Assessing the Effects of a Rectangular Rapid-Flashing Beacon on Vehicle Speeds along a Four-Lane Divided Highway

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ASSESSING THE EFFECTS OF A RECTANGULAR RAPID-FLASHING BEACON ON VEHICLE SPEEDS ALONG A FOUR-LANE DIVIDED HIGHWAY

by

Michelle VanWagner

A Dissertation
Submitted to the
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Advisor: Ron Van Houten, Ph.D.

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In 2008, nearly 31% of vehicle fatalities were related to failure to adhere to safe vehicle speeds (National Highway Traffic Safety Administration (NHTSA), 2009). Two studies were conducted to evaluate the effects of a Rectangular Rapid-Flashing Beacon (RRFB) triggered by excessive speed on vehicle speed using a combined alternating treatments and reversal design. Experiment 1 assessed the RRFB’s impact on speeds as compared to baseline conditions only. Experiment 2 compared the RRFB to two standard beacon configurations. Both experiments were conducted at the same site during approximately the same time period and both employed the same data collection methodology. The results of Experiment 1 showed that the RRFB resulted in better speed compliance as compared to baseline conditions. Experiment 2 indicated that the RRFB appeared to result in improved speed compliance over both the standard beacon configurations. Overall results of the two studies indicate that the RRFB may be a viable new intervention for reducing speed in transition zones and entries to roadway curves.
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INTRODUCTION

In 2008, the National Highway Traffic Safety Administration (NHTSA) published a report on speeding and its societal impact (National Highway Traffic Safety Administration (NHTSA), 2009). This report indicated that nearly 31% (11,674 fatalities) of the motor vehicle fatalities in 2008 were related to speeding. Crashes were considered speeding-related if officers indicated that racing, driving to fast for conditions, or exceeding a posted limit was a contributing factor or if a driver was issued a citation for a speeding related offense.

Relationship between Speed and Vehicle Crashes

Speeding is dangerous because it reduces a driver’s ability to safely respond to unexpected roadway elements or obstacles and increases the distance required to stop a vehicle. All of the aforementioned hazards can increase the probability of motor vehicle accidents. In addition to being a cause of motor vehicle accidents in its own right, speeding can also limit or dilute the effectiveness of traffic safety programs designed to reduce other traffic safety risks, such as impaired driving, and pedestrian and motorcycle safety initiatives (National Highway Traffic Safety Administration (NHTSA), 2005).

Taylor, Lynam, and Baruya (2000) conducted a large scale study of drivers in the United Kingdom to assess the impact of speeding on the frequency of traffic accidents. The authors discuss the difference between absolute and relative speeds and indicate that the speed distribution (spread of speeds above and below the mean) and relative speeds (speed of a single driver as compared to the aggregated average speed of all drivers) are
more predictive of accident potential. According to the authors, two identical roadways with the same average speeds could have different accident rates if the variability in speeds were different. Results of the Taylor, Lynam and Baruya study indicated that reducing the speed of faster drivers is likely to have a more positive impact on crash reduction than reducing the overall average speed for all drivers. In other words, the biggest impacts can be maintained by moving the speeds of drivers in the faster extremes of the distribution closer to the mean.

**Strategies for Controlling Vehicle Speeds**

Given the dangers of speeding, many intervention strategies have been implemented with the intent of increasing compliance with posted speed limits, narrowing variability in speed distributions and reducing speeding related crashes, injuries and fatalities. Popular interventions include the establishment of recommended and mandatory speed limits, police enforcement and penalties for speeding, feedback, and traffic calming measures.

**Speed Limits**

Speed limits can be considered one of the most basic ways that driver behavior and ultimately vehicle speeds can be impacted. The imposition of mandatory speed limits has consistently resulted in better compliance and reduction of excessive speeds (Van Houten, Nau, & Marini, 1980). One way the relationship between speeding and vehicle crashes has been studied by researchers is to examine crash data for stretches of road where posted speed limits were recently changed.

In 1974, the United States established a national maximum speed limit of 55 miles per hour (Feng, 2001); (Renski, Khattak, & Council, 1999). While the initial goal of the
The national speed limit was to reduce oil consumption by 25%, actual fuel consumption reduction was closer to between two to six percent. However, as Forester et al. report, a side effect of the intervention was a corresponding drop in injuries and fatalities from traffic accidents. Although correlated with reductions in injuries and deaths, the national speed limit legislation was controversial since its inception. Central to the argument was the role that other factors might play in accidents as well as the balance that must be struck between safety (reducing injuries and deaths) and efficiency (getting from Point A to Point B efficiently) (see Forester, McNown, and Singell (1984) for an example of a contemporary critique of the speed limit law on the basis of a cost-benefit analysis).

According to Feng (2001) and Renski, Khattak and Council (1999), in 1987 the national speed limit in the United States was raised to 65 miles per hour. A case study conducted by Brown (1990) in Alabama reviewed accident records for the year before and the year after the speed limit change. Resulting analyses were mixed, but overall seemed to indicate that the frequency of accidents increased following the speed limit changes, although increase accident severity did not appear to be correlated with the increase in posted speed limits.

The National Highway System Designation Act of 1995 eventually repealed the national speed limit which gave states the right to set their own speed limits (Feng, 2001). (Farmer, Retting, & Lund, 1999) conducted a study of fatalities covering an eight year period spanning from 1990 through 1997 in order to assess the impact of the repeal of the national maximum speed limit. Their analysis reviewed speed-related traffic fatalities for 24 states that raised speed limits following the repeal and seven states that did not raise limits. Results indicated that fatality rates were 17% higher following the increase of
speed limits as compared to observed fatality rates before the repeal of the 1995 law. The authors note that this is similar to results observed by researchers when the national maximum speed limit was raised in 1987. While speed limits clearly have a regulatory impact on driver behavior and vehicle speed, and crashes appear to vary systematically with posted limits, speed limit manipulations should be considered a minimal sort of intervention, and many supplemental approaches to controlling driver behavior and vehicle speed exist.

The challenge with fixed speed limits is that most often they are set based on the recommended speed under ideal conditions and do not take into account traffic density and other environmental variables. According to (Sisiopiku, 2001), there are six elements that are considered when determining a fixed speed limit. First, one must consider the surface of the road, shoulder condition, grade of the road along with road alignment and sight distance. Second, the pace speed and 85-percentile speed is considered. Third, cultural and local development conditions are assessed. Fourth, curves and other obstacles that might impact safe speeds are considered. Fifth, parking needs and pedestrian traffic are considered. Finally, before a speed limit is set the recent accident reports are reviewed (typically for the prior 12 month period). Once static speeds are set, they can help the driving public select appropriate speeds under ideal conditions, but under non-ideal driving conditions, speed selection becomes more subjective.

**Enforcement**

While posting speed limits has been demonstrated to reliably impact observed vehicle speeds, improving and maintaining compliance with posted limits can be a challenge and police enforcement is one of the best known methods of intervention.
Many studies have assessed the effects of police interventions to reduce speeding, and most have found reliable reductions in mean speeds which persisted for sometimes several weeks following a targeted enforcement period (See Holland, 1996; Sisiopiku & Patel, 1999; Vaa, 1997 for examples of such studies). In 1979, Galizio, Jackson, and Steele published an enforcement study. The authors observed that, upon sight of the marked police vehicle, not only did vehicles that had been exceeding the posted speed limit slow down, even vehicles that were already in compliance slowed down further.

While speed enforcement is often associated with issuing fines, having police officers pull-over drivers to issue written warning messages, rather than citations, has also been found to impact vehicle speeds. Research has shown that resulting speed reductions from warning-only interventions can persist for up to a year following discontinuation of the targeted warning message intervention (Van Houten & Nau, 1983).

**Automated Enforcement**

As Sisiopiku and Patel (1999) point out, the primary issue with enforcement strategies tends to be cost, which makes the relatively recent trend toward automated enforcement appealing. In order to execute an effective enforcement intervention, law enforcement personnel are typically deployed to targeted roadways and spend their time monitoring speeds and issuing warnings and citations to drivers who violate speed limits.

Retting and Farmer (2003) assessed the impact of a speed camera enforcement program on traffic speeds in Washington, DC. A comparison site was selected in Baltimore, MD. Speeds at the Washington, DC sites declined by 14% and the proportion of vehicles traveling more than 10 miles per hour (16.09 km/hour) over the speed limit declined by 82% in treated areas.
Cunningham, Hummer, and Moon (2008) conducted a three year long pilot study evaluating the effects of automated speed enforcement cameras in North Carolina. Dependent variables observed by the authors included vehicle collision rates as well as changes in mean speeds and focus group feedback from community members. Messages alerting drivers to the automated enforcement contingency were attached to speed limit signs in the enforcement areas. Launch of the program kicked off with a media campaign.

The automated enforcement units were mobile, and thus could be moved to different sites throughout the study. The devices captured speed values as well as photographs of the vehicle and license plate, which were used for purposes of justifying the citations. The citations were then mailed to registered vehicle owners. Dollar amounts of the fines were set at $50 for a single infraction. The intervention was found to reduce speeds and overall received positive feedback from focus groups. The authors also reported an associated marked decrease in collisions during daylight hours but night collisions appeared unaffected. Data on speed changes were not broken out by night and daylight hours.

Pilkington and Kinra (2005) conducted a systematic literature review of controlled trials and observational studies of automated speed enforcement interventions. The goal of this review was to assess the impact of these intervention strategies on collisions, injuries and fatalities. In total, the authors analyzed 14 studies. Results indicated that overall, automated enforcement appears to reduce collisions and that the impact is sustained across multiple years, but the authors also note concerns given the fact that most studies did not include sufficient control conditions to demonstrate a clear functional relationships between enforcement and crashes. Although enforcement
strategies are common, and probably the best known by the general public, there are
many other interventions that do not necessarily include the use of penalties.

**In-Vehicle Speed Reduction Techniques**

A variety of in-vehicle technologies have been developed to attempt to prevent
drivers from exceeding safe speeds. Várhelyi and Mäkinen (2001) conducted field tests in
Europe of a speed limiter which used transmitters installed in speed limit signs along the
roadway to control the maximum speed allowed by the in-vehicle device. As vehicle
speeds approached the maximum allowable speed for the stretch of roadway, the in-
vehicle device would increase the force required to continue accelerating, in essence
making it more effortful to continue increasing vehicle speed. Once the vehicle reached
maximum speed, the speed limiting device also restricted the vehicle's fuel injection in
order to prevent the vehicle from exceeding the posted speed limit. The limiter was
designed so that it would allow the vehicle to exceed the posted speed limit at first then
gradually engage the active speed limiting process to prevent abrupt transition into the
fully controlled and compliant speed.

The device produced notable reductions in mean speeds as well as speed
variability. It also had mixed impact on following distance. For slower speeds, following
distances appeared to increase, but for areas with faster speed limits, following distance
was shown to decrease slightly, meaning drivers were slightly less safe when the speed
limiter was in use, at least in terms of following distance. The authors also collected self-
report measures from participants to capture subjective measures of perceived workload,
performance and emotional responses. Participants expressed frustration and also
reported increased workload and that they felt their driving performance was reduced.
Schulman (2005) discussed drawbacks of speed governors and limiters and the application of a different type of in-vehicle device that functions by gradually increasing the levels of force required to depress the accelerator and increase vehicle speed. While the device described by Várhelyi and Mäkinen (2001) also uses counter-force, the difference is that the device described by Schulman (2005) still allows drivers to exceed the speed limit but requires increasing effort to do so. Schulman (2005) distinguishes between necessary speeding, momentary increases in vehicle speed in response to threats of an accident or hazard where speed must be used to avoid danger and unnecessary speeding which is typically more sustained and not related to avoiding hazards. The author originally conducted field tests of the device in 1985 and found that the device reliably showed increased speed limit compliance when in use and also demonstrated that when the device was deactivated, non-compliant rates of speeds reliably returned.

Feedback and Speed Monitoring Displays

Publicly posting feedback on speed limit compliance has also been a documented and effective method for reducing speeds and increasing adherence to posted limits. One early study by Van Houten, Nau, et al. (1980), sought to determine whether public posting of driver performance could improve speed limit compliance. Data were collected on the percentage of vehicles not speeding. This percentage was then posted on a wooden sign so that it was visible to passing motorists. The sign displayed the previous day’s percentage as well as the record for the highest percentage. The results showed that the intervention was effective in reducing speeds when the numerical percentages were presented. The authors also tracked citations during the course of the study and reported that citations were more frequent during baseline and sign-only without percentage
feedback conditions as compared to daily and weekly feedback conditions.

Following onto the 1980 study, their first experiment used an intervention very similar to the one used in the original 1980 study, but the authors systematically manipulated the criteria used to define what constituted speed violations. The more lenient the criteria was; the higher the percentage that could be posted on the feedback sign. The authors found that using more lenient criteria for defining the posted percentage was most effective. The second experiment was designed to assess (1) whether the feedback signs would work on a different sort of roadway with limited access and more constant speeds and (2) how far beyond the feedback sign speed reduction effects could be observed. The third experiment compared the feedback intervention to the presentation of an unmanned police car. Results indicated that speed reductions were strong at first but waned over time. The study also assessed the effects when the feedback sign was combined with presence of a police vehicle. The fourth experiment investigated the effects of speed aircraft patrols as an enforcement strategy to reduce speeding. Air patrols were tested alone and with patrols plus posted feedback. Patrols plus feedback had the highest speed reductions. The last experiment investigated the effects of a package intervention that included warning tickets in lieu of citations with fines and feedback fliers. Because police were issuing warnings instead of citations, the criteria for pulling vehicles over could be more strictly administered. When issuing citations, for example, police might choose to only pull people over if they were exceeding the posted speed limit by a certain threshold. For this study, the threshold used was any speed in excess of the posted limit. This meant that many more drivers were stopped that normal. This package intervention was then combined with feedback signs as tested in earlier studies.
The results indicated that the package intervention was again effective in reducing speeds. The warning message intervention was only in place for one week, but speed reduction effects persisted for a year following the intervention.

Roqué & Roberts (1989) attempted to replicate the results of (Van Houten et al., 1980), but failed to produce the same speed reducing effects of the original study. The authors attributed this failure to replicate to differences in baseline compliance rates as well as differences in methodology and site characteristics. A later replication study, conducted by researchers in Iceland in 1991 did successfully replicate results further demonstrating that posted feedback did result in reduction in observed vehicle speeds over baseline conditions (Ragnarsson & Björgvinsson, 1991).

Another common type of feedback display is the use of speed monitoring displays also referred to as dynamic speed displays. Dart and Hunter (1976) conducted research on a device that measured the speed of approaching vehicles and displayed the measured speed on a board that was visible to the driver. The device was set up so that it could display a message if the vehicle speed was above a specific threshold. This intervention continues to be popular. These devices typically measure the speed of an approaching vehicle and then display that speed on an electronic display board in such a way that it is visible to the driver. The most common configuration is to place the display in close physical proximity to signage that displays the posted speed limit which allows drivers to quickly make comparisons between the speed displayed on the device and the posted speed limit.

McCoy, Bonneson, and Kollbaum (1995) used automated visual feedback to decrease vehicles speeds. The experimenters used radar to detect the speed of
approaching vehicles; vehicle speed was then presented to drivers on a digital display panel as their vehicles passed the display device. Average vehicle speed was reduced by 4 to 5 miles per hour (6.44 to 8.05 km/hour).

Pesti and McCoy (2001) assessed the impact of such speed monitoring displays on vehicle speeds in work zones. Speed displays were deployed for a five week period in three work zones. The authors found that the speed monitoring displays resulted in lowered speeds as well lower variability in speeds over the 5 week observation period. Results were statistically significant for two of the three sites. The authors also found that, although speeds did increase when the displays were removed, they were still observed to be lower than pre-deployment conditions, which the authors indicated provides some evidence that speed reducing impact may linger for a period of time after the device has been in place (Pesti & McCoy, 2001).

Speed monitoring displays have also been used at roadway transitions, that is, at locations where speed limits change. Sandberg, Schoenecker, Sebastian, and Soler (2006) used dynamic speed monitoring displays targeting transitions from rural highways, with relatively high speed limits, to urbanized areas with relatively lower speed limits, a setting very similar to the current study. The impact of this the speed monitoring displays was evaluated over a one year period to assess the long-term effects of the intervention. Results indicated that the device was effective in reducing speeds and increasing compliance with fixed speed limits posted in transition areas and the speed reductions were maintained over time.

**Variable Speed Limits and Dynamic Messaging**

In order to provide drivers with more accurate estimates of safe speeds while
taking into account real-time driving conditions, variable speed limit systems have been
developed. These systems typically use technology to monitor real time environmental
conditions (e.g., traffic speed, vehicle volume, weather conditions and road surface
conditions) to display appropriate real-time speed recommendations to drivers. For these
systems to work properly they must: (1) collect data on environmental conditions (2) use
data to calculate a recommended speed limit and (3) display that calculated speed limit so
the information is available to drivers in a timely fashion (Sisiopiku, 2001).

Rämä (1999) conducted a study of weather-controlled variable speed limits on
driver behavior in Finland. The dependent variables for this study were mean driving
speeds, speed distribution as well as following distance between vehicles. Road
conditions were categorized into three classes from poor to good conditions on the basis
of precipitation intensity, visibility and wind speeds. Results indicated that when poor
weather/driving conditions were easy to detect (salient), the difference in mean speeds
between experimental and control conditions were smaller. The experimental condition
was 3.4 km/h lower than corresponding speeds observed in the control condition when
poor weather conditions were obvious.

When the poor conditions were more difficult to detect, the differences between
control and experimental conditions were more substantial. The mean speeds under the
experimental condition when poor conditions were difficult to detect I was 5.3 km/h
lower than the control condition. Reductions in speed variability were also observed
(Rämä, 1999). From a behavioral perspective, these results seem logical. Under
conditions where relevant naturally occurring stimuli are salient, then supplemental
stimuli may, such as dynamic warning messages may not be necessary to establish speed
reduction as a reinforcer because the naturally occurring stimuli (e.g. high speeds in snow and visible ice conditions) already likely function as aversive stimuli and drivers are more likely to slow down, although results demonstrated that reductions still occurred (3.4 km/h reduction) (Rämä, 1999).

It follows logically then that when naturally occurring stimuli are still dangerous, but less salient (e.g. “black ice”), drivers are less likely to slow down because the relevant warning stimuli may not be salient enough. This gives the advantage to drivers in the experimental condition because the supplemental stimuli presented by the dynamic message sign offers salient stimuli to alert drivers to conditions by way of the variable speed limit sign. One interesting anomaly of this study is that when the variable speed limit sign was combined with the variable message signs, differences between experimental and control condition mean speeds were less pronounced than when the variable speed limit alone condition was in effect. The authors attribute this to particularly salient adverse road conditions which suppressed vehicle speeds across both conditions (Rämä, 1999). In addition to variable signs based on weather conditions, variable speed limit signs have also been used to reduce traffic congestion (Abdel-Aty, Dilmore, & Hsia, 2006; Bertini, Boice, & Bogenberger, 2006) and reduce speeds in work-zones (Kwon, Brannan, Shouman, Isackson, & Arseneau, 2007; Lin, Kang, & Chang, 2004).

**Rectangular Rapid-Flashing Beacon (RRFB)**

Recently, a new device, referred to as a Rectangular Rapid Flashing Beacon (RRFB) (sometimes referred to as a stutter-flash beacon), has been demonstrated to be highly effective for improving motorist yielding to pedestrians (Shurbutt, Van Houten,
Turner, & Huitema, 2009; Van Houten, Ellis, & Marmolejo, 2008). Unlike more traditional standard 12” round beacons which blink in a slow (one cycle per second) and predictable (“wig-wag” or back-and-forth) pattern, the RRFB is a new type of beacon that makes use of high-intensity, light-emitting diodes (LEDs) that blink in a rapid and irregular pattern, similar to what is seen on many modern emergency vehicles.

Van Houten et al. (2008) tested the effects of a solar-powered stand-alone pedestrian crossing sign with a button that pedestrians could press to activate RRFB beacons. Beacons were only activated when pedestrians were present. The RRFB is believed in this case to make the presence of pedestrians and the occasion for yielding more salient, thereby increasing stimulus control over drivers’ behavior.

The RRFB’s effects on yielding rates were strong for both staged pedestrians (research confederates who crossed the road with and without use of the RRFB for purposes of data collection) as well as for local residents. For staged pedestrians, baseline yielding percentages were on average around 1.7% and rose to 60% under the RRFB condition. For local residents baseline yielding was 0% and yielding rose to 65% during the RRFB condition.

Shurbutt et al. (2009) also evaluated the RRFB by conducting a series of three experiments. The first experiment sought to compare the RRFB device to baseline conditions with no beacons. Under baseline, the only stimuli available to prompt yielding behavior were the pedestrian presence and a static pedestrian crossing sign, with no flashing lights. During the treatment condition, RRFB beacons were activated. Results showed marked increases in yielding percentages. Under baseline conditions, approximately 18.2% of vehicles yielded to pedestrians. During RRFB conditions,
yielding increased to over 80%. The second experiment compared standard 12” round amber beacons to baseline and RRFB conditions.

During this study, baseline yielding was approximately 10.9%. Standard beacons only increased the yielding percentage slightly, raising the overall yield percentage to 15.5%, in spite of the fact that, like the RRFB, the beacons were activated by pedestrians and did not run continuously. For the same site, when a two-beacon RRFB configuration was introduced, yielding went up to 78.3%. The third study yielded similarly high yielding rates for the RRFB device across a total of 19 different sites.

**High Risk Settings**

While excessive speeds on any road conditions can present risks, some driving situations are more risky than others with respect to vehicle speeds. Increased speeds give drivers less time to react to unexpected events. Settings that tend to present a high frequency of potentially unexpected driving events and obstacles tend to be the areas where the risk associated with speeding is the highest.

**Transition Zones**

Transition zones are common areas where speed violations tend to occur and as such, often make ideal research sites. Van Houten and Nau (1981) chose a transition zone as the setting for a study where they evaluated the effects of posted feedback and traditional police enforcement. Cruzado and Donnell (2009) evaluated the effects of dynamic speed displays in a transition zone where a high speed two-lane rural highway transitions to slower speeds as the road crosses through a populated community.

From a behavioral perspective, the challenge at transition zones is that drivers often fail to adjust vehicle speeds when they transition from a high-speed section of a
rural highway with low population density to a low-speed section of the same roadway with higher population density. Although relevant stimuli may be present (reduced speed limit signs, the increased frequency of houses and businesses in the more densely populated area, etc.), drivers still often fail to fully adjust their speeds accordingly so supplemental measures often have to be taken.

**Roadway Curves**

Roadway curves are also a common setting for interventions to reduce speeds. Much like transition zones between unpopulated and populated sections of roadways where a reduction in speed is required, sharp curves also often require drivers to reduce their speeds in order to travel safely around the curved roadway. If drivers fail to slow their speeds when they enter sharp curves, the probability of an accident is increased. As a result, many roadway curves have special speeds posted to prompt drivers to reduce their speed. Even with recommended speeds posted in advance of a curve these sections of roadways are still a common problem area and often are targeted for supplemental intervention.

Monsere, Nolan, Bertini, Anderson, and El-Seoud (2005) evaluated a dynamic speed display and messaging system intended to reduce speeds of vehicles as they enter into a sharp curve in the roadway. The dynamic message board was mounted directly next to a sign denoting the speed limit for the curve and displayed the vehicle’s current speed so that it could be easily compared to the recommended speed for the curve. The intervention resulted in a two to three MPH reduction in mean speeds compared to baseline conditions.

In the current studies, the RRFB device was used to reduce speeding on a four-
lane rural highway. The roadway used for the current study was an ideal location to test the RRFB for speed reduction effects because the section of roadway was a transition zone between a rural highway with a speed limit of approximately 55 MPH and an urbanized area with a speed limit of 35 MPH. As drivers enter the 35 MPH zone, they also enter a sharp curve with limited visibility due to a bridge which blocks visibility to the other side of the curve.

Enforcement in the area had been historically difficult because the stretch of roadway before and after the curve does not have a shoulder to allow police to pull over drivers without blocking traffic. The purpose of the current study was to explore the RRFB device as a mechanism to reduce speeding. An experimental device designed to trigger the RRFB when vehicles approached at excessive speeds was evaluated.

**Experiment 1**

This study examined the effects of the RRFB on vehicle speeds as compared to baseline conditions using a multi-element treatments design with a baseline phase. Data were collected for this experiment during August of 2009.

**Method**

**Participants and setting.** Participants for this study were motorists in Mundelein, Illinois traveling along Lake Street/US Route 45 during daylight hours. US Route 45 is a four-lane divided highway with a grass-covered center median with a sharp curve. As drivers approached the curve, the legal speed limit transitioned from 45 MPH (72.4 km/hour) to 35 MPH (56.3 km/hour); a speed limit sign signaled the change. The area was known for speeding, but police could not easily pull over drivers because the road had no shoulder.
**Dependent variables.** Vehicle speed at the 35 MPH sign was the dependent variable. Speed data were analyzed in terms of the percentage of vehicles per session exceeding 41 MPH, mean speeds and speed distribution across conditions. The percentage of vehicles exceeding 41 MPH was calculated for each session by dividing the number of vehicles exceeding the 41 mph by the total number of vehicles observed per session (sessions were comprised of 200 individual vehicle observations). These percentages were then averaged to calculate an overall mean percentage for each condition. Mean speeds were also calculated for each session and then averaged to arrive at overall means for each condition. Finally, frequency distributions were calculated for each condition.

**Data collection.** Data were collected using modified hand-held radar that was attached by a long cable to a custom triggering device. Human observers were stationed at the 35 MPH sign because it gave them the best vantage point from which to observe traffic and trigger the device accurately. The radar was mounted on a tripod approximately one hundred feet (30.48 m) beyond the 35 MPH sign where observers were stationed. Tall weeds and small trees served to hide human observers from view by oncoming traffic, and the tripod-mounted radar was obscured using camouflage netting. One observer operated the radar as vehicles passed the 35 MPH sign while the other entered data into a small laptop computer. Data collection occurred on Saturdays and Sundays during the month of August. A session was comprised of 200 trials. A trial consisted of a single vehicle speed observation. Observers typically completed eight to ten sessions per day, between the hours of 8:00 AM and 5:30 PM. To avoid inadvertently measuring the same vehicle twice or measuring a vehicle at the wrong location, observers
only measured speeds of lead vehicles (i.e., the first vehicle in a large group of vehicles). Observers were fully trained prior to the start of the study. If vehicles approached the speed limit sign in groups, only the first vehicle’s speed was measured. The next trial could not begin until the space between the speed limit sign and the radar had been cleared of vehicles. This ensured that vehicles were only measured at the speed limit sign and not inadvertently picked up as they came closer to the radar gun being used to monitor speeds. Data were collected regardless of whether the vehicle being measured activated the beacons, and some vehicles were measured even though they passed the sign during the time-out periods.

To assess inter-observer agreement, two observers collected data independently for 26% of observation sessions across both Experiment 1 and 2. One observer operated the radar trigger device, and then both observers silently recorded the speed displayed on the trigger device. Agreement occurred when both observers recorded the same speed. Inter-observer agreement was calculated by dividing the total number of agreements by total observations (agreements plus disagreements) and converting the result into a percentage. Mean inter-observer agreement was 99% (range, 96% to 100%).

We also conducted basic treatment integrity checks to ensure that the beacon was functioning as designed. These checks involved driving the first author’s vehicle past the beacon to verify that it was activating properly and monitoring the device at the beginning of each session to ensure accuracy. The device functioned as designed on 100% of these checks.

**RRFB condition.** The RRFB, consisting of two small panels of high-intensity LEDs, was mounted along the bottom edge of the 35 MPH (56.3 km/hour) speed limit
sign. The beacons were directional so only approaching vehicles could see them. The RRFB beacons flashed with a speed, pattern and intensity similar to the rapid flashing, bright lights used on emergency vehicles. Each LED flasher is 6 inches wide and 2.5 inches high and placed 9 inches apart. In addition, each unit is dual indicated, with LEDs on the front and back. Each side of the LED flasher illuminates in a wig-wag sequence (left and then right). The left LED flashes two times in a slow volley each time it is energized (124 ms on and 76 ms off per flash). This is followed by the right LED, which flashes four times in a rapid volley when energized (25 ms on and 25 ms off per flash) and then has a longer flash for 200 ms.

The RRFB activated only when vehicles traveling at speeds above 41 MPH (66 km/hour) approached within 200 to 300 feet (60.96 to 91.44 m) of the sign. A small radar device mounted to the speed limit sign. The radar measured oncoming vehicle speeds, and when the speeds exceeded the 41 MPH threshold, the beacon was activated. The radar mounted to the speed limit sign was separate from the radar used by researchers for data collection purposes. The radar attached to the speed limit sign only served to provide data inputs that were used to activate the device based on vehicle speed automatically. The activation distance varied depending on vehicle size. For example, smaller trucks, vans, sport utility vehicles (SUV), and cars activated the device at a distance of 200 ft (60.96 m) while larger vehicles like semi-trucks and large busses activated it at distances of up to 300 feet (91.44 m). It was visible at a distance of 200 feet (60.96 m). Because traffic at the research site could be heavy during peak times of day, the device was programmed with a mandatory 5-s time-out period after each activation cycle to prevent continuous cycling. When the device was timed-out, it could not be activated by any
vehicle, even if that vehicle was exceeding 41 MPH. Following the time-out, the device remained turned off until the next vehicle traveling above 41 MPH triggered it.

**Baseline condition.** Baseline condition consisted of the 35 MPH with no beacons activated. The RRFB was installed on the 35 MPH speed limit sign prior to the start of the experiment and was present across all baseline observations; however, the RRFB itself was quite small and inconspicuous unless flashing.

**Experimental design.** A multi-element design with baseline was used to evaluate the effect of the RRFB on vehicle speed. The experiment began with thirteen baseline sessions across one Saturday/Sunday period to demonstrate stability across day and time. Following baseline, conditions alternated between baseline and RRFB for fourteen sessions conducted during the next two weekends. The next phase was comprised of eight RRFB-alone sessions. Following the RRFB sessions, the researchers began Experiment 2. After completing Experiment 2, follow-up data was gathered to conclude Experiment 1. Follow-up data consisted of eight sessions alternating between baseline and RRFB conditions conducted on a Sunday.

**Results**

**Percentages of vehicles above 41 mph.** Figure 1 depicts the percentage of vehicles traveling above the 41 MPH (66 km/hour) trigger speed per session. Mean percentage of vehicles above 41 MPH during the first baseline phase was 73%. During the second phase, the mean percentage of vehicles traveling above 41 MPH during baseline was 74% while the mean percentage during RRFB conditions was 52%. During the third phase (RRFB only), the mean percentage of vehicles traveling above 41 MPH was 55%. During the fourth and final phase, the mean percentage of vehicles traveling...
above 41 MPH during the baseline condition was 74% while the mean percentage during the RRFB condition was 53%. The mean percentage of vehicles traveling above 41 MPH (66 km/hour) across all baseline and RRFB conditions was 73%, and 53%, respectively.

![Graph showing percentage of vehicles above 41 MPH across baseline and RRFB conditions.]

*Figure 1.* Percentage of vehicles per session traveling in excess of 41 MPH across baseline and Rapid Rectangular Flashing Beacon (RRFB) conditions.

**Mean speeds.** The mean speed across all baseline sessions for Experiment 1 was 44.76 MPH. The mean speed across all RRFB sessions for Experiment 1 was 42.12 MPH. On average speeds under the RRFB condition were 2.64 MPH slower than speeds under Baseline conditions.

**Speed distributions.** Figure 2 depicts speed frequency distribution by percentage of total observations during both conditions across sessions. This panel is comprised of the combined set of 4800 baseline trials from a total of 24 baseline sessions and the combined set of 3600 RRFB trials from a total of 18 RRFB sessions. This distribution
shows a shift toward lower speeds under RRFB conditions, particularly in the upper end of the distribution.

Figure 2. Speed distributions (in MPH as a percentage of total vehicles) for baseline and RRFB conditions.

Note: Only includes RRFB data from Experiment 1.

Experiment 2

Experiment 2 occurred immediately following the RRFB-alone phase of Experiment 1 with no significant delays. Immediately following the completion of Experiment 2, a follow-up a multi-element phase comparing baseline and RRFB conditions was collected for inclusion in the data set for Experiment 1. The purpose of Experiment 2 was to compare the effects of the RRFB to two of the most common standard beacon configurations. Participants and setting were the same as Experiment 1 and data was collected during roughly the same time period as Experiment 1 (August
2009). Speed data, inter-observer agreement and independent variable reliability were all measured in exactly the same manner as in Experiment 1.

**Method**

**RRFB.** The RRFB was activated in the same manner as in Experiment 1. When vehicles traveling at speeds above 41 MPH (66 km/hour) approached within 200 to 300 feet (60.96 to 91.44 m) of the sign the relevant beacon would be activated. Just as in Experiment 1, the device was programmed with a mandatory 5-s time-out period after each activation cycle in order to ensure that the beacons did not run continuously during heavy traffic periods. When the triggering mechanism was in the time-out period, beacons could not be activated. Following the time-out, the device remained turned off until the next vehicle traveling above 41 MPH (66 km/hour) triggered it. This time-out protocol was implemented to prevent the device from running continuously during heavy traffic.

**Standard single and double beacons.** Both the single and double standard 12” beacons were ITE (Institute of Transportation Engineers) approved and had standard LED light housing and configuration. Flash pattern was set at 60 flashes per minute, within guidelines of the MUTCD (Manual on Uniform Traffic Control Devices). In the case of the double beacon, two standard amber colored 12” ITE beacons were horizontally aligned to approximate the horizontal configuration of the RRFB beacons. Double beacon flashed in a standard wig-wag pattern, a pattern frequently seen on railway crossings. Both the single and double beacons were activated in the exact same manner as the RRFB. They only came on when vehicles approached the speed limit sign at speeds above 41 MPH. Just like the RRFB, once activated the standard beacons would cycle for 5-s and then turn off for a mandatory 5-s timeout period.
**Experimental design.** A BCBD modified reversal design with no baseline condition was used for Experiment 2. The first RRFB condition consisted of the seven RRFB-alone sessions from the third phase of Experiment 1 which immediately led into Experiment 2. This was followed by eight sessions under the Single 12” ITE amber-colored beacon condition. Next in the sequence was a return to the RRFB condition for a period of eight sessions. The RRFB condition was then followed by introduction of the double 12” ITE amber-colored beacon condition for an additional eight sessions.

**Results**

**Percentages of vehicles above 41 MPH.** Figure 3 depicts the percentage of vehicles traveling above the 41 MPH (66 km/hour) trigger speed per session across conditions. The first phase of the graph in figure 3 displays the percentages observed during the RRFB-only condition toward the end of Experiment 2. This was included in the graph because those data were collected immediately prior to the start of Experiment 2.

As mentioned in the Results section for Experiment 1, the percentage of vehicles above 41 MPH for this phase was 55%. Mean percentage of vehicles above 41 MPH during the Single Standard Beacon condition was 68%. The mean percentage of vehicles traveling above 41 MPH when conditions were returned to RRFB only was 54%. When the Double Standard Beacon was presented, the mean percentage of vehicles traveling above 41 MPH increased again to 64%.

**Mean speeds.** Mean speeds were lowest for the RRFB conditions, and on average, 1.39 MPH below the next slowest condition (Double Beacon). Mean speed under the Single Beacon condition was 43.99 MPH. Mean speed for the RRFB condition during Experiment 2 was 42.21 MPH. Mean speed for the Double Beacon condition was 43.6 MPH.
Figure 3: Percentage of vehicles per session traveling in excess of 41 MPH across single beacon, RRFB and double beacon conditions.

Note: RRFB data from experiment included where noted.

Speed distributions. Figures 4, 5 and 6 depict speed frequency distribution by percentage of total observations across different conditions. Distributions are based on 1600 RRFB trials (from 8 sessions), 1600 Single Beacon trials (from 8 sessions) and 1600 Double Beacon trials (from 8 sessions). Figure 4 shows a comparison between the RRFB and Single Beacon distributions. Figure 5 shows a comparison between RRFB and Double Beacon distributions. Finally, Figure 6 shows a comparison between Single and Double Beacon conditions. Both Figures 4 and 5 show distinct points of separation between the data paths, particularly at the higher end of the distribution. Figure 6 shows very little separation between Single and Double Beacon conditions
Figure 4: Speed distributions (in MPH as a percentage of total vehicles) for the RRFB and single beacon conditions.

Note: Only includes RRFB data from Experiment 2.

Figure 5. Speed distributions (in MPH as a percentage of total vehicles) for the RRFB and double beacon conditions.

Note: Only includes RRFB data from experiment 2.
Figure 6. Speed distributions (in MPH as a percentage of total vehicles) for the single and double beacon conditions from experiment 2.

DISCUSSION

Although the differences between mean speeds under baseline and RRFB conditions were modest, the intervention produced consistent reductions in mean speed over baseline and other beacon conditions. When speeds over 41 MPH are considered, the differences between conditions become clear, as shown in figures 1 and 3. Speed distributions further demonstrate the impact the RRFB has on drivers at higher speeds as compared to baseline and other conditions as shown in figures 2, 4, 5, and 6.

Beyond speed reductions, anecdotal evidence seemed to show that the beacon activation seemed to be frequently correlated with increased braking and braking distance. Topographically, driving behavior when braking is quite different from depressing the gas pedal to increase or maintain speed, and it is likely that the simple act
of self-monitoring vehicle speeds and reducing gas pedal pressure or applying brake pressure may prepare the driver to respond more effectively should emergency stopping be required.

From a behavioral perspective, the process of a driver complying with the posted speed limit may be best explained as a behavior chain which begins when the first step of the chain, is evoked by presentation of the speed limit sign. Figure 7 depicts the chain of behavior that is hypothesized to occur when drivers comply with the posted speed limit. Under baseline conditions, sight of the speed limit sign likely functions as a discriminative stimulus which evokes the behavior of looking at the vehicle’s speedometer. Upon sight of the speed limit sign, a driver whose learning history is such that compliance with legal speed limits is reinforcing will look at the vehicle’s speedometer which produces current vehicle speed as visual stimuli. In other words, the driver sees the sign then looks at the speedometer, which results in knowledge or awareness of the vehicle’s current speed as a consequence. Sight of the vehicle’s current speed, in turn, functions as a discriminative stimulus which evokes a comparison response which is likely in the form of covert verbal behavior where the driver compares the speed posted on the speed limit to the vehicle’s current speed and assesses the magnitude of the difference between the two.

The result of this covert verbal behavior comparing posted speed limit with actual speed results in signs of non-compliance if the difference between posted speed limit and actual speed is large. The resulting signs of non-compliance, then likely function not only as discriminative stimuli that evoke a speed reduction response, but also as a reflexive conditioned motivating operation condition where the reduction or elimination
of signs of non-compliance – or its opposite, signs of increased compliance – are established as reinforcers and evoke behaviors which in the past, have reduced or terminated signs of non-compliance.

**Overarching Motivating Operations and Learning History**

Rules/traffic laws; relevant learning history with respect to following traffic rules

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Discriminative Stimuli</th>
<th>Behavior</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed-Contingent Beacon Activation*</td>
<td>Sight of 35 MPH speed limit sign</td>
<td>Look at speedometer</td>
<td>Sight of vehicle's current speed</td>
</tr>
<tr>
<td></td>
<td>Sight of vehicle’s current speed</td>
<td>Compare current speed to speed limit</td>
<td>Signs of non-compliance</td>
</tr>
<tr>
<td></td>
<td>Signs of non-compliance**</td>
<td>Reduce speed</td>
<td>Signs of increased compliance</td>
</tr>
</tbody>
</table>

*Speed-Contingent Beacon Activation: All three beacons, at least to some extent likely function as both unconditioned stimuli which elicit an orienting response from the driver and reflexive conditioned motivating operations (generalized conditioned aversive stimuli) through pairing with similar stimuli under related conditions (e.g., sight of police lights when being pulled over)

**Signs of Non-Compliance: These stimuli likely function as discriminative stimuli and conditioned aversive stimuli / reflexive CMO that establishes its own termination or reduction in intensity as a reinforcer

*Figure 7. Compliance behavior chain.*

Speed reduction responses could take the form of easing the force applied to the gas pedal, removing the foot entirely from the gas pedal, or depressing the brake pedal.

For drivers of vehicles with manual transmissions, down-shifting might be another behavior within the speed-reduction response class.

The speed compliance behavior chain described above likely occurs to some extent any time a sufficiently motivated driver with the requisite learning history observes a speed limit sign, but very commonly, drivers may not see the speed limit signs
while driving. As a result, drivers may not engage in the speed compliance behavior chain because the relevant discriminative stimuli are not salient in the driving environment. One function of the RRFB (and to a lesser extent, the standard beacons) may be to function as an unconditioned stimulus which elicits an orienting response. The orienting response, turning head or shifting eye gaze to the flashing lights then increases the probability of the driver observing the speed limit sign. It is possible, following this logic that the response to the RRFB is the strongest because it is the most intense and also the most novel. Standard beacons are more common and may already be subject to some habituation. As a result of this habituation, the standard beacon may not produce the orienting response as reliably.

While orienting response likely plays a role, especially with the RRFB, it is plausible to surmise that the speed-contingent beacon activation also plays an important role. Speed contingent beacon activation, particularly in the case of the RRFB shares many stimulus properties with the speed-contingent on-set of police flashers when a driver is pulled over for a speed violation. With the advent of automated enforcement technologies, it is possible that the RRFB, and to a lesser extent, the standard beacons, function as conditioned aversive stimuli, or reflexive motivating operations which establish their own termination, removal or reduction in intensity as a reinforcer and evoke responses which in the past have resulted in termination, removal or reduction of these stimuli (Michael, 1993). Galizio et al. (1979) found that upon sight of a police vehicle, even drivers who were already complying with the speed limit often slowed their vehicles down further.

From a behavioral perspective, this may be evidence that stimuli that have been
paired with speed enforcement and aversive consequences such as being pulled over and/or ticketed may function as very powerful aversive conditions or CMOs, so strong that the speed reduction response occurs without the comparison response that is shown as the second step in the behavior chain.

Speed distributions shown in Figures 2, 4 and 5 do seem to show shifts in speeds for drivers who were already in compliance, and anecdotally, observers noted that some drivers slowed their vehicles dramatically in response to the RRFB, sometimes as low as 19 MPH. This seems to indicate that, while the chain described in Figure 7 may be applicable in some instances, there is a chance that the aversive properties of the speed-contingent on-set of the RRFB as a reflexive CMO may also play an important role. The current study’s research design does not provide an opportunity to determine controlling variables and function of stimuli with such granularity, but both the speed compliance hypothesis and the reflexive CMO hypothesis appear to be plausible. Further research might employ survey methods or protocol analyses, perhaps with simulated driving tasks to attempt to determine the precise behavioral function of the RRFB.

Although results for the standard beacons that were reported in Experiment 2 did not produce the same level of speed reduction as the RRFB, both the Single and Double beacons produced mean speeds that were lower than baseline conditions. This could be attributed to the impact of the standard beacons in their own right, but it may also be an artifact of the research design. The RRFB was presented first, and it is possible that frequent travelers of the roadway may have begun to monitor the beacon when they passed the sign. By anticipating the beacon activation, they might have been attending more to beacons than would have been observed under normal circumstances. Future
studies might consider multiple sites and counterbalancing to determine whether a carryover effect could be occurring.

Shurbutt et al. (2009) found that for the pedestrian-activated RRFB, treatment effects did not greatly diminish over time. However, the pedestrian version of the RRFB allowed the device to operate for each pedestrian, creating a natural one-to-one correlation between on-set of the RRFB device and presence of a pedestrian. This configuration may be ideal for maintaining compliance. However, a similar one-to-one correlation between excessive speed and activation of the RRFB could not be arranged in the current study. During early pilot testing, we frequently noted that multiple vehicles, often traveling at different speeds, passed the RRFB unit at nearly the same time. Thus, it is likely that at least some vehicles that were not traveling at excessive speeds were exposed to the RRFB device inadvertently. Further, vehicles that were speeding but approached the device during the 5-s time-out period likely never contacted the intervention. This means that it is likely that the effects may be underestimated.

The study has several limitations. First, the device was set to cycle off for 5 s after it flashed for an initial 5 s. During this time period, no vehicles were exposed to the intervention. This means that some drivers traveling at excessive speeds did not contact the intervention. Another limitation was that the device was activated only when drivers were traveling more than 41 MPH (66 km/hour) in a 35 MPH zone. Both of these limitations may have limited the overall speed reductions that were observed. The use of human observers also was expensive, inefficient (slower data collection), and lacked the precision that could be gained by more automated data collection procedures.

Other technologies, such as electronic speed sensors installed directly in the
roadway, could be used in future studies to gather data more quickly and to more readily
capture data on other important variables, such as traffic density, vehicle types, and road
conditions (temperature and moisture level). Some locations, however, are not conducive
to these technologies (e.g., some speed sensors will not function properly if placed in
close proximity to railroad tracks).

Another weakness of the current study was the overall short duration. Both
studies were conducted over the course of roughly a month. It is possible that over time,
drivers might habituate to the RRFB, although longer term studies of pedestrian
applications have shown sustained results over time. Future studies might further
investigate the long-term effectiveness of this intervention. If future studies continue to
find the device to be effective in reducing speeds, the RRFB could offer a relatively
inexpensive and energy efficient method for increasing motorist safety. Because the
RRFB runs on solar power, installation is less complex than that for similar beacon
installations, and once installed, the device requires very little maintenance.

In future studies, experimenters might consider setting the RRFB trigger point to
be the same as the actual speed limit rather than 6 MPH above the posted limit. Future
studies could also explore applications of the RRFB in other settings where speed
reduction is required (e.g., construction zones, school zones, etc.). The device could also
be used on other types of signs to increase vigilance and awareness. For example, unsafe
speed was also involved in 54% of fatal crashes that occurred under snowy conditions
and 59% of fatal crashes that occurred under icy conditions in 2008 (NHTSA, 2009). If
combined with moisture and temperature sensors, the device might be used to alert
drivers to slippery road conditions.
REFERENCES


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doi:10.1016/S0968-090X(00)00025-5
Appendix A

RRFB Affixed to a 35 MPH Speed Limit Sign
Below is a photograph of the RRFB affixed to the 35 MPH speed limit sign.
Appendix B

HSIRB Approval Letter
Date: May 9, 2011

To: Ron Van Houten, Principal Investigator
   Michelle VanWagner, Student Investigator for dissertation

From: Amy Naugle, Ph.D., Chair

Re: HSIRB Project Number 11-05-07

This letter will serve as confirmation that your research project titled "Assessing the Effect of Rectangular Rapid Flashing Beacons on Vehicle Speeds: Continuation of Project 07-10-02" has been approved under the exempt category of review (to analyze data collected under previously approved protocol 07-10-02) by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note that you may only conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek reapproval if the project extends beyond the termination date noted below. In addition if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: May 9, 2012