Safety Effects of In-Roadway Warning Lights or "Flashing Crosswalk" Treatment: A Review and Synthesis of Research

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Abstract

In-roadway warning lights or "flashing crosswalks" are a currently-accepted treatment in MUTCD for use at uncontrolled crosswalks. This review of nine before-after evaluation studies including surrogate measures of safety effectiveness indicates that the treatment is not a panacea for all problem crosswalk locations. While motorist yielding to pedestrians has improved to varying degrees at most locations examined, the evidence is relatively weak, and yielding has also decreased or remained at low levels at some locations. Effects on traffic speeds, and on pedestrian use of the crosswalks have also varied, even in direction. Positive effects observed may also degrade over time. While there is suggestive evidence, it is not clear from the evaluation studies to date, under what conditions flashing crosswalk treatments may be most beneficial over the longer term, and not recommended for others.

Key words

In-roadway warning lights, flashing crosswalks, pedestrian safety, motorist yielding, uncontrolled crosswalks

1. Introduction

Many streets in some communities have long sections between controlled intersections and may have added marked crosswalks, particularly at locations connecting pedestrian destinations. At uncontrolled midblock crosswalks or uncontrolled intersection crossings, the unpredictability of motorist yielding often puts crossing pedestrians at risk. Such crossings may also result in long delays to pedestrians waiting to cross with an adequate gap in traffic, or induce some pedestrians to cross without a safe gap. Drivers may have a reduced expectation of pedestrians at mid-block or uncontrolled intersection locations, or fail to observe pedestrians waiting to cross due to parked vehicles, other objects or even vehicles stopped for the pedestrian in an adjacent lane. Drivers traveling at higher speeds also may have a reduced tendency to stop or yield to pedestrians in crosswalks (Garder, 2004).

The goal of providing safe pedestrian access has many communities exploring the use of newer technologies, including experimental treatments, to enhance the safety of midblock crossings. Marking midblock crosswalks without "other substantial improvement" is not recommended for multi-lane, higher volume or higher speed limit (> 40 mi/hr) roads (Zegeer et al. 2005, p. 52). One technology thought to have potential for improving both pedestrian safety and reducing wait time at uncontrolled crosswalks, is the flashing crosswalk warning system or in-roadway warning lights, the terminology used in MUTCD. "Flashing crosswalks" were first introduced and tested in Santa Rosa, California in the mid-1990s. An in-roadway warning light system (IRWL) "consists of a series of amber or white lighting units encased in durable housings and embedded in the pavement parallel to a marked crosswalk" (ITE Traffic Engineering Committee TENC-98-03, 2001). The lights typically only display outward in the directions of oncoming traffic and may be activated passively by pedestrians passing through or waiting in a detection area, or actively, by push-buttons.

Such a system underwent testing in seven cities in California and Washington State in the late 1990's (Whitlock and Weinberger Transportation, Inc, 1998). This study included a follow-up of the first known pilot installation in Santa Rosa (since removed), and evaluations at six other California locations and two sites in Kirkland, Washington. Following this study, the devices were approved in the 2003 edition of the MUTCD for use at marked crosswalks with applicable warning signs that are not controlled by stop or yield signs or by traffic signals. The systems have since been implemented at a variety of locations in different states, both at mid-block locations and uncontrolled intersections. However, there are still many questions about the efficacy of the systems. Some communities are considering whether the treatment may help to improve motorist yielding to pedestrians crossing under less than ideal circumstances, but where a traffic signal may not be warranted by current standards, including pedestrian counts.

2. Review of Evaluation Studies

2.1 Methods

A review of evaluation studies was conducted to assess what existing research indicates about the effects of in-roadway warning lights on pedestrian safety at uncontrolled crossings. A search of the National Transportation Library, TRIS Online database; the ISI Citation Database;

and strategic internet searching was conducted for papers on "flashing crosswalks," "in-roadway warning lights," "in-pavement warning lights," and related terms. Several papers were also obtained through professional contacts. Papers published by February, 2009 were included. Papers were screened to determine whether they were reports of evaluation studies of IRWL employing measures of safety effects or surrogates. Papers that reported on planning or feasibility studies or were to establish guidelines for use of IRWL were also identified, but these were not reviewed as they provided no additional information on safety effects. Data elements extracted included study location(s) and descriptions, study design, outcome measures, results reported, authors' conclusions, and study quality elements including numbers of sites, sample sizes, whether statistical tests were performed, and potential confounders mentioned such as other treatments or time-related trends.

2.2 Results of review

Nine studies were identified that provided some evaluation of safety effects (using surrogate measures) of IRWL; eight were from U.S. communities, and one was from Israel (Hakkert, Gitelman, and Ben-Shabat 2002). One study intended to evaluate the long-term effects has not been completed due to a malfunction of the lights and inability to complete data collection (Rousseau, Tucker, and Do, 2004; personal communication, 2008).

Most of the studies were reports submitted to state or local agencies. No studies were identified of the effects on pedestrian-motor vehicle collisions at the treated locations. All nine of the studies provided before-after comparisons of various behavioral measures of effectiveness. None of the studies included use of a comparison group to control for unknown or unmeasured factors such as time-related trends. Three studies did not report statistical analyses of the data (Malek 2001; Van Derlofske, Boyce, and Gilson 2003; Whitlock & Weinberger Transportation, Inc**.** 1998). One study reached conclusions that were not supported by the study design or analyses (Malek 2001).

Of the outcome measures employed, each of the nine studies included some assessment of effects on motorist yielding behavior. Eight of the studies also included some speed assessment(s), either on approach to and/or near the crosswalk (except Huang 2000). Four studies provided assessments of effects on conflicts (Hakkert et al 2002; Huang, Hughes, Zegeer, and Nitzburg 1999; Karkee, Nambisan, and Pulugurtha 2006; Van Derlofske, et al. 2003); and two studies assessed effects on braking distance (Malek 2001; Whitlock & Weinberger 1998). Five studies examined pedestrians' use of the crosswalks (Whitlock & Weinberger; Huang et al. 1999; Huang 2000; Prevedouros 2001; Hakkert et al. 2002). One study examined effects on pedestrian delay and crossing time (Prevedouros 2001). One of the studies examined effects of IRWL at one location and overhead flashing beacons at a separate location (Malek 2001).

Although there were similarities in many of the measures of effectiveness, methodologies and definitions varied from study to study, making comparisons of the outcome measures across studies infeasible. All of the studies evaluated effects at individual treated sites, even when multiple sites were included in a study. Therefore, no studies have controlled for variations among sites to determine conditions for which this treatment might be most suited. Only two studies clearly conducted observations at night (under conditions of darkness); apparently none did during rain or other adverse weather conditions. The effects over time have been studied to varying degrees, with the longest interval examined being a two year follow-up of one of the original Santa Rosa installations. Most of the studies examined the effects for intervals from a few weeks to several months.

The largest study to date is still the first evaluation study of nine sites from California and Washington. Whitlock and Weinberger Transportation (1998) evaluated the effects of IRWL treatments at five midblock crosswalks, three T-intersection crosswalks and one four-way, uncontrolled intersection crosswalk in seven California and Washington cities. Sites varied widely by traffic function and volume, area type and other conditions, including added signs or other enhancements. Outcome measures included driver approach speeds (500 to 300 feet in advance of crosswalk), travel time and deceleration (500 to 100 feet in advance of crosswalk), distance from crosswalk at which brakes were first applied, and driver reaction (defined as "yielded," "reacted but didn't yield," and "did not yield/no reaction"). After-data were collected about eight weeks following implementation. Observations of motorist behaviors/yielding were collected with a staged pedestrian at all sites. Data were collected for four to five hours during daylight and two to three hours in the evening. This was one of only two studies that examined effects at nighttime as well as under daylight conditions.

Key findings and study issues are described in brief in Table 1. Motorist yielding eight weeks after treatment had increased at eight sites (unknown statistical significance). Results were mixed at the 9th location with slight improvement in one direction and a decrease (daytime) or no improvement (nighttime) in the other. Generally, braking distances also increased at most locations for those who slowed or stopped. The four locations with improvement to highest yielding levels (around 85% and higher) were those deemed by the authors to be friendliest to pedestrians initially. These sites also had higher pedestrian activity and higher before yielding rates, at least in the daytime. Several sites with very low before yielding rates saw improvements in yielding, but the yielding rates were still low, no better than 30% to 40% in the daytime, and a little better at night. The authors attributed these low yielding rates to low expectation of pedestrians, and excessive speeds and platooning of vehicles that made it difficult for motorists to stop. At the site with decreased yielding, a steep grade was thought to have possibly affected sight distance in the uphill direction and ability to slow and stop on the downhill. Long-term data from Santa Rosa also found that yielding had degraded from the initial improvement in the two years since the installation, but remained above the before-treatment level. Over all the sites, there was little effect on speeds measured, with slight decreases at only two locations.

Pedestrian observations at one location indicated that the number of pedestrians using the crosswalk did not change after the addition of the lights, that where pedestrians entered the street did not change, and that looking behaviors did not change, but the supporting data were not reported. Interview results indicated that 80% of pedestrians using one location were aware of the lights. Only 23% of those indicated that they relied on the lights to cause drivers to stop and give them the right of way. From one location that used push-button activation, 33% of pedestrians used the push button to activate the lights. There was no mention of the results of driver interviews.

Whitlock & Weinberger Inc. concluded that IRWL had a positive effect on enhancing drivers' awareness of crosswalks and modifying driver behaviors, and that IRWL effects were more significant under adverse conditions such as darkness, fog, and rain. This latter conclusion may be overly broad, given that data were apparently collected during sunny daytime conditions, or at night. No mention was made of collecting data during fog or adverse weather conditions. The authors also suggested that over a longer term, positive effects will degrade, but still be an improvement over initial conditions. This conclusion was evidently based on the single long-term follow-up at Santa Rosa. Although they did not compare sites or control for pedestrian volumes or other conditions, they concluded that the devices seemed most effective at locations with at least moderate pedestrian volumes which also tended to have site characteristics which would lead drivers to expect pedestrians. The authors also provided recommendations based on their observations.

[Insert Table here]

In the report version available to this reviewer, the appendices were, unfortunately not included, so detailed results and information on sample sizes was unavailable. There was no mention of whether statistical tests were performed to assess significance of before-after changes, and so the robustness of the results is unknown. There was also no information on how vehicles were sampled for the speed studies and yielding behaviors estimates. Although the sites were described in detail in the study, no attempt was made to analyze the data in aggregate to determine which conditions might be conducive to high yielding rates with this treatment, so some conclusions were based on anecdotal comparisons of results.

Huang, et al. (1999) conducted a before-after study of effects of IRWL at a single midblock crosswalk connecting a hotel/conference center with a performance hall and walkways leading to a sports arena in Orlando, Florida. Number of through lanes, speed limit, nor AADT, were reported, but the roadway is apparently four lanes (from image). Pedestrian traffic is light except during events. Huang et al. also used a staged pedestrian (waiting to cross) for observations of motorist yielding and motor vehicle approach speeds to the crosswalk. Observations were conducted for one afternoon each, before, and approximately one year following installation (daylight only). In addition, Huang et al. made separate after-period only observations and comparisons of pedestrian choice of crossing location and pedestrian-motor vehicle conflicts. As seen in Table 1, there was some improvement in the proportions of motorists slowing or stopping in response to the staged pedestrian. Still, two-thirds of motorists neither slowed nor stopped when a pedestrian was obviously waiting to cross and the lights were flashing. Both yielding/stopping rates and slowing rates were higher in the after period when flashers were *not* activated, but the difference in after-period conditions was not statistically significant. The authors do not speculate about this result. There was not a significant reduction in speeds. Although there was no comparison with before period crossing behavior, only 28% of pedestrians crossing in the area used the flashing crosswalks; a majority crossed at unmarked locations. Even when police officers were present and directing pedestrians toward the flashing crosswalk, many preferred to use more direct paths and only 57% used the flashing crosswalk; the proportion declined as time drew closer to nearby evening performances. Those that did cross in or near the flashing crosswalks, however, had a lower rate of conflicts with motor vehicles compared with those crossing in other areas. In a small set of interviews, some pedestrians thought IRWL a good idea, but also expressed a lack of understanding of use/function of the system.

Huang et al. concluded that the IRWL had small positive effects on increasing motorist yielding and reducing speeds, but was not effective at inducing pedestrians to use the flashing crosswalk. However, they did not collect before data on pedestrian crosswalk use, so the 28% could represent improvement. They surmised that the limited improvement in motorist yielding at this location may be due in part to the likelihood that motorists traveling through the crosswalk area are visitors or drive infrequently in the area, and are also often on their way to scheduled 'events.' The effects of the system at night or under adverse weather conditions were not evaluated. Given the proximity to entertainment venues, this information would have been very useful.

Huang (2000) reported on before-after studies of IRWL from two other Florida locations. One location was a midblock crosswalk on a two-lane university campus road in Gainesville, Florida. The roadway included bike lanes and a painted median, a 20 mph speed limit and carried an average of 14,500 vehicles daily. As expected on a university campus, pedestrian volumes were heavy, particularly between class changes. Three hours of before data, and 1.5 hours of after data were collected 2 months following implementation. The outcomes measured included motorists yielding to pedestrians when pedestrians were crossing or waiting to cross; pedestrians to whom motorists yielded; pedestrians crossing at normal walking speed; and pedestrians who crossed in the crosswalk. There was a statistically significant *decrease* in motorist yielding, although the decline was not large (Table 1). The IRWL did not enhance the proportion of pedestrians using the crosswalk. Most pedestrians at both Gainesville, and Lakeland (discussed below) crossed normally (no running, hesitations, aborted crossings, etc.) before the treatment, so there was little room for improvement. Huang concluded that the IRWL did *not* have a positive effect on yielding or crossing behavior at this location, but before period yielding and good crossing behaviors were already high. The author suggests that the before and after data collection periods may have been a factor in results, resulting in different populations of drivers and pedestrians during the two periods. Before data were collected in the summer while after data were collected in the fall shortly after a new semester began. Nighttime or adverse weather effects were not examined, but there was apparently little nighttime pedestrian activity at the location.

The IRWL treatment in Lakeland, Florida was installed at a crosswalk connecting a senior citizen residential area with a dining and social facility across a two-lane road (Huang 2000). Speed limits were 25 mph, ADT was 2000 – 2500; pedestrian traffic was light; intermittently heavier. In addition to the IRWL, the pedestrian crossing warning signs used included flashing lights. Observations were collected during days and times (daylight only) when activities were scheduled at the adjacent senior center. Outcome measures were the same as for Gainesville. Motorist yielding increased from 18% before to 30% after, but the increase was not statistically significant. A small sample size likely affected power to detect an effect. The proportion of pedestrians crossing within the crosswalk increased from 76% to 89%. Huang concluded that the IRWL had a positive effect on yielding and pedestrian crossing behavior at this location, although overall yielding by motorists was still only 30% in the after period. According to the author, low pedestrian volumes in the area may have been a factor in the results, contributing to a low driver expectation of pedestrians. Again, nighttime effects were not examined, but there was reported to be little nighttime activity.

Prevedouros (2001) evaluated IRWL treatment on a six-lane, median-divided arterial in Honolulu, Hawaii. The site was at an intersection with a residential street in the vicinity of a large elderly population. Three senior pedestrians had been killed near this intersection during the 1990s. The crosswalk spanned the arterial with an ADT of 30,000 per direction. The flashing lights were push-button activated at this site. In addition, there were two additional custom pedestrian warning signs that included flashing lights, as used in Lakeland, Florida. Observations were made on site and included days and period coinciding with times of past collision experience. Outcome measures included traffic volumes; traffic speeds at the crosswalk before installation, after with pedestrian present (system flashing), and after with no pedestrians present (system off); pedestrian wait times at the curb, duration of crossing, pedestrian actions such as running, and whether pedestrians activated the lights; and motorists' reactions to pedestrians: disregarded, or yielded (including stopping, or slowing if at a distance from the crosswalk). Motorist and pedestrian perception surveys were also conducted.

Results are also summarized in Table 1. Traffic volumes were lower in the after period but these changes were not attributed to the flashing crosswalk and were considered not to impact the other study results. Mean and 85^{th} percentile speeds all declined from before to after (lights flashing), but did not decrease when lights were not flashing, apparently illustrating an effect of the flashing lights. However, in this study, speeds were apparently measured at the crosswalk as opposed to approach speeds, and included many speeds of 0 mph in the after period when motorists were stopped. Therefore, it is unclear whether speeds on approaches to the crosswalk were affected by the system. The percentage of vehicles that slowed or stopped essentially doubled from 30% before to 62% after the IRWL installation. The proportion of pedestrians using the crosswalk also increased. The amount of time pedestrians had to wait at the curb before crossing decreased. The crossing time also decreased, as fewer pedestrians had to wait in the median to complete the second leg of the crossing. In addition, fewer pedestrians crossed at a natural gap in traffic after the IRWL was installed, which could have effects on traffic flow.

Prevedouros concluded that the IRWL produced positive results through reduced delay to pedestrians and improved safety (more vehicles slowing or stopping). Conflicts between motorists and pedestrians who had begun their crossing were not examined in this study. Although there were improvements in yielding and reduced delay, an inability to obtain very high motorist compliance was considered a problem. Pedestrian survey results, as well as professional opinion considered the flashing lights a stop-gap measure until a traffic signal could be installed. Considering the large senior population, the three senior fatalities, and the very heavy traffic volumes, the IRWL was not the ultimate solution for this location, although the researcher supported relocating the lights to another location. A traffic signal was activated in October, 2000.

In a study from Israel, Hakkert, et al. (2002) evaluated effects of IRWL at four midblock crosswalks on urban, divided arterials with a "relatively high concentration of pedestrian accidents." Sites 1 and 2 were in Haifa City. Sites 3 and 4 were along the same transit corridor in Bat Yam City. Speed limits were not stated. Observations were conducted for about 6 to 8 hours at two week and two month intervals, weekdays only, mostly sunny, during various rush and non-rush times of day. Two types of flashing crosswalk systems were used, but these were confounded with the cities/locations. There is little discussion of the systems, except that there were installation and operational problems in Bat Yam that resulted in loss of the two week data collection periods at those locations. Outcome measures included motorist yielding for three situations - pedestrians still on the sidewalk (1a in Table 1), pedestrians just stepping out into the first lane to begin crossing (1b), and pedestrians beginning the second leg/lane of the crossing (1c); driver free approach speeds at about 90 m from the crosswalk, and near the crosswalk, disaggregated by lane, car/bus vehicle type, and by traffic volume conditions; and conflicts in the crosswalks (unclear how determined). Motorist yielding rates were coded from data indicating how many vehicles passed while a pedestrian or group of pedestrians were waiting to cross. If the value was not 0, then the event was coded as 'vehicle does not yield;' therefore each 'vehicle does not yield' event could include multiple vehicles not yielding.

Results were somewhat mixed across locations, time periods and depending on the stage of crossing. In general, before-treatment yielding was lowest for pedestrians who were still waiting on the curb, somewhat higher for pedestrians beginning their crossing, and highest for those midway across. However, yielding to pedestrians still waiting on the curb showed the most significant improvements (at three of 4 locations) after the IRWL installations. Still only about one-fourth to one-third of motorists yielded to pedestrians waiting to cross. The effects on pedestrians already midway in their crossing were more mixed, with a decrease seen at one location. At the two locations with both two week and two month observations, initial improvements in yielding rates had declined for four of six measures by two months. The rate of conflicts in the crosswalk areas improved at all locations, but significantly at only two. Speed results also varied by location. In general there were more decreasing trends in average speeds at three of the four sites, but evidence of an upward creep at the later time interval. The authors also reported that a lower proportion of pedestrians crossed outside the crosswalk area following treatment, although these results were also rather mixed by location, time period and the other factors.

Hakkert et al. concluded that IRWL can, under certain conditions, reduce average vehicle speeds near the crosswalk and increase the rate of yielding to pedestrians waiting or just beginning their crossing. However, these yielding rates were still quite low. The authors also reported that there was no evidence of increased risk-taking (ignoring safe-crossing rules) by pedestrians, although the results for this measure were not provided. The numerous disaggregated measures of speeds and yielding made the paper somewhat challenging to interpret, although the authors attempted to summarize the results. The numerous measures do perhaps illustrate that effects may be complex, as in the differing results for yielding depending on the stage of the pedestrian crossing. The multiple speed measures were even more difficult to interpret. It would have been informative to model yielding as a function of speed and traffic type and volume conditions, in conjunction with IRWL activation. In addition, the longer, two-month time interval of the later observations is still a short-term period over which to measure effectiveness.

Kannel and Jansen (2004) reported on a study of IRWL effects at a crossing of a four-way intersection at a busy, downtown, Cedar Rapids location. The IRWL was installed on a multi-lane street (4-through lanes plus two-way left turn lane, and parking lanes on both sides), with a speed limit of 25 mph, and ADT of 25,000. The crosswalk was at an intersection location also affected by a service drive that partially falls within the crosswalk, an adjacent parallel railroad crossing, and a shared-use path that crosses at the crosswalk. Before data were collected only during the pm peak traffic period whereas after data were collected at am, lunch, and pm peaks at 2 weeks, and 6 months after implementation. However, examination by time of day did not reveal any obvious pattern in yielding by time of day. The outcome measures included percentage of 1^{st}, 2^{nd}, and 3^{rd} vehicles yielding to pedestrians who had already stepped from the curb into the parking lane or into an adjacent lane to the motorist's travel lane in keeping with state vehicle code; and approaching vehicle speeds before and after implementation, with pedestrians present and not present.

Motorist yielding improved to quite high levels with near 90% and above of first vehicles yielding in the after periods (Table 1). Starting yielding rates were also high, although varied by direction. Results (not shown in Table) suggested that yielding was initially slightly lower in the inside lanes, but there was a greater percentage improvement in yielding in these lanes where pedestrians would be midway in their crossings. While their methodologies were not the same, these results are in apparent contrast to those found by Hakkert et al. (2002). Kannel and Jansen also report that mean spot speeds generally increased across lanes and directions following implementation. It was not specified if lights were always flashing for the 'pedestrians present' condition but apparently so. Average speeds in the after period were lower, however, when pedestrians were present than when pedestrians were not present. The authors suggested that some motorists may have relied on the lights to let them know when pedestrians were present. Scale ratings from pedestrian surveys indicated fairly neutral pedestrian responses to the treatment. The most positive results indicated that pedestrians felt that IRWL increased motorist nighttime awareness. Motorist responses were somewhat more positive that IRWL increased nighttime awareness, and increased awareness of pedestrians in the vicinity.

Kannell and Jansen concluded that there was a marked improvement in compliance with a state law requiring yielding to pedestrians in the crosswalk. They also noted that approximately half the motorists not yielding at six months didn't do so when a train was approaching (that would block the street). The authors noted that the complexity of the location may make it difficult to obtain greater yielding. Speed changes were deemed to be insignificant or too small to make a meaningful difference to pedestrians. However, increases of 1.4 mph in mean speed, and 1.3 mph in 85^{th} percentile speeds when pedestrians were present in the after period could be significant. Results from this study may unfortunately be confounded by a treatment installed prior to this study. "Yield to Pedestrians" signs were installed in the street along the center line in the year before. Before the IRWL treatment was implemented, trends already showed improvements in motorist yielding over time. It is unknown whether the trends would have continued, based on prior attention to the crosswalk, even in the absence of IRWL. In addition, there was enhanced enforcement of motorist yielding on at least one occasion, between the first and second after period observations. Results should therefore be interpreted as resulting from the combination of treatments.

Karkee, Nambisan, and Pulugurtha (2006) evaluated IRWL effectiveness at a single midblock crosswalk with a multi-family residential driveway and a park entrance on either side. There were two through lanes plus left turn lanes in each direction and speed limit of 35 mph. Traffic volumes were reported to be about 300 vehicles per hour per direction. The number of observations and the before-after interval were not reported. In addition to IRWL, it is not clear if "Yield Here to Pedestrians" signs and pavement markings were added concurrently with the IRWL or were in place before the study began. Outcome measures included: yielding of motorists (lead or single vehicle) to pedestrians outside an estimated stopping sight distance (SSD) of 246 feet of the crosswalk before, and 169 feet after treatment (assuming a 2.5 second reaction time in the before period and 1 second after). Yielding of motorists in the first half of roadway was scored to pedestrians who had entered the roadway. Yielding in remaining lanes was scored once pedestrians approached the middle of roadway, but the results were analyzed together; yielding distance (not defined, presumably stopping position) from crosswalk; average, median, and 85th percentile speeds for the 246 foot (SSD) distance to crosswalk when a) no pedestrians were in crosswalk, b) pedestrians were waiting to cross, and c) pedestrians were in the crosswalk; conflicts, defined as either pedestrian or vehicle changed paths/directions.

Results were that motorist yielding increased from an average of 36% before to 73% after IRWL (Table 1). Mean speeds were lower in both directions after IRWL. The yielding distance increased in one direction and decreased in another (closer to the yield pavement markings) than before. This increase may have been related to the initially large stopping distance on one side due to geometric issues (driveway influence). Conflicts increased marginally, but not significantly. Karkee et al. concluded that IRWLs were effective at increasing motorist yielding in the situation of low traffic and pedestrian volumes. Since the study period was not described, it is not clear whether these are short or longer-term results. The effects of IRWL may also be confounded with the effects of added signs ("Yield Here to Pedestrians") and changes in pavement markings. It is also unknown whether the assumptions of decreased brake reaction times and shorter stopping sight distances (based on an increased expectation of pedestrians) in the after period are correct. This assumption affected the distance at which motorists were assumed to have sufficient distance to safely stop and were scored as not yielding. However, it seems that any bias introduced would likely have underestimated beneficial effects of motorist yielding.

Boyce and Van Derlofske (2002; also Van Derlofske, Boyce, and Gilson, 2003) conducted a multi-stage before-after study of the effects of enhanced visibility crosswalk striping and sidewalk improvements, followed by treatment with IRWLs at a complex T-intersection in Denville, NJ. Speed limits were 30 mph, and an athletic complex driveway egress was in the middle of the T. Outcome measures included the number of vehicles passing through the crosswalk area without yielding to waiting pedestrians. They also assessed changes in mean vehicle approach speeds, and motorist-pedestrian conflicts (defined as a vehicle passing through the crosswalk while a pedestrian was using it). Using video-taped recordings, they conducted a laboratory evaluation, using volunteers and videotaped sequences, of the noticeability of the different crosswalk treatments. Pedestrian intercept surveys were conducted after the enhanced striping and nine months after the flashing lights installation. These authors also reported on operational (failure to flash and false positives) and maintenance issues, but these results are not discussed here.

The number of motorists passing through the crosswalk without yielding to waiting pedestrians increased after the initial crosswalk improvements, decreased after the IRWL was installed, decreased further at the 9 months interval, but by 12 months had risen slightly. Speed results were mixed, showing apparent improvement in response to IRWL, but then increasing to above baseline levels when pedestrians were present by one year following. Results from a small sample suggested that pedestrians interviewed after the IRWLs were installed did not feel safer than those interviewed following the initial crosswalk improvements.

Boyce and Van Derlofske concluded that high visibility marking of a crosswalk enhanced the visibility of the crosswalk and reduced conflicts between pedestrians and vehicles. The enhanced visibility markings alone did not reduce the mean speed of vehicles approaching the crosswalk, or the mean number of vehicles passing over the crosswalk while a pedestrian was waiting to cross. The authors further concluded that the addition of IRWL to a high visibility crosswalk led to reduced mean approach speeds and a reduction in the mean number of vehicles passing while pedestrians waited to cross. It was also found, however, that the impacts tended to diminish over time, as speeds when pedestrians were present had increased above the baseline level by one year following, and the number of vehicles passing pedestrians waiting to cross had also risen from the previous time interval, although not back to baseline levels. This study performed no statistical tests to determine if the changes reported were statistically significant. Sample sizes were not reported for the speed studies.

The City of San Jose, CA compared before and after driver reactions and survey results for pedestrian-actuated overhead flashing beacons (OHFB) and IRWL at separate crosswalks on two different roadways (Malek 2001). The roadways at the crosswalks had a number of different characteristics, including roadway width and speed limit, and different starting yield rates, seriously confounding the comparison of the two treatments. Outcome measures included motorist yielding or braking; traffic speeds; distance from crosswalk when brakes were applied; and travel time to crosswalk. The road where the overhead beacon was installed had a five-lane profile (70 feet curb to curb), no on-street parking, and carried 10,000 vehicles per day, a speed limit of 30 mph, and 85^{th} percentile speed of 34 mph. The roadway where the IRWLs were installed had a three-lane profile plus bike lanes, on-street parking (removed in vicinity of the crosswalk) and carried 6,000 vehicles per day. Speed limit was 35 mph, with 85^{th} percentile speed being 42 mph.

Results for the two evaluations are shown in Table 1. Only very slight improvements were seen at the sight with the OHFB while larger improvements were observed for IRWL. Sample sizes or statistical tests were not reported. In addition, no results were reported for several of the outcome measures indicated. The author concluded that the IRWL was more effective at alerting motorists of pedestrian presence than the overhead yellow flashing beacon, particularly at night. However, as noted, the treatments were confounded with the two different sites and no direct statistical comparisons of the results at the two sites were conducted, so the conclusions did not reflect the study design.

3. Further Discussion

In general, most of the studies observed some measure of short-term increase in yielding to pedestrians at most (but not all) locations or directions after treatments were installed. However, many of the studies reviewed were quite small and included limited before and after period observation sessions (often only one), and several did not test the significance of results. There were also acknowledged potentially confounding factors in several studies. There was no use of comparison groups to control for potential unknown or seasonal/time effects. Nevertheless, the cumulative evidence suggests that IRWL usually leads to some improvement in motorist yielding behaviors, at least over the short term. Reported improvements in yielding and braking were in general more dramatic for nighttime, although these results were based on only two studies that conducted observations at night. One of these, was, however, the nine-site study.

While at least short-term improvements in motorist yielding to pedestrians were reported from most sites, *no* improvement, or improvement only to low levels was reported in several studies for some locations, approaches, or study conditions (for example, position of the pedestrian). Unfortunately, it cannot be ascertained how much of the variability in outcomes was due to differences in study methodologies, and how much may result from additional treatments, different site conditions, populations, and other unmeasured factors. Factors such as number of lanes, traffic volume and speed, adjacent land use, prevalence of pedestrians using the location, initial yielding rates, as well as operational factors such as visibility of the flashing lights, frequency of false flashing (no pedestrian present) or failure to flash or be activated when pedestrians are present, may affect the suitability and effectiveness of this treatment. Population differences could include variations in local behavioral norms, seasonal differences, or special circumstances such as a predominance of non-local or special event traffic at some locations. Unfortunately, although there are suggestive trends, none of these possibilities may be ruled out based on the studies conducted to date. All could, in fact, be important just as they may affect the condition and safety of a crosswalk in the absence of IRWL.

In fact, evidence from several studies suggests that if motorist yielding is quite low before treatment (less than 10%), the addition of flashing crosswalks alone may be insufficient to bring motorist yielding rates up to a desirably high level (daytime yielding rates remained well below 50%). These results suggest that poorly functioning crosswalks may warrant either alternative treatments or improvements in addition to IRWL, or reconsideration of the location.

In addition, results from a few studies that conducted assessments after different time intervals suggest that initial improvements in yielding and other outcome measures have usually degraded over longer time intervals. With the longest-term follow-up being a two year revisit of a single site, more research is needed into the long-term effects of IRWL. A longer study period might also allow the accumulation of crash evidence, particularly if a number of locations were included.

The effect of IRWL on those in the middle of their crossing, particularly for multi-lane roads should also be studied further. The potential to increase the risk of the multiple-threat type of collision exists. There were inconsistent results on whether IRWL improves yielding to pedestrians in the middle of crossing or approaching a second travel lane. This measure of effectiveness may have a greater bearing on safety than that for pedestrians waiting or just beginning to cross, but not yet in the path of vehicles. Two studies included such a measure of effectiveness.

Speed is crucial to motorists' ability or willingness to stop when needed. Reported effects on motorist speeds are mixed. In at least two cases where speeds had initially decreased, longer-term data found that speeds had tended to rise back toward, or even above initial speeds. Differences in speed by approach lane were also noted in some studies. One research team suggested that some motorists may learn to rely on the lights to indicate when pedestrians are present (Kannel and Jansen, 2004). If speeds increase following treatment, collision risk as well as risk of more serious injuries in the event of a collision could increase.

Conflicts may provide an estimate of the occasions in which motorist and pedestrian were potentially on a collision course; however the measures employed in these studies varied and the outcomes also varied. In addition to enhancing yielding and reducing speeds near the crosswalk, another desired effect of the treatment may be to increase the proportion of pedestrians using the crosswalk, if it is indeed safer. Again, results were mixed. It is likely, as observed by Huang et al, that pedestrians, particularly at midblock crossings, are often going to cross at the most convenient or direct line to their path. Thus, the location of midblock crossings seems to be a key to encouraging use, in addition to pedestrians' perceptions of safety.

The longer term experiences of some communities may also be informative. Although there was no intent nor a concerted effort to follow-up on all of the sites reported on in this review or other locations that have used IRWL, it was learned that some communities that had installed flashing crosswalk treatments to improve pedestrian safety have since removed them. Santa Rosa, CA removed the treatment from the first experimental location due to concerns with maintenance and sustained visibility of the lights over time, although they note that some of the issues may have been addressed in later improvements to the light systems. Santa Rosa engineers report that they have since adopted use of overhead flashing lights at midblock crossings (personal communication). These overhead flashing systems are also activated by pedestrian use of the crosswalk and are blank when not in use. They deem the overhead flashing lights to be more highly visible. Because they are raised above traffic, they are also visible to non-lead vehicles in a queue, and are somewhat less costly to install.

As reported by Prevedorous, the flashing crosswalk in the Honolulu study was also subsequently replaced with a traffic signal. Despite relatively low numbers of pedestrians, it was replaced due to safety concerns. It was thought that the IRWL treatment was not sufficient to address concerns of an elderly pedestrian population, and that some residents avoided or did not allow their children to cross at this high volume, multi-lane location even after the installation of the flashing embedded lights.

University Place, Washington (not reported on in this review) also removed in-pavement flashing lights from two locations along Bridgeport Way. "Because of reduced driver compliance over time and five vehicle-pedestrian collisions, the in-pavement lights are being replaced in summer 2002 with pedestrian traffic signals. The signals will be interconnected with other signals along the corridor to optimize traffic progression and minimize vehicle-pedestrian conflicts (Stamatiadis and Sugg, 2004). The City of Boulder, CO has also discontinued the use of IRWL in favor of pedestrian-activated, sign-mounted flashing lights, 'State Law' signing, and raised crossings at right-turn bypass islands (Tuttle, n.d.).

Finally, an IRWL evaluation study begun by Rousseau, Tucker, and Do (2004) in Rockville, Maryland has not been completed (personal communication). The study site was located near a Metro station and bus driveway. The researchers report that the study, intended to evaluate long term effects of IRWL, has not been completed due to a malfunction of the lights and inability to complete data collection.

3.1 Conclusions

Motorist yielding to pedestrians improved in the short term to varying degrees at most locations examined. However, yielding may not improve to a sufficiently high degree or may worsen at some locations with poor pedestrian conditions and initial very low yielding rates. The effects of IRWL on conflicts, traffic speeds and on pedestrian use of the crosswalks is not at all clear, as results have varied among the studies. Positive effects may also degrade over time as found in several studies. Unfortunately, it is not clear from the evaluation studies reviewed, under what conditions flashing crosswalk treatments may be most beneficial over the longer term, while not recommended for others. Clearly, the location should be carefully evaluated to determine if this treatment, alone or in combination with other treatments, is the best solution for a particular location and conditions. Some communities have also removed IRWLs due to both safety and efficiency reasons. If installed, the treatment should be carefully evaluated and monitored long term for effects on pedestrian safety and mobility. Ideally, in future research, studies would control for confounding treatments, use standard measures of effectiveness, such as those recommended in and use comparison locations with similar behavioral trends, environmental and user characteristics to control for time-related trends and other unknown effects.

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Table 1. Summary of In-Roadway Warning Light evaluation studies.

Study Sites	Safety Outcome measures[*]	Key Findings	Study issues
Boyce and Van Derlofske (2002) and Van Derlofske, Boyce and Gilson (2003)			
1 site: T-intersect-ion near rec. field and major highway	1) No. of vehicles not yielding per crossing 2) Speeds 3) Conflicts (vehicle passed through crosswalk while pedestrian was using it) 4) Conspicuity of crosswalk (lab evaluation) Other System reliability; Observations of driver responses; Conspicuity of crosswalk; Pedestrian survey Time periods See Key Findings	1) Mean number of motorists *passing* pedestrians without yielding: Before/baseline – 1.52 After Other crosswalk improvements – 1.75 After IRWL, 1-2 weeks – 1.33 After IRWL, 9 months – 1.06 After IRWL, 1 year –1.33 2) When pedestrians were present, mean approach speeds declined after crosswalk improvements and again after flashing treatment, then started to increase over subsequent time periods. 3) Mean no. of conflicts decreased when crosswalk improvements made; no further improvement after IRWL installed.	Daylight only. Successional before/after with 2 stages of treatment (initial crosswalk improvements, followed by IRWL). Mix of staged and nonstaged pedestrians (sporadic pedestrian traffic). Sample sizes not reported for approach speed data. No statistical tests were reported.

[*] Although described cryptically in this table for brevity's sake, the outcome measures were differently defined and study methodologies varied from study to study, so that yielding rates, speed effects or conflicts, should not be compared across studies.

Hakkert, Gitelman, and. Ben-Shabat (2002)			
4 midblock sites in 2 cities in Israel; all on divided high vol. arterials	1) Motorists yielding to peds a) on sidewalk, b) at beginning of crosswalk, c) in middle (at 2nd lane) of crossing. 2) Speeds 3) Conflicts 4) Pedestrian use of crosswalk. <u>Time periods</u> 2 weeks 2 months	1a) Motorist yielding to pedestrians waiting to cross (still on sidewalk): Before – Rates from 11 to 18% (4 sites) After 2 weeks – 27% and 49% at 2 sites After 2 months – increased significantly at 3 of 4 sites compared to Before, but highest level only 35% by this time period; decreased at the 4th site, n.s. 1b) Motorist yielding to pedestrians just entering crosswalk: Before – 5 to 32% After – Initial improvement at two sites, but then decreases and none were sign. at 2 months. After 2 months, highest yielding = 37% 1c) Motorist yielding to pedestrians in the middle of crossing: Before – 55 to 82% After - Only one significant improvement, from 55% to 100% A *n.s. decrease* observed at one site 2) Speeds showed a mix of improvement trends and worsening trends at all sites 3) Conflicts reduced at all sites 4) Pedestrians crossing outside crosswalk improved at 2 of 4 sites	Apparently daylight only data collection. Short term (2 months) results. Unable to complete data collection at 2 weeks time period at 2 sites due to installation and operational problems. Multiple disaggregated measures somewhat difficult to interpret, but illustrate the complexity of outcomes by different measures of effectiveness.

Huang (2000)			
2 sites: midblock crosswalks in Gainesville (Univ. campus) and Lakeland (near senior center/residence)	1) Motorists yielding to peds 2) Pedestrians to whom motorists yielded 3) Pedestrians crossing at normal walking speed (no runs, hesitations, aborted crossings) 4) Pedestrian use of crosswalk <u>Time periods</u> Gains. 2 months Lake. 3-4 months	1) Motorist yielding – Campus site: Before – 81% After – 75% (campus site, sign.decrease) 2) Motorist yielding – Senior Center site: Before – 18% After – 30% (senior center, n.s.) 2) Pedestrian % yielded to – Campus site: Decrease (sign.) Senior Center: Increase (sign.) 3) No change in % crossing at normal walking speed at either location (> 98% before and after at both locations). 4) Pedestrian % crossing within crosswalk: decreased – campus; increased – senior center	Daylight only, dry conds. Short term (2-4 months) results. Lacks detail on how yielding was coded from videotape. Possible confounding of data collection in after period with start of new academic year at Gainesville location - possible changes in motorist and pedestrian populations.
Huang, et al. (1999)			
1 midblock, Orlando, Florida	1) Motorist yielding (stop) or slow for staged pedestrians waiting to cross 2)Motor vehicle approach speeds 3) Pedestrian crossing locations (after period only) 4) Conflicts (after only) 5) Activation of the system <u>Other</u> Pedestrian interviews <u>Time period:</u> 1 year	1) Motorist yielding/slowing for peds: Before – 13% After – 34% (sign.). (More motorists slowed/stopped when lights were *not* flashing in after period, but not signif. different than when lights flashing.) 2) Before to After – No significant changes in approach speeds with or without pedestrian presence 3) After (only) – 28% of pedestrians used flashing crosswalk; others crossed at unmarked locations and two other nearby crosswalks without IRWL 4) Fewer conflicts for those who did use the IRWL crosswalk compared with those who didn't (After only) 5) Three-fourths of peds crossing at the crosswalk activated the IRWL Other: See text	Daylight only, dry conds. Single observation for before and after; small sample sizes may have limited ability to detect effects. Based on only one before and one after observation period. Although small sample sizes, did test statistical significance.

Kannel and Jansen (2004)			
1 site: intersect-ion, Cedar Rapids, Iowa urban area	1) Yielding: 1st, 2nd, and 3rd vehicles slowing/stopping for peds in adjacent lane 2) Speeds Other Ped and motorist surveys Time periods 2 weeks 6 months	1) 1st vehicle yielding – Eastbound: Before – 62% After 2 weeks – 91% (sign.) After 6 months – 88%. 1st veh. yielding – Westbound: Before – 92% After 2 weeks – 94% (sign.) After 6 months – 96% > 96% of 2nd and later vehicles yielded at all time periods and both directions. 2) Mean spot speeds increased 1.4 mph when pedestrians were present ($p = .063$) and by 0.8 mph without pedestrians present ($p = .014$). 85th %-ile speeds increased by 1.3 mph with peds present, but remained same without pedestrians present. Other – see text	Apparently daylight only. Attempted to measure yielding response as obligation is defined by legal statute. Results may be confounded with other treatments including center line Yield to Peds in crosswalk signs installed the prior year, (but removed prior to the study) and enhanced police enforcement during the study period
Karkee, Nambisan, and Pulugurtha (2006)			
1 site: midblock Henderso n, NV (push-button activated)	1) Motorist yielding (lead or single veh.) 2)Yielding distance 3) Speeds 4) Conflicts Time periods Not stated	1) Yielding: Before – 36% (AM and PM avg) After – 73% (significant change) 2) Yielding distance increased in one direction and decreased in the other 3) Mean and 85th percentile speeds decreased in both directions when pedestrians were waiting to cross or in crosswalk. (significant before to after change) 4) A marginal (insignificant) increase in conflicts observed	No mention of nighttime observations. Study period and before-after intervals not reported, so it is unknown whether these are short or longer-term effects. Effects of "Yield Here to Pedestrians" signs and pavement markings may confound effects of IRWL

Malek (2001)			
IRWL 1site: major collector intersect-ion; 25 mph speed limit; 36 feet curb to curb; San Jose, CA <u>Comparison</u> Overhead ped-activated flashing beacon (OHFB) installed at 1 site: T-intersect-ion with major collector; 35 mph speed limit; 65 feet curb to curb	1) Motorist yielding or braking 2) Approach speeds 3)Distance brakes applied 4) Travel time to crosswalk <u>Other:</u> Maintenance issues <u>Time periods:</u> 1 month 6 months	1) **Daytime** yielding **IRWL** site: Before – 10% northbound (NB); 12% southbound (SB) After 1 month – 44% NB; 54% SB After 6 months – 46% NB; 52% SB **Nighttime** yielding IRWL site: Before – 5% NB and SB; After 1 month – 64% NB; 68% SB After 6 mos – 80% NB; 72% SB **Daytime** yielding **OHFB** site: Before – 1% eastbound (EB); 5% westbound (WB) After 1 month – 4% EB; 14% WB After 6 months – 2% EB; 8% WB **Nighttime** yielding **OHFB** site: Before – 0% EB; 2% WB After 1 month – 5% EB and WB After 6 months – 8% EB and WB 2) Not reported 3) Braking distances (for those who did slow or stop) increased at both sites/ treatments except for southbound/IRWL in the daytime 4) Not reported	Day and nighttime observations. Sample sizes not reported. No statistical analyses. Comparison study of two types of warnings, but the two treatments were confounded with the two sites which differed in a number of characteristics including roadway width and speed limit. Results for the two treatments not compared statistically. Results for outcome measures 2) speeds, and 4) travel time to crosswalk, were not reported. Contradictory information on how vehicles were sampled (for speed and yielding measures).

Prevedouros (2001)			
1 site: arterial intersection with residential street in Honolulu, HI (push-button activated)	1) Motorist yielding (stopping or slowing) 2) Speeds 3) Traffic volumes 4) Crosswalk use <u>Other</u> Pedestrian crossing time, wait time, other <u>Time periods</u> ~ 2 months (not clear)	1) Motorist yielding: Before – 30% After – 62% 2) Mean speeds decreased about 25% from before to after (with lights flashing); 85th percentile speeds decreased by 14%. No significant change before to after when lights not flashing. 3) Traffic volumes were 5% lower NB and 7% lower SB in after period 4) Proportion crossing outside crosswalk: Before – 16% After – 8% <u>Other</u> See text	Daylight only. Short term results. One of the larger speed studies (large samples). After speeds included 0 mph speeds when motorists were stopped for pedestrians – few 0 speeds in before period.

Whitlock & Weinberger Transportation, Inc. (1998)			
9 sites: Varied sites in 7 California and Washington cities (12 sites planned) (3 sites push button activated)	1) Motorist reaction (yielded, reacted, but did not yield, did not yield) 2) Speeds 3) Travel time to crosswalk 4) Braking distance <u>Other</u> Pedestrian interviews – one location only <u>Time periods:</u> 8 weeks Approx. 2 years after at one site	1) Motorist yielding increased at eight sites (unknown which were statistically significant or if significance tests were conducted); results mixed at the 9th Summary of motorist yielding changes among the sites: • Four sites with moderate daytime Before yielding rates (~45 to 70%) improved to 85 – 90% day and night at 8 weeks After. • Most sites had very low (0 to 20%) nighttime yielding in the Before period, so nighttime improvements were larger. • One site with 20 – 35% daytime Before yielding improved to 60 – 68% After for daytime and nighttime. • Two sites with very low before daytime yielding rates (<10%) improved to <30% to 35%; nighttime somewhat better. • One other low-yielding site (<20%) saw mixed results with a decrease in daytime yielding and little nighttime improvement (to about 40%). • Long-term follow-up, 1 site – daytime yielding: Before – 25% After, short-term - 62% After 2 years – 48% 2) No significant changes in speeds at five locations; slight decreases at 2 locations, and mixed results at one location. Speed results were not reported for Santa Rosa. 3) Travel time results not reported consistently 4) Braking distances improved at most locations/directions, but did not improve or decreased at two locations.	Daylight and nighttime observations. Staged pedestrians used. Short term (8 weeks) effects (except for one location). Sample sizes not reported (may be in original appendices). Significance testing not mentioned explicitly.