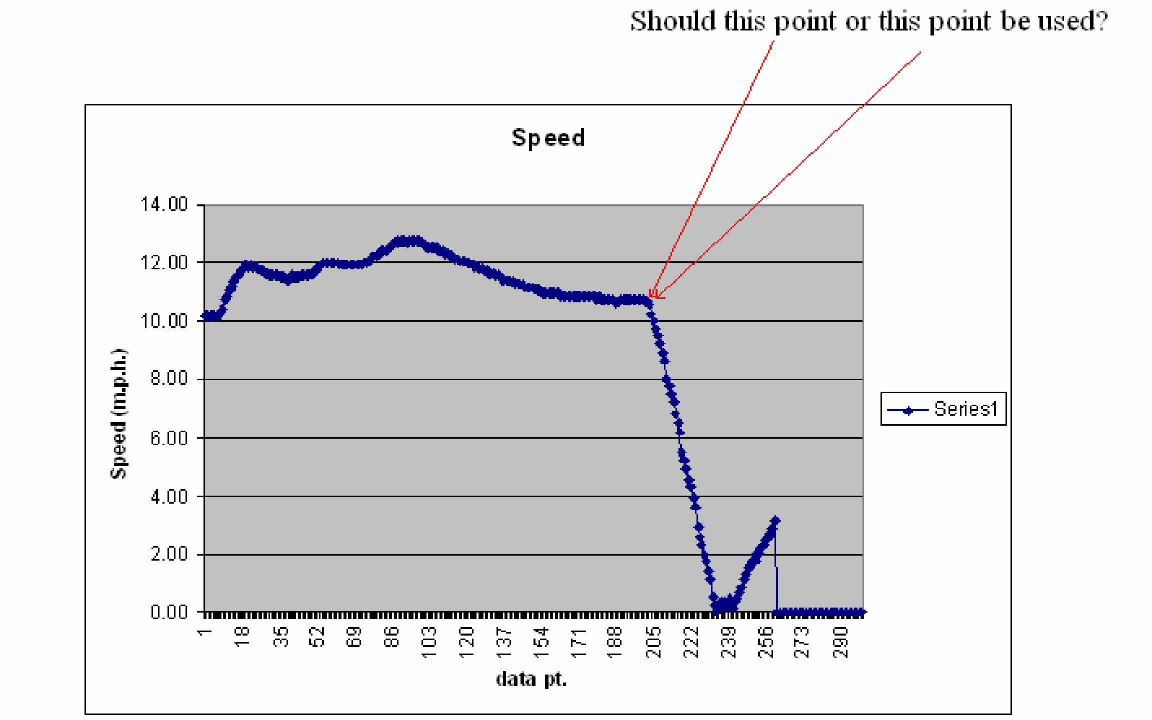

Figure 28: A graph of speed (converted to m.p.h.) of sequential data points for one of the trials. Note that there is an ambiguity in which data point should be chosen. This is actually one of the "cleaner" graphs. A magnification around the "knee" shown is of little help; either one of the two points could credibly be claimed as the start of braking and thus an uncertainty of at least 65 ms (the sampling interval between points) is introduced.

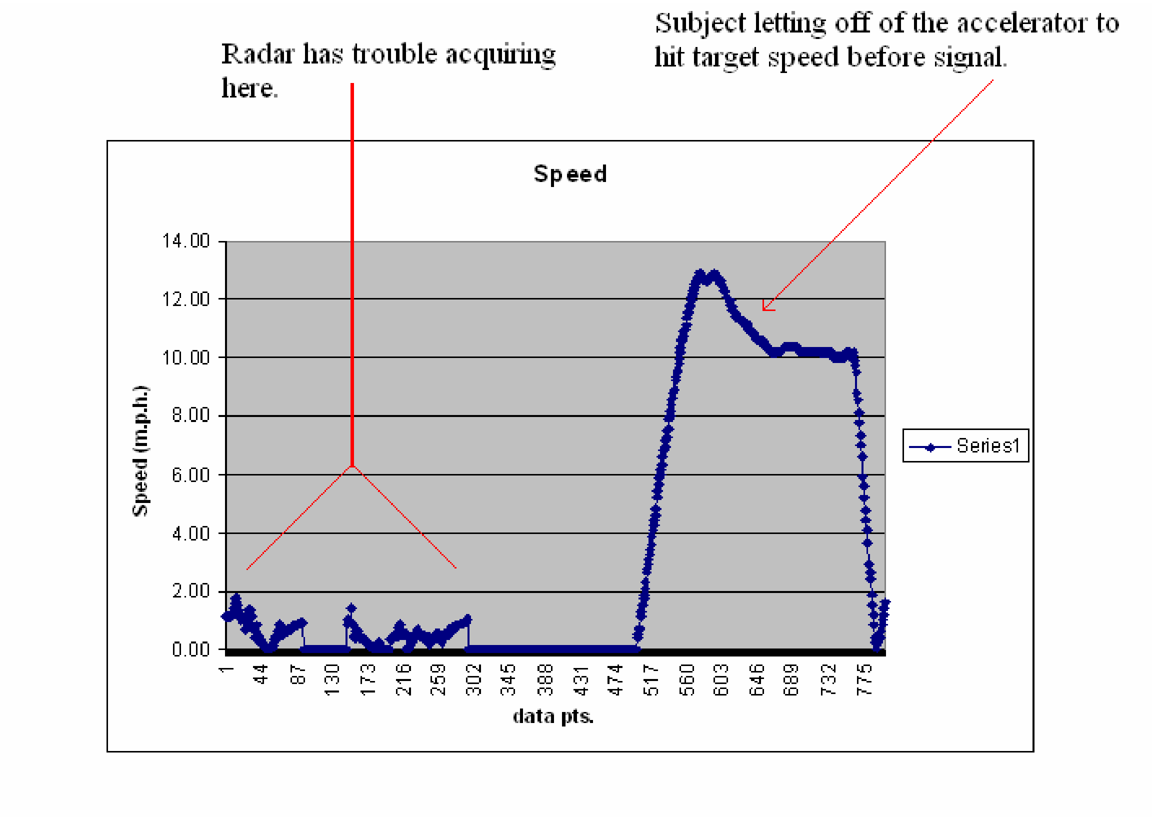

Figure 29: The first few hundred data points are useless, as the vehicle has not even started moving. These seemingly random jumps as the radar tries to acquire the (stationary) vehicle nonetheless could be interpreted by an automated inspection of the data as accelerations. The subject later decelerates as he tries to achieve the target speed. This could be misinterpreted by a program as the "real" braking point.

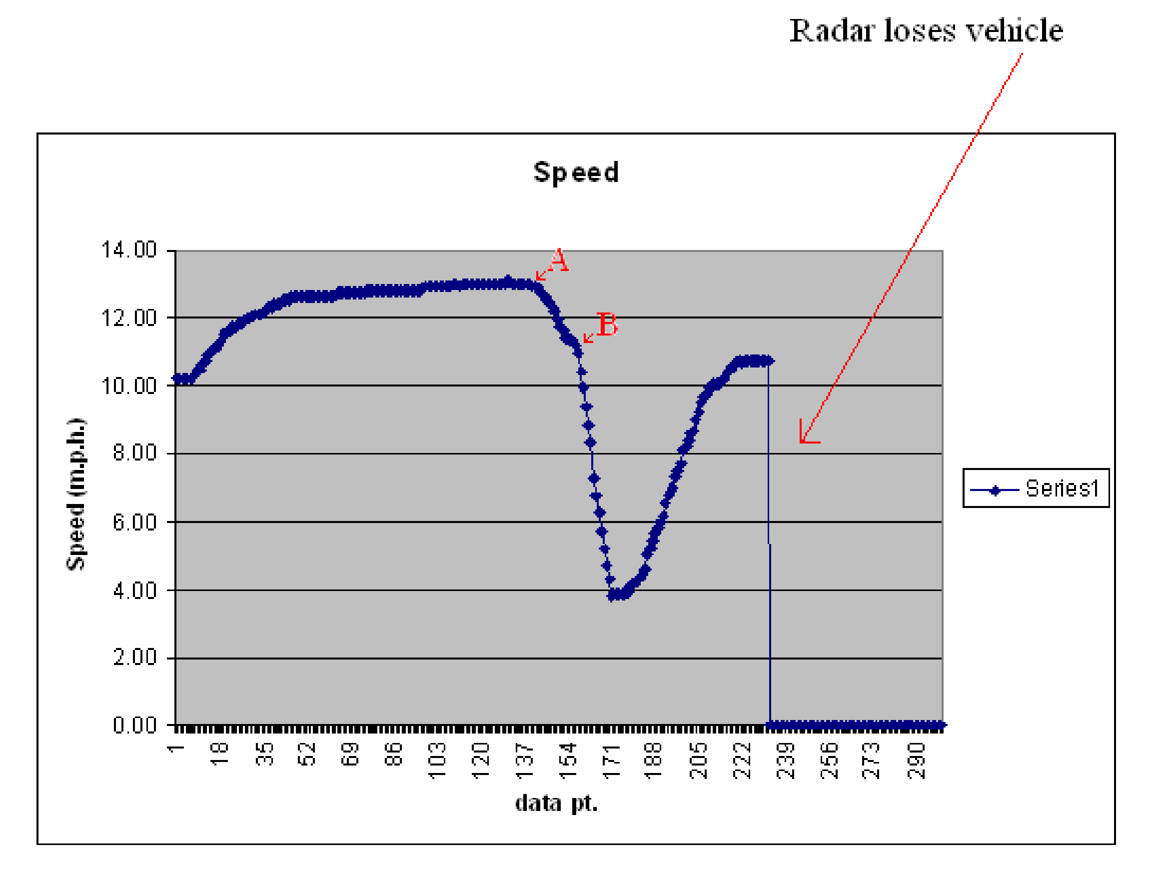

Figure 30: Point A is not the point at which reactive braking took place; rather the response to the signal is at B. This illustrates why the data must be examined "by hand".

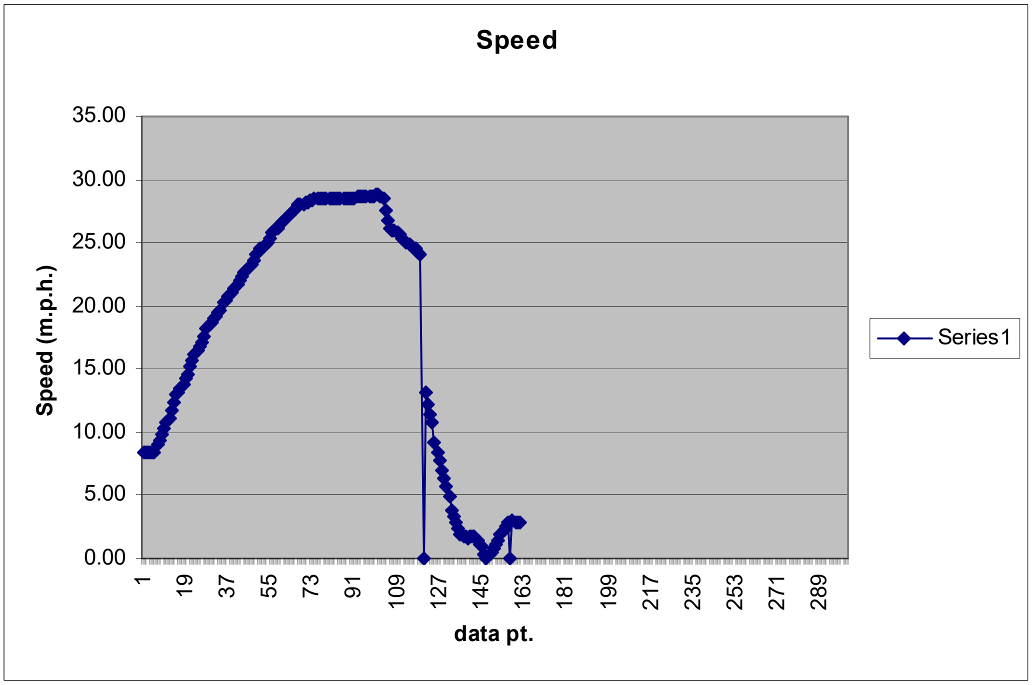

Figure 31: Does (reaction) braking occur where the signal has been lost?

Having examined each trial "by hand" and determined, with some unavoidable ambiguity, the point in time that represents the start of reactive braking, the signal start was subtracted from this value; the result was the reaction time for each trial.

The reaction times for each of the five trials for each condition and subject were averaged and the result is the following tables.

Subject:	**Pattern 2 (ms)**	**Pattern 4 (ms)**	**Difference (Patt. 2 – Patt. 4)**
a	604.3[19]	578	26.3
b	627.2	722.6	-95.4
c	576.2	564.6	11.6

Table 15: Reaction time in milliseconds for the 10 m.p.h. driving condition.

Subject:	**Pattern 2 (ms)**	**Pattern 4 (ms)**	**Difference (Patt. 2 – Patt. 4)**
a	562.8	575.8	-13.0
b	668.0	709.2	-41.2
c	564.6	577.8	-13.2

Table 16: Reaction time in milliseconds for the 25 m.p.h. driving condition.

In Table 7 only one of the three results is, in absolute value, bigger than the radar sampling interval. Furthermore, it is of the opposite sign to the other two! Table 8 has <u>no</u> values bigger than the sampling interval. In addition, the differences in Table 8 switch sign for two of the subjects from Table 7 while the magnitude decreases for the third subject. In other words, moving to a higher speed had an inconsistent sign of change among the subjects: two had the difference move in the negative direction and the third had movement in the positive direction.

It is hard to see how these results can be interpreted as anything other than statistical fluctuation in small samples with limited resolution. VDL thus determined that further trials of this sort would be very unlikely to give any meaningful result.

It should also be pointed out that one of the properties of the radar and data acquisition system available to us was that *<u>every 7th data point doubled in time spacing</u>*. In other words, points 1 and 2 (say) were 65 ms apart but points 6 and 7 were separated by 130 ms. This repeated every 7th time interval—the 7th, 14th, 21st, etc. intervals were all 130 ms while those intervals not a multiple of seven had a separation of 65 ms. Any future field test would benefit from use of a radar and data acquisition system with much faster sampling rate and without the data point time spacing anomaly.

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[19] This average was based on four rather than five values because the braking point could not be determined for one of the trials.

VI. Conclusions

While the equipment available to us for field testing, in particular the radar system with its limited resolution[20], restricted our ability to discern statistically significant differences among light bar firing patterns in the field, the laboratory test results, in contrast, were quite striking.

The difference in reaction time was about 60 ms between the best and the worst of the patterns tested. That is equivalent to a gain of 4 extra feet at 45 m.p.h. and this is only the difference among the limited number of patterns we could test. A wider variety of patterns would most likely result in an even bigger discrepancy in reaction times; *clearly the choice of signal pattern can (at least for some types of signals) mean a big difference in reaction times.*

Furthermore, not only were the differences in reaction times for the best and worst patterns statistically significant, the differences were consistent in sign across subjects (Table 2) and the best pattern had the least variation and the worst had (essentially) the most (Table 6).

The shadow truck warning signal was also a success from a qualitative point of view. A look at Figure 14 or 17 shows that the device is quite conspicuous and was built in accordance with the initial specifications. The electronic design used gave it tremendous flexibility within its (intentional) limitations and allowed for very easy computer-controlled testing within the laboratory.

From the laboratory results we can gain some insight into what makes an effective signal pattern. Referring to Table 1, *quick change (MEWS-type) during the first 200 ms or so followed by a 'long'[21] hold-on-full period seems to give the best results (patterns 4 and 3).* In contrast, the mimicking of a constant speed of approach to a fixed object (pattern D—see Appendix 1) resulted in the longest reaction times of those tested, a result which was contrary to our initial expectations. In conclusion, the results of our experiments indicate that among the patterns tested, pattern 4 is the most effective in terms of eliciting the fastest observer reaction time.

VII. Acknowledgements

The staff at VDL would like to thank Scott Johnston and Paul Kretz (Senior Development Engineers at PATH) for their help in connecting the shadow truck warning signal to the radar unit and explaining the software interface for the radar.

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[20] Appendix 2 tries to quantify how much the limitations of a coarse resolution system can be overcome by large amounts of data or, put another way, how to make a silk purse out of a sow's ear. This Appendix is just meant to be for reference however. That approach is largely academic—the large number of trials needed would be wholly impractical within the scope of this project.

[21] 'Long' meaning comparable to the whole interval during which the apparent motion takes place and much longer than the time a given segment change is lit.

Appendix 1: Origin of the Shadow Truck Hyperbolic Display Pattern (Pattern D)

This appendix gives the physical and quantitative reasoning behind the development of the “hyperbolic” warning pattern, referred to in the above as pattern D. We start with how a large object immediately in front of a driver appears to her as she approaches it head-on.

If a vehicle is at a distance d_0 from a rectangle that has its long side (width L) horizontal and perpendicular to the vehicle’s direction of travel at time zero then as that vehicle approaches at a constant speed v the visual angle (θ) subtended by the rectangle’s width will change as follows.

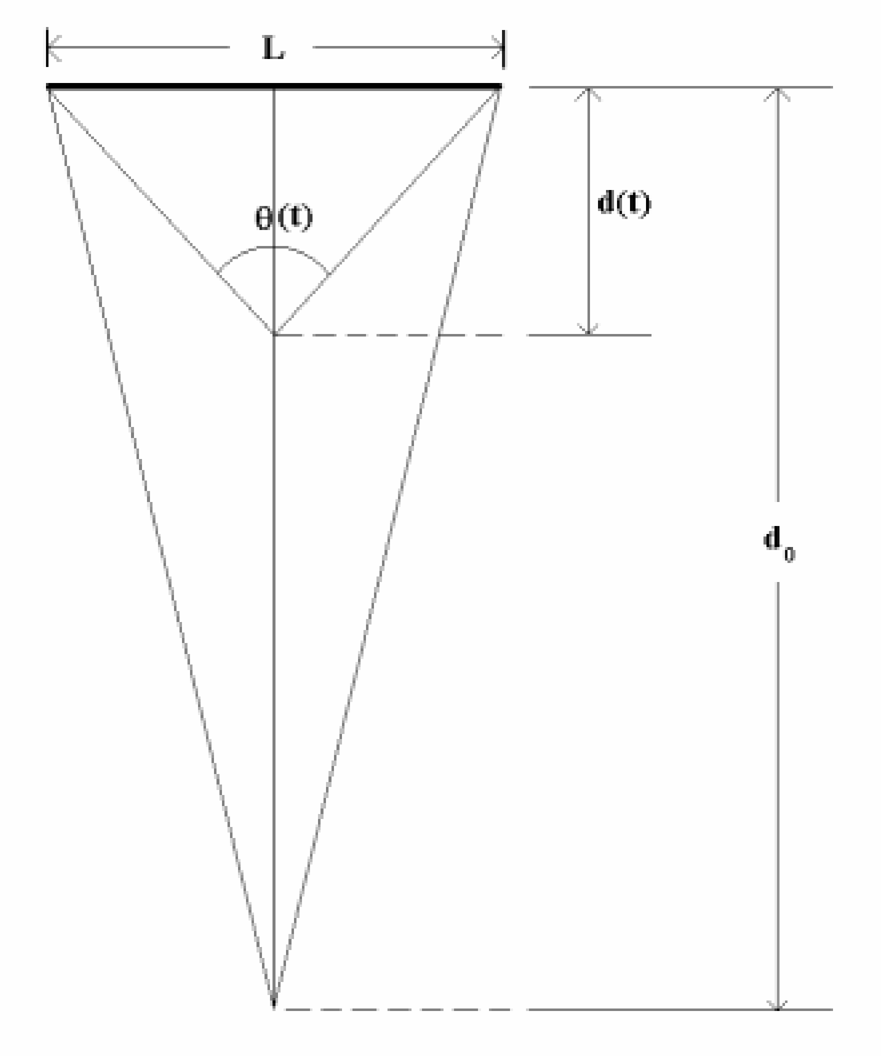


Figure A1: Angle subtended by L as a function of time

Clearly,

$$d(t) = d_0 - vt$$

and

$$\tan\left(\frac{\theta}{2}\right)=\frac{L/2}{d(t)}.$$

Thus,

$$\theta = 2\tan^{-1}\left(\frac{L}{2d(t)}\right)=2\tan^{-1}\left(\frac{L}{2(d_0-vt)}\right)$$

is the angle as a function of time.

Now if an observer is at rest (or moving comparatively slowly) with respect to a rectangle that is growing in size, how does that rectangle (i.e. the shadow truck display) grow to mimic the above situation? Let w(t) be the [changing] width of the rectangle situated a *fixed* distance s from an observer.

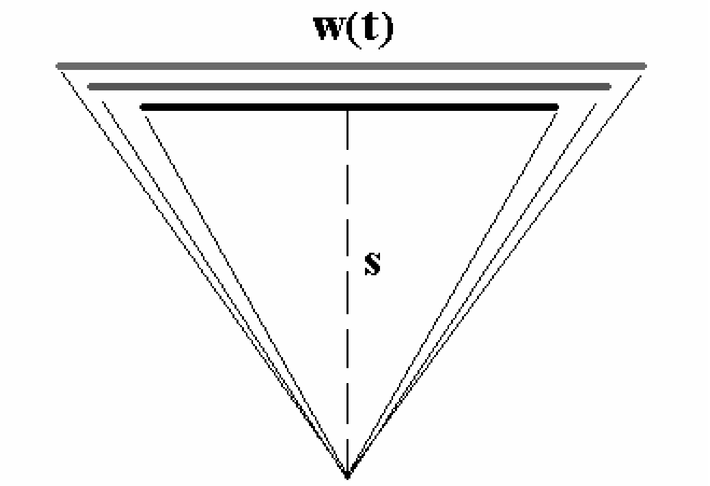


Figure A2: Different widths (ideally superimposed but separated here for clarity) give rise to different angles subtended

As before,

$$\frac{w(t)/2}{s}=\tan\left(\frac{\theta}{2}\right).$$

Equating to the above expression for tangent,

$$\frac{w(t)}{2s}=\frac{L}{2d(t)}\Rightarrow w(t)=\frac{sL}{d_0-vt}.$$

Thus a graph of the changing width as a function of time is a (shifted) *hyperbola*. In general $xy = const.$ (or $y = c/x$) is a hyperbola and hence $y = c/(x_0 \pm x)$ is a hyperbola shifted along the x-axis.

For our laboratory testing purposes, w(t) is the width of the shadow truck warning light display at time t, assuming that the display could grow continuously while s is the distance from the stationary observer to the display. In the laboratory setting, the "fixed width" L, initial distance d_0 and speed v become adjustable parameters.

The value of s is fixed by the observer's separation from the display and is very nearly 20 ft (6.096 meters) in the lab. A starting guess of v ~ 20 mph = 8.94 m/s, L ~ 10.5″ = 0.267 m, d_0 ~ 50 ft. = 15.24 m was tried. Unfortunately, those values didn't work.

The problem is that we have to match the widths of the display at certain times. The widths of the light segments of the display are multiples of 0.275 m (give or take a centimeter or so):

$$\begin{aligned} w_1 &= 0.275\, m \quad (\textit{actually about } 0.27\, m) \\ w_2 &= 0.55\, m \\ w_3 &= 0.825\, m \quad (\textit{actually about } 0.84\, m) \\ w_4 &= 1.10\, m. \end{aligned}$$

One can imagine the edge of the *continuous* lighted rectangle sweeping out with time. As this imaginary rectangle coincides with the actual segments those segments should light up. In an obvious notation let these times be t_1, t_2, t_3, t_4. But since the first segment *lights up* at t_1, it stays on alone until t_2. Thus *time t_1 is effectively time zero* as far as the observer of discrete segments is concerned and the first relevant time is $t_2 - t_1$.

In other words, we tell the computer controlling the lights, "begin the cycle by turning on the first light segment alone for $t_2 - t_1$ seconds". Thus the time *intervals* must be a) practical and b) interesting.

"Practical" means between a few ms and maybe 250 ms. Any shorter and you can disregard human response because observers cannot notice. Any longer and you are unlikely to have a significant effect on reaction time.

"Interesting" means having the segments light on "both parts" of the hyperbola specifying w(t). In other words, the segment lighting times are not all on the "flat" part of the curve and not all on the asymptotic part of the curve. (See Figure A3 below.)

To get such time intervals the speed had to be cranked up from the original guess. A reasonable set of values is:

s = 6.096 m (20 ft.)

L = 0.35 m (1.15 ft.)

$$d_0 = 14 \text{ m } (45.93 \text{ ft.})$$

$$v = 17 \text{ m/s } (38 \text{ mph}).$$

The computed (absolute) times are then,

$$t_1 = 367\ ms$$
$$t_2 = 595\ ms$$
$$t_3 = 671\ ms$$
$$t_4 = 709\ ms$$

which are shown in Figure A3, and from which the time *intervals* can be computed as

$$\Delta_1 = 228\ ms$$
$$\Delta_2 = 76\ ms$$
$$\Delta_3 = 38\ ms$$
$$\Delta_4 = 114\ ms.$$

Here Δ_1 is the time that the first segment is on alone. The number Δ_4 was determined from $d_0 / v - t_4$ where d_0/v is the time at which our *moving*, virtual observer would crash into the sign.

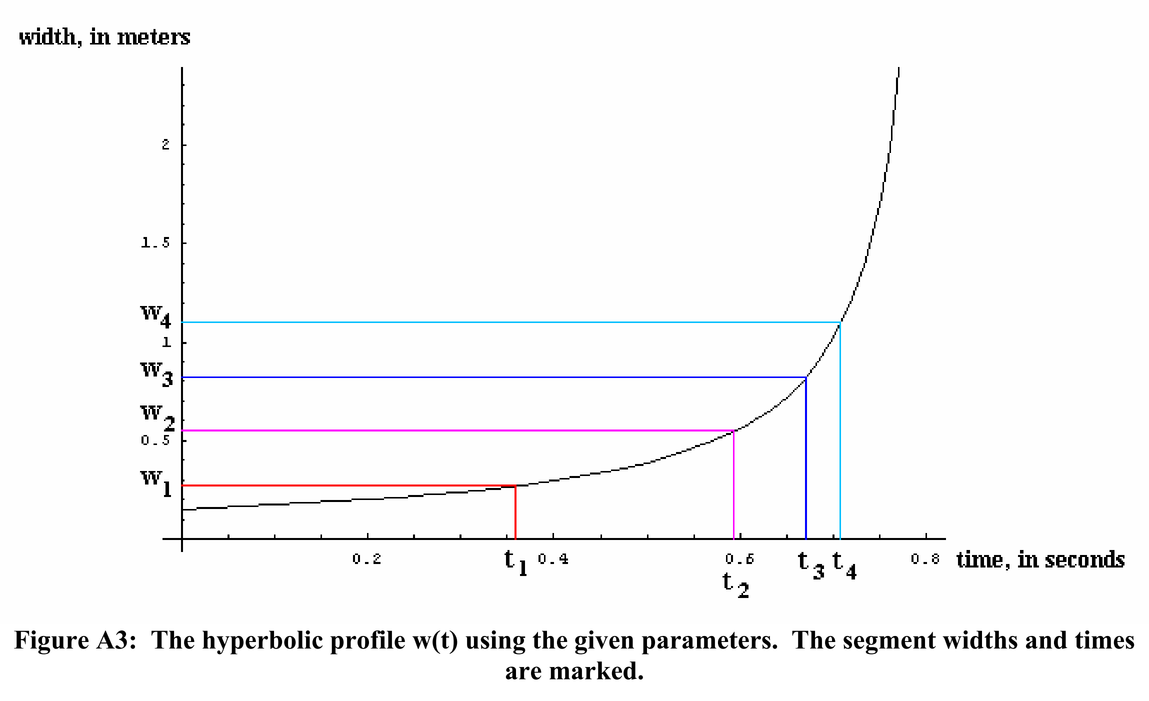


Figure A3: The hyperbolic profile w(t) using the given parameters. The segment widths and times are marked.

A somewhat arbitrary blanking time of 200 ms was used to complete the timing sequence. The cycle then repeats; the result is pattern D as mentioned in section 2 of this report.

Appendix 2: Monte Carlo Estimates of the Minimal Field Data Needed to Achieve Sufficient Statistical Resolution Given a Fixed, Low Sampling Rate

The radar sampling interval used in the field testing for the *Shadow Truck Light Bar* posed quite a problem; the time between samples was comparable to the expected difference in reaction times between the patterns tested. This is like trying to measure someone's height with a yardstick with no finer gradations. Now given the inherent limits in field testing of this type that is the end of the problem as a practical matter.

But it does raise some questions of a theoretical nature whose answers may be of utility in a slightly different situation. The problem here is very akin to *quantization noise*: when an analog signal is digitized the signal level (say a voltage) at a given sampling time is assigned to one of several discrete values (typically the closest one) and this "rounding" of a continuous signal's value distorts the signal and can be thought of as added "noise".

Of course in the case of quantization noise the signal is deterministic and consists of a dependent variable (say a voltage) occurring as a function of an independent variable (time) while in the radar case there is only one variable (the reaction time) and it comes from a probability distribution—a stochastic function. Thus while the analogy is not perfect the essential character of the problem is the same—a value to be measured is pigeon-holed into one of several fixed, discrete levels and therefore some information is lost. The question then becomes how much information is lost and what, if anything, can be done to reduce that loss.

Suppose a probability distribution function (call it f(t)), representing a reaction time distribution, has a lower limit of t_0 and an upper limit t_n. In other words, the function is identically zero prior to time t_0 (which could be zero) and identically zero after time t_n (which could, in principle, be infinite). The true average is, of course,

$$t_{avg.} = \int_{t_0}^{t_n} t\, f(t)\, dt \tag{A.1}$$

But suppose that the time domain is divided up into n intervals (taking t_n as large but finite) and that any "draw" from the distribution is recorded as coming from the *end* of the interval from which it is drawn. For example, if the (equal) intervals start from zero and are 65 ms wide then a value of 123.7 ms is recorded as $2 \times 65 = 130$ ms since it is greater than 65 ms and less than 130 ms. Under such a procedure, with *an infinite number of draws* (read <u>exceedingly large</u> in practice), what is the resulting "average"?

Each interval endpoint would be weighted by portion of the curve's area falling within that interval. In other words,

$$t_{eff.\ avg.} = t_1 \int_{t_0}^{t_1} f(t)\, dt + \ldots + t_{i+1} \int_{t_i}^{t_{i+1}} f(t)\, dt + \ldots + t_n \int_{t_{n-1}}^{t_n} f(t)\, dt. \tag{A.2}$$

This can be illustrated by an example, but first we need to take a brief digression.

Reaction time distributions can be modeled, at least within the accuracy needed here, by a *shifted gamma distribution*. This is given by

$$f(t) = \begin{cases} \dfrac{(t-c)^{a-1} e^{-\frac{(t-c)}{b}}}{\Gamma(a) b^a}, & t \geq c \\ 0 & , t < c \end{cases} \tag{A.3}$$

where t (reaction time) is in milliseconds (ms); b and c are also in ms. The parameter '*a*' is dimensionless. This distribution has its average and variance given by

$$\begin{aligned} \mu &= c + ab \\ \sigma^2 &= ab^2. \end{aligned} \tag{A.4}$$

A value of c, say 200 ms, can be assumed as reasonable and then the average and variance from a real data set can be put into equation(s) (A.4) and then solved for the parameters a and b. In this way, an analytical expression with *realistic* numbers can be used to model (via Monte Carlo) what can be expected, at least to first order, from a statistical analysis of data.

For example, in the figure below is a histogram [red] of the actual reaction time response of subject C to pattern 4 (the lab data not the minimal field data) overlaid with a (scaled) shifted gamma distribution [blue] with fit parameters: a = 12.206, b = 19.978 ms and c = 200.0 ms. The fit is not perfect but it does not need to be. The average with these parameters is 443.85 ms and the variance is 4871.69, which can be checked against table 2 in the text and the square of the entry in table 6.

Now by design the theoretical average of this distribution will be via equation (A.1),

$$\begin{aligned} t_{avg.} &= \int_c^\infty t \, \frac{(t-c)^{a-1} e^{-\frac{(t-c)}{b}}}{\Gamma(a) b^a} dt = \int_0^\infty (\tau + c) \frac{\tau^{a-1} e^{-\frac{\tau}{b}}}{\Gamma(a) b^a} d\tau \\ &= \int_0^\infty \frac{\tau^a e^{-\frac{\tau}{b}}}{\Gamma(a) b^a} d\tau + c \int_0^\infty \frac{\tau^{a-1} e^{-\frac{\tau}{b}}}{\Gamma(a) b^a} d\tau \\ &= b \frac{\Gamma(a+1)}{\Gamma(a)} + c = c + ab = 200 + 12.206 \times 19.978 \\ &= 443.85, \end{aligned} \tag{A.5}$$

in agreement with (A.4). But what about the "effective average" (equation (A.2)) when the draws are "quantized" as discussed above?

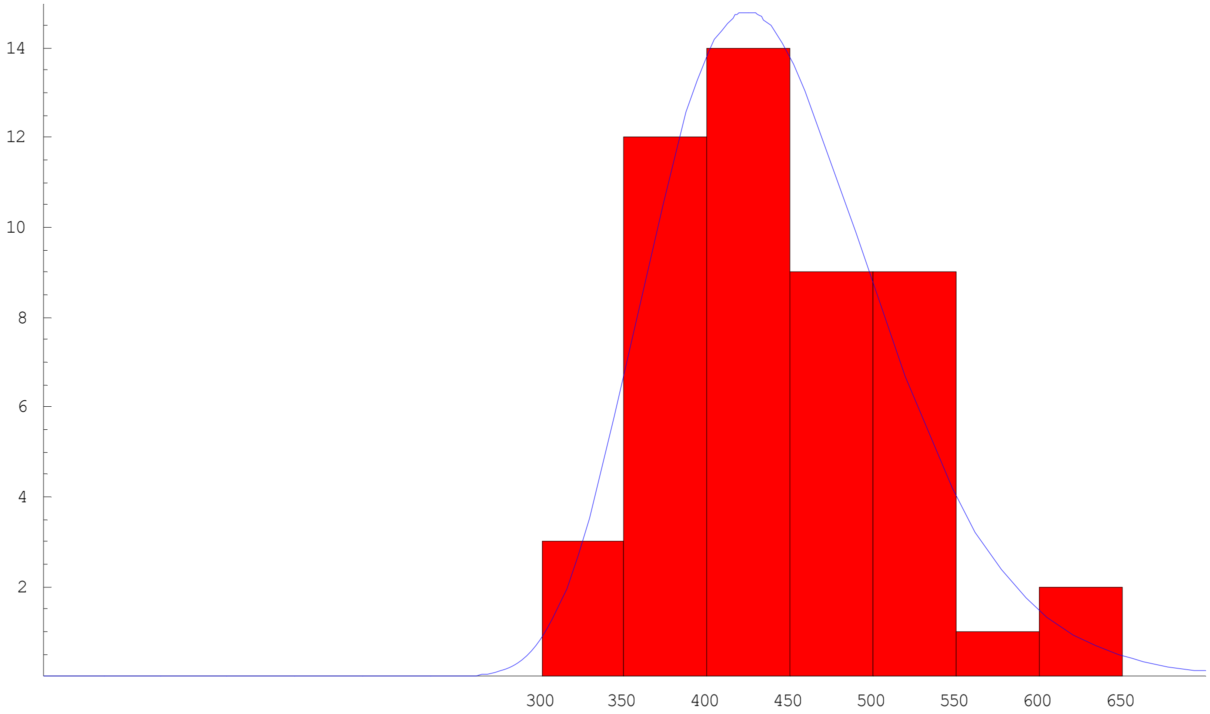


Figure B1: A histogram of the actual reaction time (lab) data for subject C to pattern 4 (the x-axis is in milliseconds). A fit of the shifted gamma distribution is overlaid on this as the blue curve (parameters are a = 12.206, b = 19.978 ms and c = 200.0 ms). The probability distribution function is scaled with an overall factor of the product of the overall number of trials histogrammed (50) and the histogram bin size (50), that is 2500, in order to get the correct comparison.

Numerical integration of equation (A.2) for these parameters with a sampling interval of 65 ms gives 476.35 ms. ***Note that this is the best that can be done with a sampling interval of 65 ms because it assumes an infinite (very large) number of samples.***

Thus in this particular case the "closest approach" to the "true" average is only within $476.35 - 443.85 = 32.5$ ms, *a sizable error*. Of course, the actual situation is much worse. The above assumes a very large number of "draws" (trials). What happens with a small number of trials?

Using the Von Neumann acceptance-rejection method a Monte Carlo simulation can be run with the shifted gamma distribution using the parameters fit to actual (lab) data. Data from the lab is used because 50 trials obviously give a better idea of real parameters than 5 trials (not to mention that the reaction times in the lab are known to within a hundredth of a millisecond!). The results of the parameter fits are shown in tables B1 and B2. The probability distribution function curves resulting from these fits are shown in figure B2 for five subjects (5 of the 8 who did the lab tests). The purple curves are the fast reaction distributions and the blue curves are the slow reaction distributions. Notice that the peaks of the purple curves are not always below the peaks of the corresponding blue curves; only the averages of the distributions shown in purple are guaranteed to be less than the averages of the distributions shown in blue.

Fit Parameters for the Shifted Gamma Distribution for Lab Data Pattern 4

Subject	Value for a	Value for b (ms)	Value for c (ms)
A	5.627	31.856	200.0
C	12.206	19.978	200.0
D	6.347	39.702	200.0
F	4.569	31.726	200.0
G	4.113	54.169	100.0

Table B1: Fit parameters to gamma distribution for lab data (pattern 4)

Fit Parameters for the Shifted Gamma Distribution for Lab Data Pattern D

Subject	Value for a	Value for b (ms)	Value for c (ms)
A	2.028	132.528	200.0
C	10.293	30.060	200.0
D	7.028	47.449	200.0
F	1.646	127.858	200.0
G	1.779	174.051	100.0

Table B2: Fit parameters to gamma distribution for lab data (pattern D)

Rather than examining a single distribution as above however, it is more instructive to simulate the actual experiment. Thus the Monte Carlo will be run to make tables for t-tests like table 4, this time only 5 “subjects” will be used however. Tables will be made for the following conditions: 1) an infinite number of draws with precision sampling (e.g. taking the average values directly from the theoretical distribution); 2) an infinite number of draws with sampling intervals pegged at multiples of 65 ms (numerical integration of equation (A.2)); 3) a finite number of draws with arbitrary precision (Monte Carlo); 4) a finite number of draws with those draws binned in multiples of 65 ms.

A comparison of the t-tests applied to the resulting tables should give a feeling for how badly small sample numbers and “quantization noise” affect the statistical results.

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
468.77	379.26	89.51
509.42	443.85	65.57
533.48	451.98	81.50
410.50	344.96	65.54
409.64	322.81	86.83
Average of Differences: 77.79		

Table B3: “Infinite” draws from distributions (tables B1 and B2) with high precision for each draw give the averages in this table.

The average difference here is greater than in §IV because the “best” five of the eight subjects there were chosen for this simulation. The t statistic for table B3 is 15.08; compare this to the associated critical (one-tail) value for four degrees of freedom (= n – 1) of 2.13 at the 95th percentile and 3.75 at the 99th percentile. The p-value (one-tail) is

5.64×10^{-5}. Clearly, the result is highly significant since it was deliberately chosen to be that way.

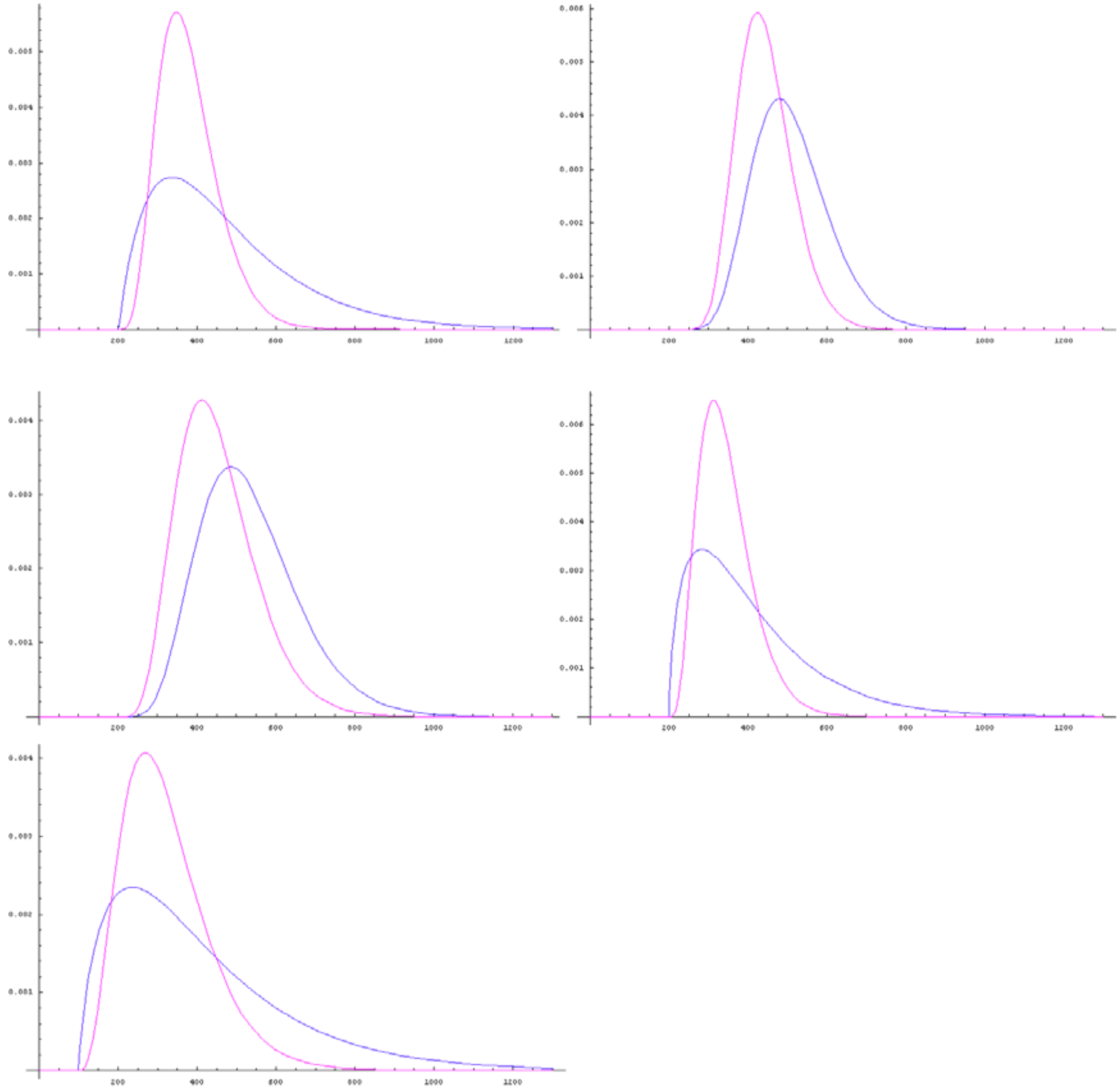


Figure B2: Plots of the fitted shifted gamma distribution for the reaction times (lab) using tables B1 and B2. Reading left to right and up to down the plots are for subjects A, C, D, F and G. In every case the x-axis runs from zero to 1300 ms. The purple curve is for pattern 4 (fast) and the blue curve is for pattern D (slow reaction).

Now what about an "infinite" number of draws where the result of each draw is forced to be a multiple of 65 ms? The results of numerical integration on equation (A.2) using the distributions resulting from the parameters in tables B1 and B2 are shown below.

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
501.18	411.79	89.39
541.92	476.35	65.57
565.98	484.48	81.50
443.02	377.46	65.56
442.11	355.32	86.79
	Average of Differences:	77.76

Table B4: "Infinite" sampling from the distributions but with quantization in multiples of 65 ms.

Table B4 represents the best "averages" that one can get with quantization. Very surprisingly, the differences in table B4 agree with those in table B3. Any discrepancies are in the second decimal place and those may be due to rounding. In fact, the t statistic is slightly higher at 15.13 and the one-tail p-value is slightly lower at 5.56×10^{-5}. But while the differences are in agreement, the actual values change quite a bit. For pattern D under the quantization scheme, subject A gets 501.18 ms while under the "exact" scheme he gets 468.77 ms. Further examination shows that **all** the values for patterns D and four are shifted up by ~32.5 ms from table B3 to B4. ***This shift is half the quantization level***.

How to explain this remarkable coincidence? Recall the trapezoidal rule of integration. A continuous function g(x) over an interval $a \le x \le b$ is divided up into n intervals of equal size h$\left(=\dfrac{b-a}{n}\right)$ such that $a = x_0 < x_1 < x_2 < \cdots < x_n = b$. The value of its integral over this range is:

$$\begin{aligned}\int_a^b g(x)\,dx &= \frac{h}{2}\sum_{j=0}^{n-1}\left(g(x_j)+g(x_{j+1})\right)+E_T \\ &= \frac{h}{2}\left(g_0+2g_1+2g_2+\ldots+2g_{n-1}+g_n\right)+E_T\end{aligned} \qquad \text{(A.6)}$$

where $g_k \equiv g(x_k)$ and E$_T$ is the error term. The error bound is $|E_T| \le \dfrac{K(b-a)^3}{12n^2}$ where K is the absolute value of the largest second derivative, $g''(\xi)$, in the interval, $a \le \xi \le b$. It is proven by integration by parts twice.

Applying the trapezoidal rule to the integrals in (A.1) and (A.2) and *assuming that the error terms* are negligible (the error bound is just that—an upper bound; the actual error terms can be much smaller), the difference between the integrals works out to be,

$$t_{eff.\ avg.} - t_{avg.} \approx \frac{h^2}{2}\left(f_0 + f_1 + f_2 + \ldots + f_n\right) \approx \frac{h}{2}\cdot 1 \qquad \text{(A.7)}$$

where h is taken as the quantization interval (65 ms in the above case) and f_0 is $f(t_0)$ and so on. Thus the factor $h\cdot\left(f_0 + f_1 + f_2 + \ldots + f_n\right)$ in (A.7) is essentially the area under the curve f(t) filled with rectangles—looking like the corresponding histogram and the area under f(t) should be one since it is a probability distribution. When the error terms can no longer be ignored with larger h and smaller n then equation (A.7) will break down.

An alternate way of looking at the answer lies in figure B2. The "bulk" of the distributions lies between 200 ms (100 ms in the last graph) and about 1000 to 1200 ms. Each tick mark on the time axis is 50 ms. Thus a 65 ms interval is somewhat fine-grained. A piecewise linear approximation to the distributions using this interval turns out to be pretty good.

What is remarkable about this result is that ***given the error terms discussed above are negligible, the differences between pattern reaction times can be preserved under this "quantization" scheme even though the individual times can change substantially.***

What happens when the quantization interval is greater than the suspected differences? Table B5 represents quantization in multiples of 100 ms. Table B6 represents quantization in multiples of 300 ms.

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
518.86	429.25	89.61
559.41	493.75	65.66
583.49	502.03	81.46
461.38	394.19	67.19
459.9	372.66	87.24
	Average of Differences:	78.23

Table B5: "Infinite" sampling from the distributions but with quantization in multiples of 100 ms.

Amazingly, the *differences* in table B5 are *still* little changed from the "exact" answers in table B3. A perusal of the right two columns in tables B3 and B5 shows that equation (A.7) (a difference in corresponding columns of ~ 100/2 = 50) is still holding. Clearly the t-test will give results like those above.

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
621.58	563.27	58.31
650.16	605.89	44.27
681.21	615.88	65.33
556.80	517.26	39.54
551.76	462.01	89.75
	Average of Differences:	59.44

Table B6: "Infinite" sampling from the distributions but with quantization in multiples of 300 ms.

Finally in table B6 we start to see the effects from the quantization interval. With the interval cranked up to a very large 300 ms we see significant departures from the previous difference numbers. The average difference is now almost 20 below that in table B5. The corresponding columns in tables B6 and B3 now have their differences diverge more than the expected 150 (= 300/2) predicted by equation (A.7). For pattern D one difference is as deviant as 141 and for pattern 4 one pair of numbers has a difference of 184. But it is truly astounding that the quantization interval has to be so large to get significant errors in the difference column to kick in. Clearly table B6 would still yield a significant t-statistic, but computing it here would give us little additional insight.

In actual practice of course, one never gets an infinite number of draws. Therefore we now turn to Monte Carlo simulation using the parameters from tables B1 and B2 to see the effect of a finite number of draws. We begin with 50 trials from the distributions with no quantization. The result is table B7.

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
450.24	375.89	74.35
505.55	443.35	62.20
550.13	483.45	66.68
376.18	352.67	23.51
426.13	342.51	83.62
		Average of Differences: 62.07

Table B7: Averages obtained from 50 trials in a Monte Carlo run (no quantization).

Naturally we expect table B7 to show significance and it does. The t-statistic is 6.02 in comparison to a (one-tail) critical t value (95%) of 2.13. The one-tail p-value is 0.002. The only thing that gives one pause is the average difference of 62.07 ms in comparison to the “real” value of 77.79 ms (table B3). Things can only get worse with fewer trials and they do in table B8.

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
493.96	357.96	136.00
484.36	448.23	36.13
488.69	467.79	20.90
393.31	348.26	45.05
331.12	303.43	27.69
		Average of Differences: 53.15

Table B8: Averages obtained from 5 trials in a Monte Carlo run (no quantization).

The results of table B8 just make the cut. The t-statistic is 2.52 which is just a bit more than the (one-tail, 95%) critical value of 2.13 and *less* than the two-tail (95%) critical t value of 2.78. The one-tail, 95% p-value is 0.033. ***This represents the bare minimum when you have precision measurement*** (and that assumes everyone shows an effect—i.e.

figure B2). Also the quite low result of 53.15 ms (compared to the "true" 78.79 ms) is a poor sign.

Now what happens when "quantization" is combined with limited data? Table B9 shows what happens when a sampling interval of 65 ms is used for the quantization level. The numbers were generated by doing the same Monte Carlo routine as above, but every time an "exact" reaction time was generated, the number was "quantized" by being recorded as a multiple of 65 ms. Thus, for example, a generated time of 138.76 ms falls between $130\ ms = 2 \times 65\ ms$ and $195\ ms = 3 \times 65\ ms$ and would be recorded as 195 ms. The numbers recorded in this manner were then averaged to produce the entries in table B9.

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
508.30	410.80	97.50
531.70	477.10	54.60
543.40	499.20	44.20
417.30	375.70	41.60
379.60	358.80	20.80
	Average of Differences:	51.74

Table B9: Averages obtained from 50 trials in a Monte Carlo run with quantization of 65 ms.

The results of table B9 are not so bad. The average difference of 51.74 ms is less than the 53.15 ms in table B8, but the t-statistic comes up to 4.08 (again compared to the one-tail, 95% level) critical t value of 2.13 and the one-tail p-value is 0.008, a respectable number. The conclusion is that many trials with quantization still give significance but the actual number of interest (i.e. the average of differences) can be way off.

Now we turn to the worst of both worlds—a low number of trials combined with quantization, as shown in table B10.

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
351.00	455.00	-104.00
585.00	429.00	156.00
494.00	507.00	-13.00
598.00	403.00	195.00
455.00	377.00	78.00
	Average of Differences:	62.40

Table B10: Averages obtained from 5 trials in a Monte Carlo run with quantization of 65 ms.

Clearly the results of this last table don't look promising despite the average difference being in the "ballpark". In fact the t-statistic for table B10 is 1.14 while the critical value (one-tail at the 95% level) is 2.13. The p-value (one-tail) is 0.16. Thus *quantization at this level with only a few trials can totally obscure a significant result and render it seemingly insignificant*. **Compare the above numbers to the "true" numbers from table B3.**

Thus our decision to forgo further field tests was justified. But even yet we don't have a comparable situation. The "real" difference between the patterns is 78 ms (table B3). The above sampling interval/quantization level is still less than this. In the field test we were hoping to see a difference maybe a little less than the sampling interval. Therefore we will up the quantization level to 85 ms; thus an average difference of 78 ms would be about the same percentage of an 85 ms interval that a difference of 60 ms (best in-lab average difference between patterns with eight people) would be of the radar's sampling interval of 65 ms. This is what is represented by the next table for 5 trials.

Table B11, like table B10, misses the mark badly. The t-statistic is 1.15 where it needs to surpass the critical value of 2.13. The (one-tail) p-value is 0.10; while nominally better than the value of 0.16 in table B10, the overall average difference is even further off of the mark at 44.20. *Clearly table B11 would represent an unreliable data set in the real world*.

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
527.00	459.00	68.00
561.00	459.00	102.00
544.00	476.00	68.00
442.00	391.00	51.00
391.00	459.00	-68.00
Average of Differences: 44.20		

Table B11: Averages obtained from 5 trials in a Monte Carlo run with quantization of 85 ms.

Finally, we answer the implicit question posed in the title of the appendix. How many trials given this type of quantization are enough to get "reasonable" data? Starting with an impractically large number *we get results akin to tables B4 and B5*.

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
505.24	420.41	84.83
555.22	489.77	65.45
572.73	494.36	78.37
465.63	387.77	77.86
442.34	366.52	75.82
Average of Differences: 76.47		

Table B12: Averages obtained from 500 trials in a Monte Carlo run with quantization of 85 ms.

From this absurdly large number of trials we see the tendency toward "infinite" sampling but with quantization. *The average difference comes out (essentially) correct as do most of the individual subject differences. The individual results for pattern 4 are pretty much the "true" results of table B3 plus half the quantization interval, that is about an additional 42 ms.* This is what we expect from our previous discussion above. The individual results for pattern D also vary by about plus 42 ms from those in table B3 but there is a little more variability, a range of 33 to 55 additional milliseconds. The (one-tail) p-value is very low (order10^{-5}).

Turning to 50 trials we still see respectable results in table B13.

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
532.10	426.70	105.40
557.60	486.20	71.40
569.50	487.90	81.60
460.70	416.50	44.20
418.20	348.50	69.70
	Average of Differences:	74.46

Table B13: Averages obtained from 50 trials in a Monte Carlo run with quantization of 85 ms.

The average difference in table B13 is largely correct. The trend mentioned above of half the quantization interval plus the exact number giving the individual numbers is now largely lost; it is only good at a large number of trials—an impractical number unfortunately. This means that the individual results are now largely "wrong".

The statistics are still good though. The t-statistic is 7.53 vs. the critical (one-tail, 95%) value of 2.13. The (one-tail) p-value of 0.001 is a good sign. *Thus if individual results are not essential and one is only looking for reasonable statistics between pattern means and a correct overall average of differences then fifty trials will work (at least for distributions like those modeled here).*

A run of fifty trials is still impractical for field testing (in most cases). Can we go lower? Table B14 shows a result for ten trials. The average difference is way off. The individual differences are way off and the t-statistic was 2.27, barely above the needed t critical of 2.13 (one-tail, 95%). The p-value (one-tail) was 0.04, just making the 5 percent cutoff.

Pattern D (ms)	Pattern 4 (ms)	Difference (Patt. D – Patt. 4)
459.00	399.50	59.50
561.00	484.50	76.50
595.00	484.50	110.50
416.50	416.50	0.00
374.00	374.00	0.00
	Average of Differences:	49.30

Table B14: Averages obtained from 10 trials in a Monte Carlo run with quantization of 85 ms.

Now another run of ten trials had low (less than 1%) p-values (and another way-off average of distances). But only three sets of ten were run and the variability of small data sets is quite large. The chances of a set like B14 are quite good. *Thus in order to ensure decent statistics more than ten trials are needed.* Furthermore, this entirely ignores the fact that 49.30 ms is quite distant from 77.79 ms (the "true" answer from table B3).

Three runs of twenty trials (tables not shown) were done. While these sets had "good statistics"—p-values (one-tail) less than 1% (say 0.003)—the average of differences went as high as 99.45. This says that you can get a fairly far off number with as many as twenty trials.

To summarize then, if you want merely adequate statistics you need at least ten trials. If you want "good" statistics you'll need twenty or more trials. In both instances however, you are merely assured that "something [a real difference between patterns] is there"; its actual value could be way off (say ~20% off the real number). To get a correct value for the average of differences you'll need to get closer to fifty trials and to get *individual results for patterns* that are correct or that can be corrected (not just correct *differences* between patterns) you'll need north of fifty trials. Since even ten trials per subject would have been burdensome in the field testing, we felt justified in not pursuing it further.

Appendix 3: Source Code for the Basic Stamp II Program used for the Shadow Truck Warning Light Testing

---

```
' {$STAMP BS2}
' {$PBASIC 2.5}
'Author:  Michael Babb
'Description:  Specifications for a highway maintenance
'truck mounted light bar to warn of imminent rear-end
'collision.
'Written for:  T. E. Cohn, Scott Johnston, Daniel Greenhouse, Kent Christianson
'of U. C. Berkeley, Visual Detection Laboratory.
'Written to the Shadow Truck Specifications Revision V5.

'Revisions
'A - Initial Realease - 040506
'B - Added additional pattern ("adhoc") for setting $C [Kent Christianson] 072506
'C - Added the hyperbolic pattern ("hyp") for setting $D [Kent Christianson] 080106

'Program types
'all_off   CON $0     'all lights off (outc=0)
'all_on    CON $1     'all lights on  (outc=$F)
'all_flash CON $2     'all lights flash - need freq and duty cycle
'c_fast    CON $3     'p8->p9->p10->p11, y on, z off. 100ms
'c_med     CON $4     'p8->p9->p10->p11, y on, z off. 250ms
'c_slow    CON $5     'p8->p9->p10->p11, y on, z off. 1000ms
'd_fast    CON $6     'p8->p9->p10->p11, z off. 100ms
'd_med     CON $7     'p8->p9->p10->p11, z off. 250ms
'd_slow    CON $8     'p8->p9->p10->p11, z off. 1000ms
'e_fast    CON $9     'p8->p9->p10->p11, y off, z on. 100ms
'e_med     CON $A     'p8->p9->p10->p11, y off, z on. 250ms
'e_slow    CON $B     'p8->p9->p10->p11, y off, z on. 1000ms

'Other constants
'leds      CON outc
'prog_select   CON    inb
switch    PIN 0       'associates Pin0 with the word switch
doubler   PIN 1       'associates Pin1 with the word doubler

'Pin initialization
DIRS = $0F00          'all inputs except for pins 8-11


'Main loop
'Checks what program is selected
what_prog:
IF (INB = $0) THEN all_off        'jumps to all_off
IF (INB = $1) THEN all_on         'jumps to all_on
IF (INB = $2) THEN all_flash      'jumps to all_flash
IF (INB = $3) THEN c_fast         'etc...
IF (INB = $4) THEN c_med
IF (INB = $5) THEN c_slow
```

```
IF (INB = $6) THEN d_fast
IF (INB = $7) THEN d_med
IF (INB = $8) THEN d_slow
IF (INB = $9) THEN e_fast
IF (INB = $A) THEN e_med
IF (INB = $B) THEN e_slow
IF (INB = $C) THEN f_adhoc
IF (INB = $D) THEN g_hyp
IF (INB = $E) THEN all_off
IF (INB = $F) THEN all_off
GOTO what_prog              'loops back to top of main loop


'Subroutines
'----------------------------------------
'all lights off
all_off:
OUTC = %0000                      'sets lights to off
GOTO what_prog                    'jumps back to main loop
                          'IMPORTANT: Logic level
                          'for "switch" & "doubler"
                          'inverted from mockup program.
'all lights on
all_on:
IF (switch = 1) THEN              'checks to see if on switch is engaged
  OUTC = %1111                    'turns all the lights on
ELSE                         'if on switch is off
  OUTC = %0000                    'all lights off
ENDIF
GOTO what_prog                    'jumps back to main loop

'all lights flash
all_flash:
IF (doubler = 1) THEN all_flash_d     'checks double speed switch
IF (switch = 1) THEN              'checks on switch
  OUTC = %1111                    'turns all lights on
  PAUSE 1000                    'for 1 second
IF (doubler = 1) THEN all_flash_d     'checks double speed switch
  OUTC = %0000                    'turns all lights off
  PAUSE 1000                    'for 1 second
ELSE                         'if on switch is off
  OUTC = %0000                    'all lights off
ENDIF
GOTO what_prog                    'jumps back to main loop

'25 ms steps for x, y on, z off
c_fast:
IF (doubler = 1) THEN c_fast_d        'checks doubler switch
IF (switch = 1) THEN              'checks on switch
  OUTC = %0001                    'turns on 2 inner most lights (step 1)
  PAUSE 25                     'for 25 ms
```

```
IF (doubler = 1) THEN c_fast_d         'checks doubler
  OUTC = %0011                     'step 2
  PAUSE 25                      'for 25 ms
IF (doubler = 1) THEN c_fast_d         'checks doubler
  OUTC = %0111                     'step 3
  PAUSE 25                      'for 25 ms
IF (doubler = 1) THEN c_fast_d         'checks doubler
  OUTC = %1111                     'step 4
  PAUSE 25                      'for 25 ms
IF (doubler = 1) THEN c_fast_d         'checks doubler
  PAUSE 100                      'y for 100 ms
IF (doubler = 1) THEN c_fast_d         'checks doubler
  OUTC = %0000                     'lights off
  PAUSE 100                      'z for 100 ms
ELSE                          'if on switch is no engaged
  OUTC = %0000                     'lights off
ENDIF
GOTO what_prog                      'jumps to main loop etc... etc...

c_med:
IF (doubler = 1) THEN c_med_d
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 62
IF (doubler = 1) THEN c_med_d
  OUTC = %0011
  PAUSE 63
IF (doubler = 1) THEN c_med_d
  OUTC = %0111
  PAUSE 62
IF (doubler = 1) THEN c_med_d
  OUTC = %1111
  PAUSE 63
IF (doubler = 1) THEN c_med_d
  PAUSE 100
IF (doubler = 1) THEN c_med_d
  OUTC = %0000
  PAUSE 100
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

c_slow:
IF (doubler = 1) THEN c_slow_d
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 250
IF (doubler = 1) THEN c_slow_d
  OUTC = %0011
  PAUSE 250
```

```
IF (doubler = 1) THEN c_slow_d
  OUTC = %0111
  PAUSE 250
IF (doubler = 1) THEN c_slow_d
  OUTC = %1111
  PAUSE 250
IF (doubler = 1) THEN c_slow_d
  PAUSE 100
IF (doubler = 1) THEN c_slow_d
  OUTC = %0000
  PAUSE 100
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

d_fast:
IF (doubler = 1) THEN d_fast_d
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 25
IF (doubler = 1) THEN d_fast_d
  OUTC = %0011
  PAUSE 25
IF (doubler = 1) THEN d_fast_d
  OUTC = %0111
  PAUSE 25
IF (doubler = 1) THEN d_fast_d
  OUTC = %1111
  PAUSE 25
IF (doubler = 1) THEN d_fast_d
  OUTC = %0000
  PAUSE 100
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

d_med:
IF (doubler = 1) THEN d_med_d
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 62
IF (doubler = 1) THEN d_med_d
  OUTC = %0011
  PAUSE 63
IF (doubler = 1) THEN d_med_d
  OUTC = %0111
  PAUSE 62
IF (doubler = 1) THEN d_med_d
  OUTC = %1111
```

```
  PAUSE 63
IF (doubler = 1) THEN d_med_d
  OUTC = %0000
  PAUSE 100
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

d_slow:
IF (doubler = 1) THEN d_slow_d
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 250
IF (doubler = 1) THEN d_slow_d
  OUTC = %0011
  PAUSE 250
IF (doubler = 1) THEN d_slow_d
  OUTC = %0111
  PAUSE 250
IF (doubler = 1) THEN d_slow_d
  OUTC = %1111
  PAUSE 250
IF (doubler = 1) THEN d_slow_d
  OUTC = %0000
  PAUSE 100
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

e_fast:
IF (doubler = 1) THEN e_fast_d
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 25
IF (doubler = 1) THEN e_fast_d
  OUTC = %0011
  PAUSE 25
IF (doubler = 1) THEN e_fast_d
  OUTC = %0111
  PAUSE 25
IF (doubler = 1) THEN e_fast_d
  OUTC = %1111
  PAUSE 25
IF (doubler = 1) THEN e_fast_d
  OUTC = %0000
  PAUSE 100
IF (doubler = 1) THEN e_fast_d
  OUTC = %1111
  PAUSE 100
```

```
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

e_med:
IF (doubler = 1) THEN e_med_d
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 62
IF (doubler = 1) THEN e_med_d
  OUTC = %0011
  PAUSE 63
IF (doubler = 1) THEN e_med_d
  OUTC = %0111
  PAUSE 62
IF (doubler = 1) THEN e_med_d
  OUTC = %1111
  PAUSE 63
IF (doubler = 1) THEN e_med_d
  OUTC = %0000
  PAUSE 100
IF (doubler = 1) THEN e_med_d
  OUTC = %1111
  PAUSE 100
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

e_slow:
IF (doubler = 1) THEN e_slow_d
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 250
IF (doubler = 1) THEN e_slow_d
  OUTC = %0011
  PAUSE 250
IF (doubler = 1) THEN e_slow_d
  OUTC = %0111
  PAUSE 250
IF (doubler = 1) THEN e_slow_d
  OUTC = %1111
  PAUSE 250
IF (doubler = 1) THEN e_slow_d
  OUTC = %0000
  PAUSE 100
IF (doubler = 1) THEN e_slow_d
  OUTC = %1111
  PAUSE 100
ELSE
```

```
  OUTC = %0000
ENDIF
GOTO what_prog

f_adhoc:
IF (doubler = 1) THEN f_adhoc_d              'checks doubler switch
IF (switch = 1) THEN                         'switch high means the device is running
  OUTC = %0001
  PAUSE 300                                  '"Adhoc" mode is ultra-slow pattern C for now
IF (doubler = 1) THEN f_adhoc_d
  OUTC = %0011
  PAUSE 300
IF (doubler = 1) THEN f_adhoc_d
  OUTC = %0111
  PAUSE 300
IF (doubler = 1) THEN f_adhoc_d
  OUTC = %1111
  PAUSE 600
IF (doubler = 1) THEN f_adhoc_d
  OUTC = %0000                               'lights off
  PAUSE 300                                  'z is 300 ms
IF (doubler = 1) THEN f_adhoc_d
ELSE                                         'if run switch is not engaged
  OUTC = %0000                               'lights off (ELSE matches 2nd IF in this section)
ENDIF
GOTO what_prog

g_hyp:
IF (doubler = 1) THEN g_hyp_d                'checks doubler switch
IF (switch = 1) THEN                         'switch high means the device is running
  OUTC = %0001
  PAUSE 228                                  '"Hyperbolic" mode follows the hyperbolic time
IF (doubler = 1) THEN g_hyp_d                'profile of a sign seen by an observer approaching
  OUTC = %0011                               'at constant speed
  PAUSE 76
IF (doubler = 1) THEN g_hyp_d
  OUTC = %0111
  PAUSE 38
IF (doubler = 1) THEN g_hyp_d
  OUTC = %1111
  PAUSE 114
IF (doubler = 1) THEN g_hyp_d
  OUTC = %0000                               'lights off
  PAUSE 200                                  'z is 200 ms -- chosen arbitrarily
ELSE                                         'if run switch is not engaged
  OUTC = %0000                               'lights off (ELSE matches 2nd IF in this section)
ENDIF
GOTO what_prog


'doubled - all subroutines reflect 2x increase in speed
```

```
'and all subroutines finish one cycle before they check
'whether or not the doubler switch is engaged.
'-----------------------------------------------------
all_flash_d:
IF (switch = 1) THEN
  OUTC = %1111
  PAUSE 500
  OUTC = %0000
  PAUSE 500
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

c_fast_d:
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 12
  OUTC = %0011
  PAUSE 13
  OUTC = %0111
  PAUSE 12
  OUTC = %1111
  PAUSE 13
  PAUSE 50
  OUTC = %0000
  PAUSE 50
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

c_med_d:
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 31
  OUTC = %0011
  PAUSE 31
  OUTC = %0111
  PAUSE 31
  OUTC = %1111
  PAUSE 32
  PAUSE 50
  OUTC = %0000
  PAUSE 50
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

c_slow_d:
```

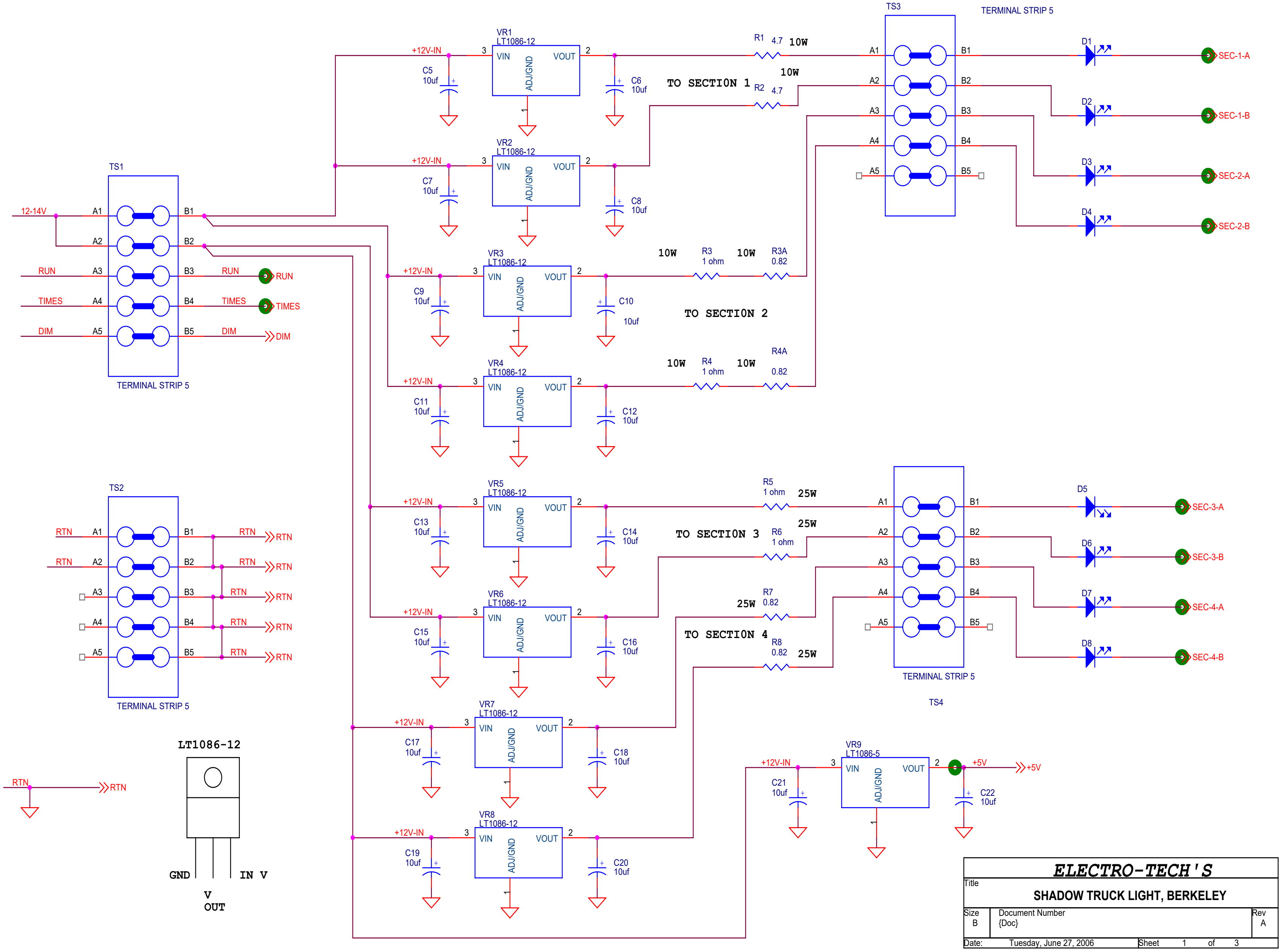
```
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 125
  OUTC = %0011
  PAUSE 125
  OUTC = %0111
  PAUSE 125
  OUTC = %1111
  PAUSE 125
  PAUSE 50
  OUTC = %0000
  PAUSE 50
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

d_fast_d:
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 12
  OUTC = %0011
  PAUSE 13
  OUTC = %0111
  PAUSE 12
  OUTC = %1111
  PAUSE 13
  OUTC = %0000
  PAUSE 50
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

d_med_d:
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 31
  OUTC = %0011
  PAUSE 31
  OUTC = %0111
  PAUSE 31
  OUTC = %1111
  PAUSE 32
  OUTC = %0000
  PAUSE 50
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog
```

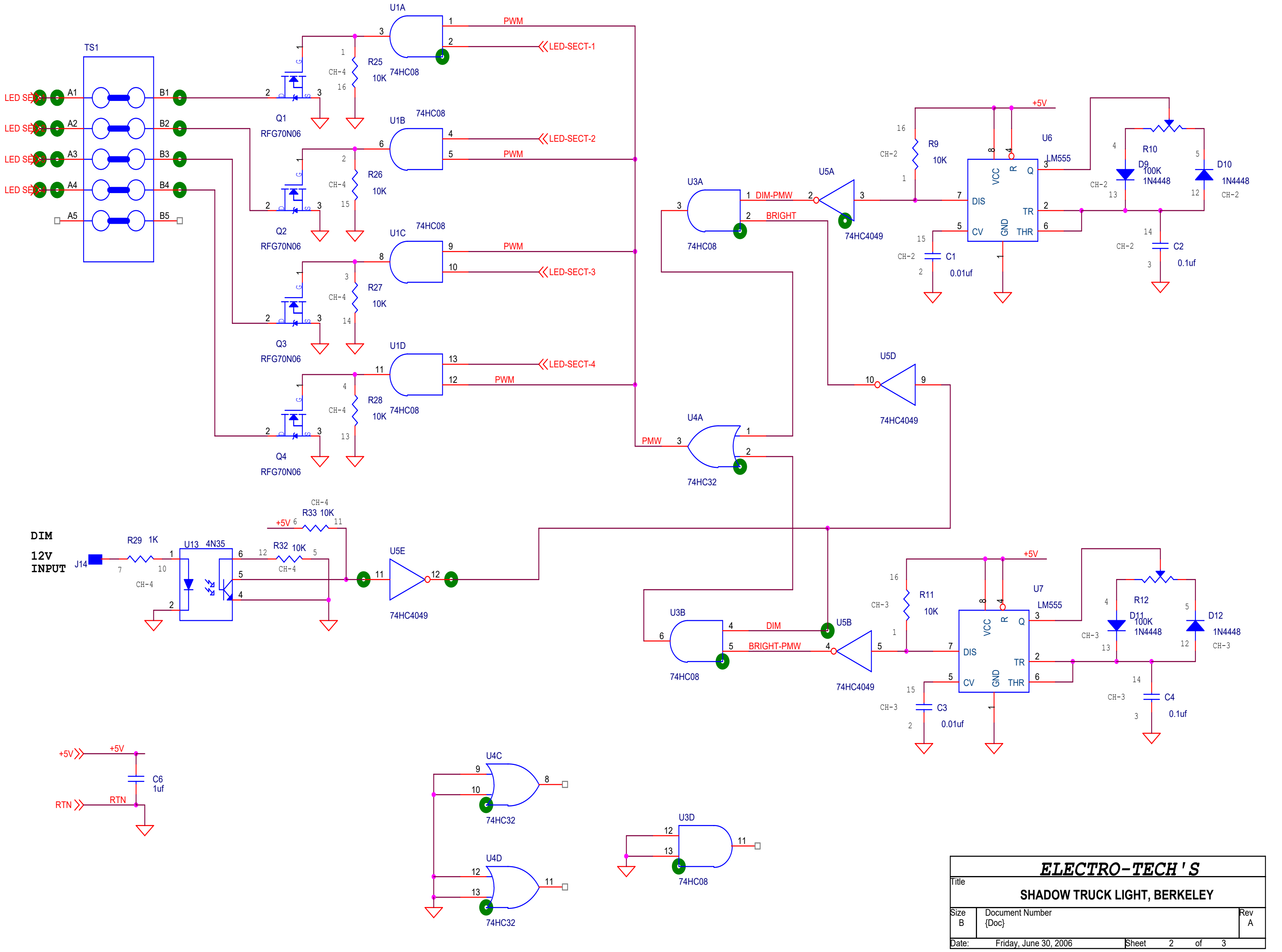
```
d_slow_d:
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 125
  OUTC = %0011
  PAUSE 125
  OUTC = %0111
  PAUSE 125
  OUTC = %1111
  PAUSE 125
  OUTC = %0000
  PAUSE 50
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

e_fast_d:
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 12
  OUTC = %0011
  PAUSE 13
  OUTC = %0111
  PAUSE 12
  OUTC = %1111
  PAUSE 13
  OUTC = %0000
  PAUSE 50
  OUTC = %1111
  PAUSE 50
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

e_med_d:
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 31
  OUTC = %0011
  PAUSE 31
  OUTC = %0111
  PAUSE 31
  OUTC = %1111
  PAUSE 32
  OUTC = %0000
  PAUSE 50
  OUTC = %1111
  PAUSE 50
ELSE
```

```
  OUTC = %0000
ENDIF
GOTO what_prog

e_slow_d:
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 125
  OUTC = %0011
  PAUSE 125
  OUTC = %0111
  PAUSE 125
  OUTC = %1111
  PAUSE 125
  OUTC = %0000
  PAUSE 50
  OUTC = %1111
  PAUSE 50
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

f_adhoc_d:
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 150
  OUTC = %0011
  PAUSE 150
  OUTC = %0111
  PAUSE 150
  OUTC = %1111
  PAUSE 300
  OUTC = %0000
  PAUSE 150
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog

g_hyp_d:
IF (switch = 1) THEN
  OUTC = %0001
  PAUSE 114
  OUTC = %0011
  PAUSE 38
  OUTC = %0111
  PAUSE 19
  OUTC = %1111
  PAUSE 57
  OUTC = %0000
```

```
  PAUSE 100
ELSE
  OUTC = %0000
ENDIF
GOTO what_prog
```

Appendix 4 – Shadow Truck Schematic



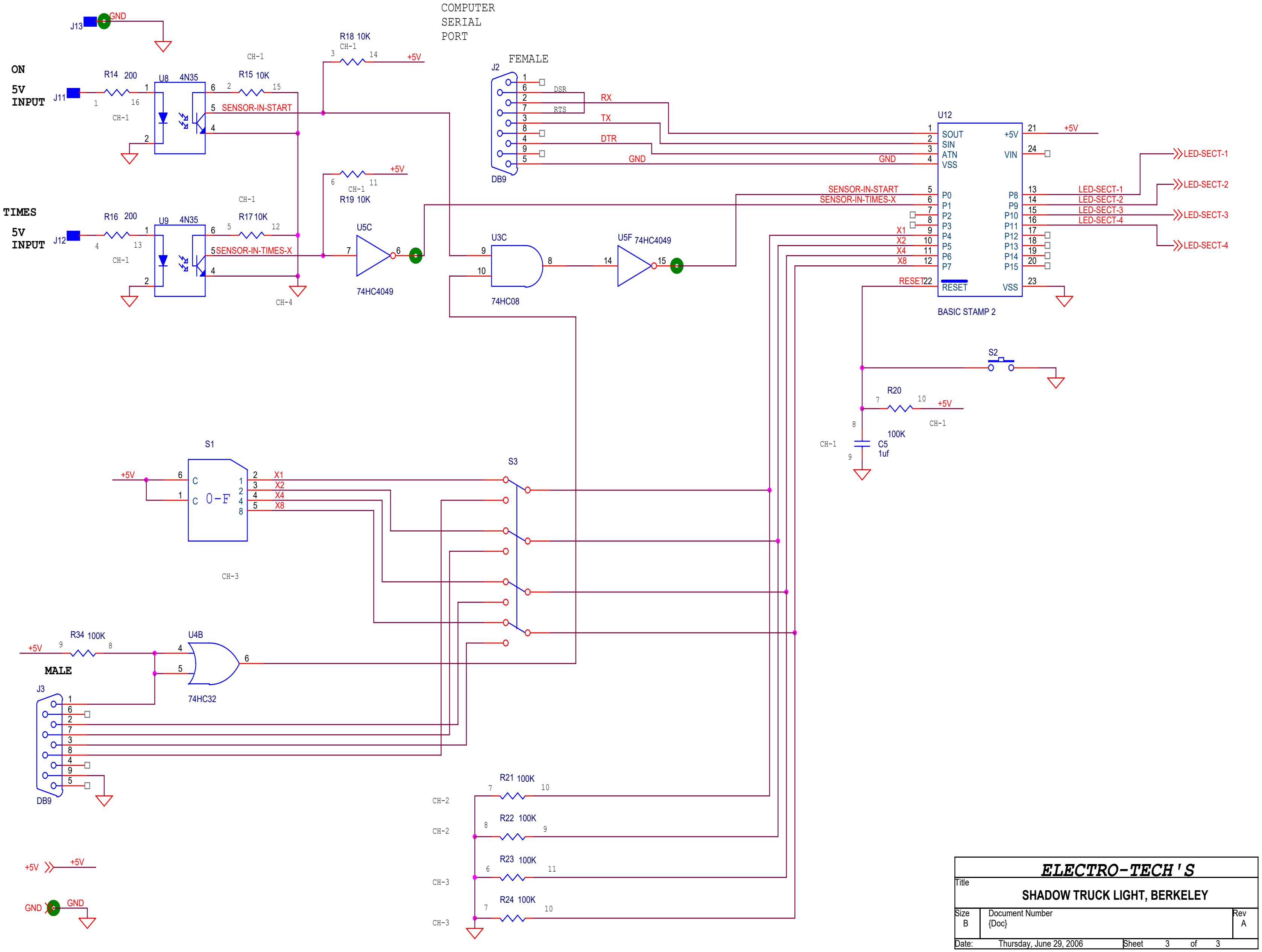


ELECTRO-TECH'S

Title
SHADOW TRUCK LIGHT, BERKELEY

Size B
Document Number {Doc}
Rev A

Date: Friday, June 30, 2006
Sheet 2 of 3

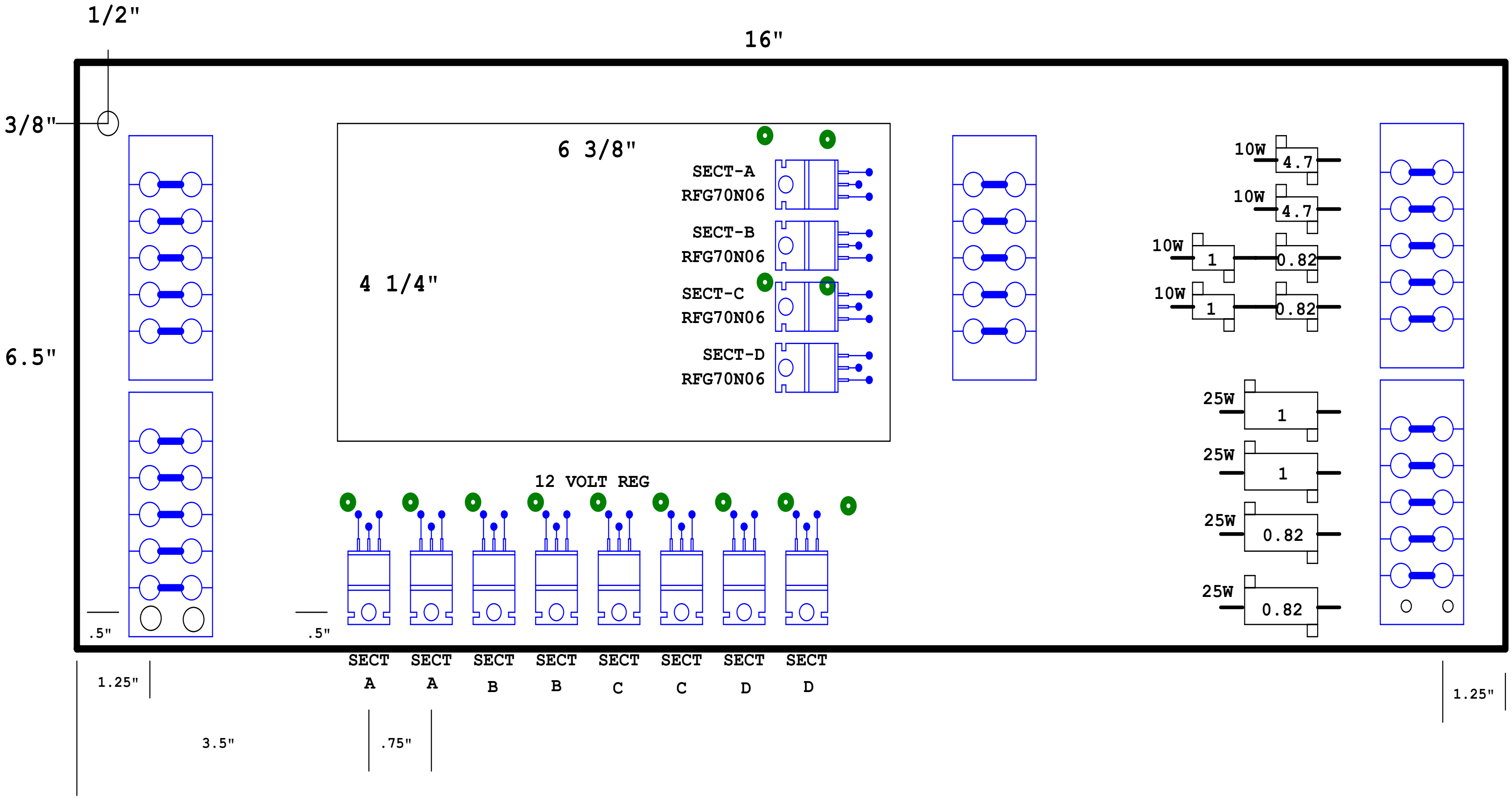


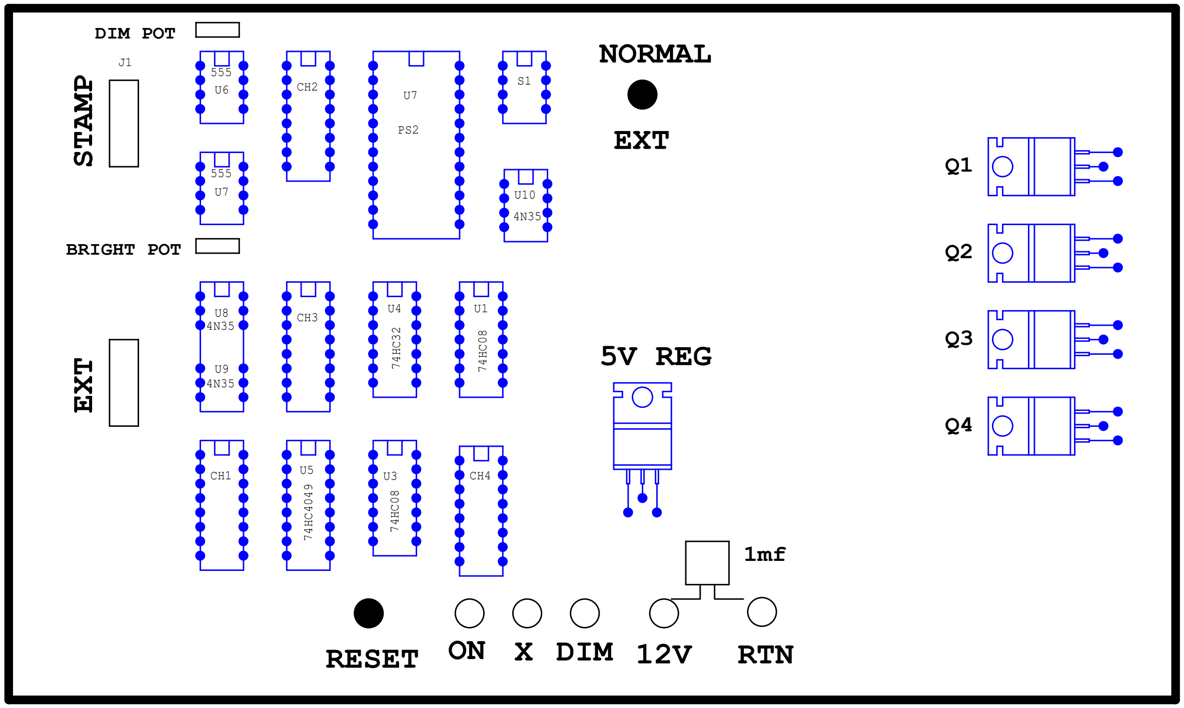
ELECTRO-TECH'S

Title
SHADOW TRUCK LIGHT, BERKELEY

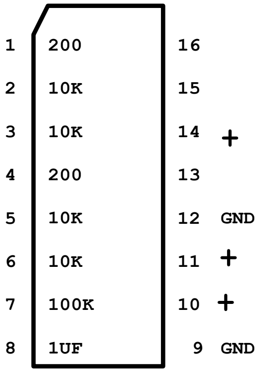
Size B
Document Number {Doc}
Rev A

Date: Thursday, June 29, 2006
Sheet 3 of 3

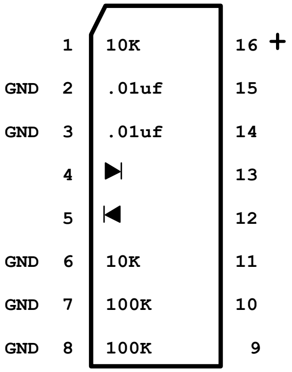

1/2"
16"
3/8"
6 3/8"
SECT-A
RFG70N06
SECT-B
RFG70N06
4 1/4"
SECT-C
RFG70N06
SECT-D
RFG70N06
6.5"
10W
4.7
10W
4.7
10W
1
0.82
10W
1
0.82
25W
1
25W
1
25W
0.82
25W
0.82
12 VOLT REG
.5"
.5"
SECT A
SECT A
SECT B
SECT B
SECT C
SECT C
SECT D
SECT D
1.25"
3.5"
.75"
1.25"



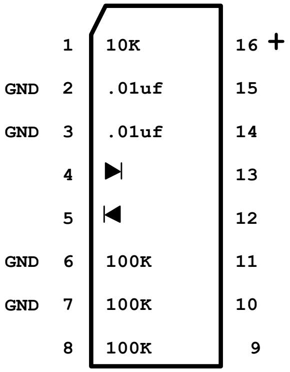
CH-1



CH-2



CH-3



CH-4