SMART SPEED BUMPS

by

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Abstract

SMART SPEED BUMPS

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The research underscores the need and importance of traffic calming devices and provides the basis for designing and building a device for traffic calming in neighborhoods with high pedestrian traffic, particularly children. The thesis focuses on developing a traffic calming device that is responsive to driver behavior rather than a static traffic calming device.

The design presented herein involves modifying conventional speed bumps used for calming traffic in areas with high pedestrian traffic; the new design appears particularly suited for sites where the traffic calming may not be required at all times such as a school zone. The relevant engineering issues include:

- The functional requirements of the overall system and each of the system components
- Operational challenges
- Testing framework for evaluating the system and system components
- Other issues such as power requirements and component communications

Two design alternatives have been presented, each having a different deployment mechanism along with a preliminary evaluation of each. A test strategy has also been developed to ascertain operational functionality, identify potential failures or loopholes and make future improvements based on it.

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Chapter 1

Introduction

Heavy vehicular traffic on urban streets has increased the importance of traffic calming to improve the safety and livability within neighborhoods. A livable community is one that provides safe and convenient transportation choices to all citizens, whether the travel mode is walking, bicycling, transit, or driving. The U.S. Department of Transportation's Federal Highway Administration's (FHWA) Livability Initiative, underscores the importance of this concept in its Transportation and Safety factsheet, which states that over the past 50 years, most roadways being designed primarily for safer automobile and truck travel, could have made them less safe for pedestrians, particularly older adults, children and people with disabilities, or bicyclists. As a result, people who do not drive or have access to private vehicles, such as children and older adults, have been disproportionately represented in accidental deaths on U.S. roads. (FHWA, 2009)

The Institute of Transportation Engineers (ITE) defines traffic calming as 'the combination of mainly physical measures that reduce the negative effects of motor vehicle use, alter driver behavior and improve conditions for non-motorized street users'. (Lockwood 1997) As shown in the following sections, traffic calming reduces traffic crashes, increases the safety and convenience for pedestrians and other non-motorists, makes neighborhoods safer for children to play and eliminates noise and pollution. This thesis studies the utility of speed bumps as an effective traffic calming measure and proposes alternate designs to solve or mitigate issues with the existing design.

Among other measures that contribute to improving pedestrian safety, such as traffic signals and stop signs, the installation of speed bumps has also been traditionally used, and as evident from some of the studies included in further sections, also has been quite effective. Traffic lights or stop signs are not self-enforcing, whereas speed bumps are continually enforced. Drivers may speed up to pass through an intersection before the traffic light's indication changes, or may ignore a stop sign, which leads to unsafe road conditions. As opposed to traffic signals or stop signs, speed bumps do not need enforcement to be effective. Besides, stop signs and signals are installed mostly at intersections, unless high pedestrian traffic at a mid-block crossing warrants installation of a traffic signal. Speeds bumps are mostly used at non-intersection locations. The National Highway Traffic Safety Administration 'Traffic Safety Facts' shows that nearly four-fifths of pedestrian fatalities in 2010 occurred at non-intersections versus at intersections. However, speed bumps penalize even the law abiding drivers who are driving within the speed limit.

Literature Review

Traffic Calming Measures

Traffic calming measures involve physically altering the road layout or appearance for slowing down or reducing motor-vehicle traffic as well as to improve safety for pedestrians and cyclists (Hass-Klau 1985). The goal of traffic calming is to reduce vehicle speeds (and in some cases, volume, too), improving safety, and enhancing quality of life. They may broadly be classified into the following four categories (Wikipedia - Traffic Calming):

1. Narrowing streets/lanes: Narrowing traffic lanes differs from other road treatments by making slower speeds seem more natural to drivers and less of an artificial imposition as opposed to most other treatments, which physically force lower speeds or restrict route choice. Such means include:
    a. Narrower traffic lanes — streets can be narrowed by extending the sidewalk, adding bollards or planters, or adding a bike lane or on-street parking.
    b. Curb extensions (also called bulbouts) that narrow the width of the roadway at pedestrian crossings.

    c. Chokers, which are curb extensions that narrow the roadway to a single lane at points.
    d. Allowing parking on one or both sides of a street to reduce the number of driving lanes.
    e. Pedestrian refuges or small islands in the middle of the street.
    f. Converting one-way streets into two-way streets.
2. Vertical deflection: This involves creating a vertical deflection in the roadway. This includes:
    a. Speed bumps, which may sometimes be split to avoid causing delay to emergency vehicles. Speed bumps are about 2 to 4 inches high and 8 to 12 inches wide.
    b. Speed cushions, two or three small speed humps sitting in a line across the road that slow cars down but allows (wider) emergency vehicles to straddle them so as not to slow emergency response time. Speed humps comparatively much wider than speed bumps, that is, about a few feet wide. These may also be trapezoidal in shape.
    c. Speed tables, long flat-topped speed humps that slow cars more gradually than humps. Speed tables are even wider than humps, that is, about 20 feet wide.
    d. Raised pedestrian crossings, which act as speed tables, often situated at intersections.
3. Horizontal deflection, i.e. make the vehicle swerve slightly. This includes:
    a. Chicanes, which create a horizontal deflection that causes vehicles to slow as they would for a curve.
    b. Pedestrian refuges again can provide horizontal deflection, as can curb extensions and chokers.

4. Block or restrict access. Such traffic calming means include:
    a. Median diverters to prevent left turns or through movements into a residential area.
    b. Converting an intersection into a cul-de-sac or dead end.
    c. Boom barrier, restricting through traffic to authorized vehicles only.
    d. Closing of streets to create pedestrian zones.

The Importance of Speed Reduction

The Accident Research Unit of the Department of Transportation and Environmental Planning at the University of Birmingham, England, studied the relationship between the number and severity of pedestrian casualties at various impact speeds.

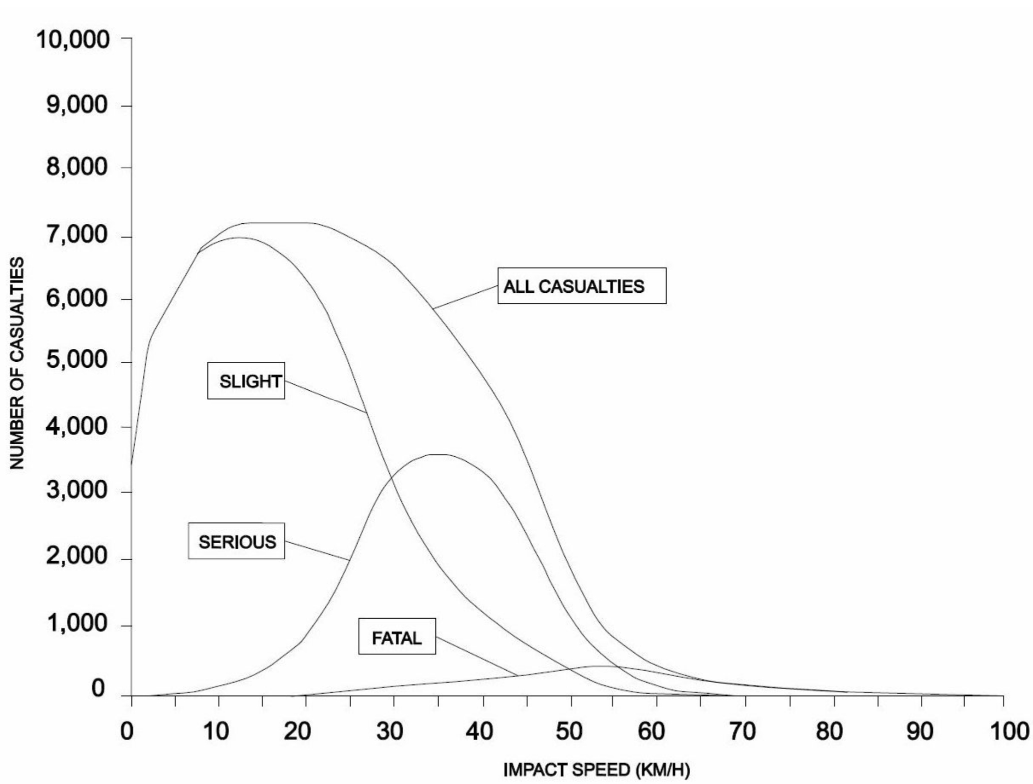

Figure 1-1 Severity and frequency of casualties at various impact speeds (Ashton and Mackay 1979)

Figure 1-1 shows the impact speed distributions for vehicles that were involved in pedestrian crashes where the pedestrian was struck by the front of the involved vehicle. This figure was derived mainly from data obtained in at-the-scene pedestrian accident studies conducted at the Accident Research Unit, University of Birmingham, with the data weighted to produce the same proportions of slight, serious and fatal casualties as occur in the U.K. nationally. The paper does not indicate whether the crash data is from surface streets only or if it includes parking lots as well. Off-street crashes may exhibit a different distribution. Pedestrians struck at impact speeds less than 30 km/h (19 mph) sustain predominantly slight (Abbreviated Injury Score or AIS 1) injuries whilst at impact speeds above 30 km/h (19 mph) the injuries are predominantly non-minor (AIS 2). The change from predominantly survivable injuries to predominantly fatal injuries takes place between 50 km/h (32 mph) and 60 km/h (38 mph). The Abbreviated Injury Scale (AIS) is an anatomical-based coding system created by the Association for the Advancement of Automotive Medicine to classify and describe the severity of injuries. It represents the threat to life associated with the injury rather than the comprehensive assessment of the severity of the injury. (Gennarelli and Wodzin 2008) The results are in agreement with those of other studies. (Ashton and Mackay 1979)

Figure 1-2 shows how the impact speed distributions are related to the severities of the injuries considered. The 50th percentile impact speed for all severities of injury is between 20-25km/h (12-16 mph). However, if only non-minor injuries are counted, the 50th percentile impact speed rises to approximately 35 km/h (22 mph), and if only fatalities are considered, to 50 km/h (30 mph). The corresponding 90th percentile impact speeds are, for all injuries 40km/h (25 mph), for non-minor injuries 50 km/h (30 mph) and for fatalities 65km/h (40 mph). (Ashton and Mackay 1979)

Thus, nearly all (97%) fatalities and almost half (47%) of all injuries may be avoided if the impact speed is brought down to 15 mph. This is based on just considering the impact speeds, which will be lower than the driving speeds as long as the drivers conduct speed, path or direction changing maneuvers to avoid the crash. If driving speeds are lowered, several crashes may be avoided altogether.

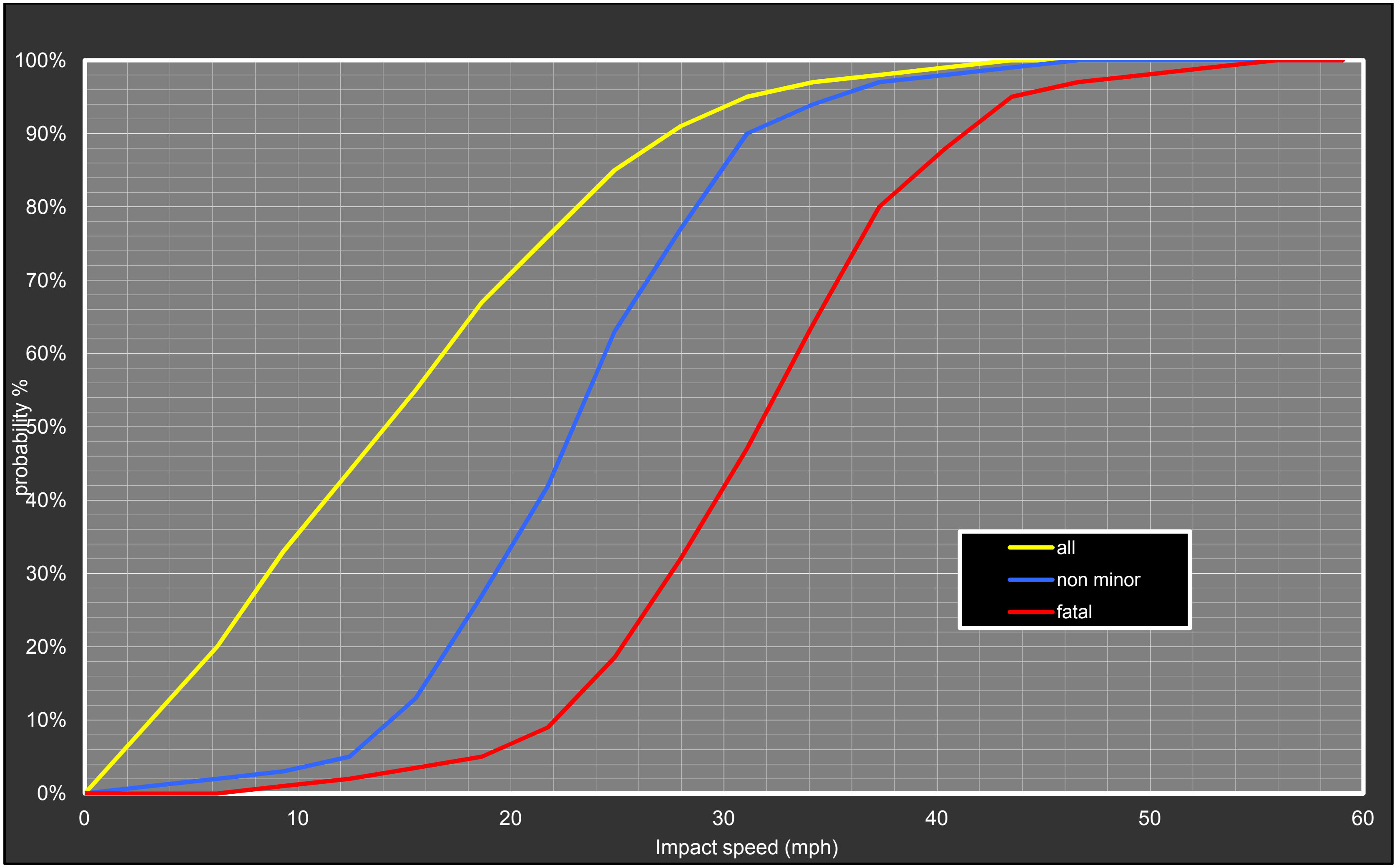

Figure 1-2 Probability of fatal, non-minor and all crashes significantly reduces in the sub-15-mph range

Source: Ashton and Mackay (1979)

Other studies corroborate the idea that a relatively small reduction in speed can make a big difference in safety for pedestrians. The following is an excerpt from the University of North Carolina Highway Safety Research Centers' Pedestrian Safety Program Strategic Plan referenced by the FHWA as a background report for its Pedestrian safety strategic plan:

> *The speed of a vehicle is a major determinant in the severity of a crash. According to one study (and several other studies have found similar results), a pedestrian hit at 40 miles per hour has an 85 percent chance of fatality, while a pedestrian hit at 20 miles per hour has only a 5 percent chance of fatality* (U.K.DOT, 1987).
>
> Figure 1-3 represents this graphically.

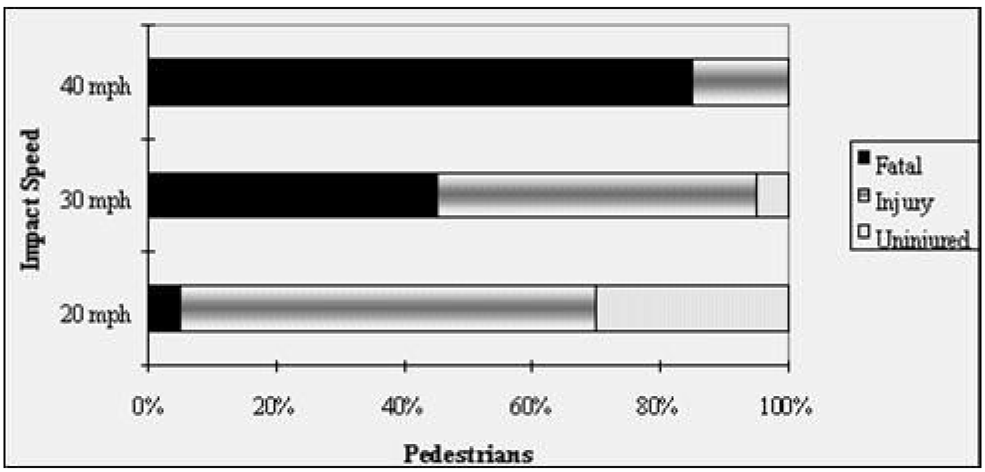

Figure 1-3 Percentage distribution of severity of casualties at various impact speeds Source: Traffic Advisory Unit, 1993

> *High vehicle speeds may be related to the road type (local/collector/arterial), road context (rural/urban), and road design (i.e., the presence of pedestrian infrastructure). Some tactics that have been implemented to discourage speeding have included traffic calming and citywide speed limit reductions. Pedestrians are likely to gain the most from speed limit reductions, but benefits have been seen for drivers as well through reductions in road crashes, generally improved attitudes and awareness towards safety, a more livable environment, and increased automobile energy efficiency* (Archer, 2008).

Several other studies, completed independently of each other, also support the relationship between higher speeds and more severe traffic-related injuries or death (Leaf &

Preusser, 1999; TRB, 1998). This relationship may occur because at higher speeds, drivers are less likely to see a pedestrian and are even less likely to be able to stop in time to avoid a collision (Harkey & Zegeer, 2004).

The Highway Safety Manual (HSM), developed by the Transportation Research Board, the American Association of State Highway and Transportation Officials and the Institute of Transportation Engineers, says the following about the influence of speed on the severity of a crash:

> *When accounting for perception-response time, a driver needs over 100 feet to stop when traveling at 30 mile per hour. Pedestrians are at risk because of the time required for drivers to respond and because of the energy involved in collisions, even at low speeds. Relatively small changes in speed can have a large impact on the severity of a pedestrian crash. A pedestrian hit at 40 mph has an 85-percent chance of being killed; at 30 mph, the risk is reduced to 45 percent; and at 20 mph, the risk is reduced to five percent.* (HSM 2010)

Case Study on Traffic Calming Effects of Speed Bumps

In early 2013, the City of Seattle installed speed humps as part of its Neighborhood Greenways and Safe Routes to School projects. Seattle Department of Transportation (SDOT) staff measured vehicle speeds at three elementary school locations to see whether the humps were actually effective. Table 1-1 shows the results of the before and after studies SDOT conducted at three schools in different neighborhoods in Seattle. At all three schools, the percent of drivers exceeding the speed limit decreased more than 70%. Perhaps more impressively, the percent driving more than 10 mph over the speed limit decreased by more than 80%.

Table 1-1 Results obtained at the three school locations where SDOT installed bumps (SDOT Blog 2014)

	Graham Hill Elementary Speed Humps Installed 2011	Highland Park Elementary Speed Cushions Installed 2012	Olympic Hills Elementary Speed Humps Installed 2014
85th Percentile Speed Before	28.3	29.7	28.7
85th Percentile Speed After	23.2	24.2	22.7
	-18%	**-19%**	**-21%**
Percent exceeding speed limit (25 mph+) Before	36%	43%	45%
Percent exceeding speed limit (25 mph+) After	8%	12%	5%
	-79%	**-73%**	**-88%**
Percent exceeding speed limit more than 10 mph (35 mph+) Before	1.0%	3.2%	1.1%
Percent exceeding speed limit more than 10 mph (35 mph+) After	0.2%	0.6%	0.1%
	-80%	**-81%**	**-91%**

This research shows that speed humps, which belong to the vertical deflection classification of traffic calming devices, are an effective tool not only at reducing speed but also at improving safety. Slowing down allows drivers to stop in a shorter distance, which can prevent a crash from happening in the first place. However, if a crash does occur, the severity can greatly be reduced because as illustrated by Figure 1-4, vehicle speed itself is a major factor in whether someone walking or biking is killed or injured if hit by a car.

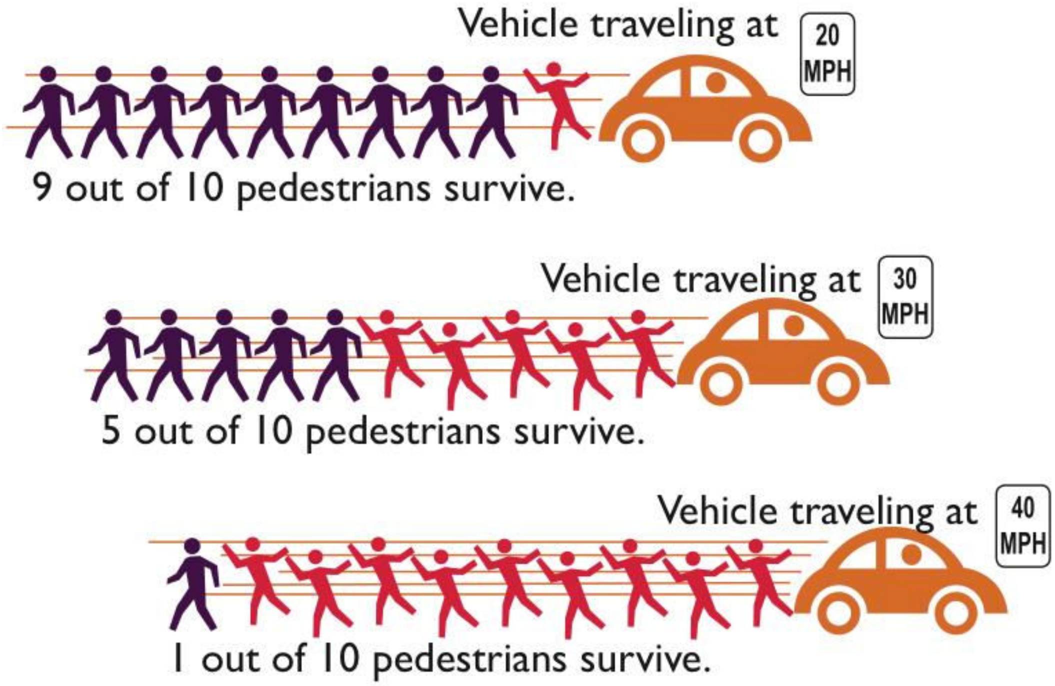

Figure 1-4 Illustration of influence of impact speed on pedestrian survivability

Source: SDOT Blog (2014)

Problem Description

While speed bumps (or other traffic calming devices) have several benefits, the key ones have been summarized below. Speed bumps:

- act as sleeping policemen, that is, they help enforce lower speeds at all times (Berthod 2011)
- offer guaranteed results at reducing speed (Berthod 2011)
- help provide safe road conditions, which results in a lower number of crashes, injuries and fatalities (Larrainzar 2014)
- lower public spending on:
  - injuries and fatalities
  - law enforcement

While these advantages make speed bumps a very advantageous traffic calming device, some concerns associated with the use of conventional speed bumps still exist. According to Citizens Rebelling Against Speed Humps (CRASH), a society of British activists, conventional speed bumps (CRASH website 2015):

i. Are detrimental to the environment, in that they increase pollution by forcing cars to slow and then accelerate away. A report produced by the Transport Research Lab (TRL), UK, in 2001 studies the effect of a number of different traffic calming measures on vehicle exhaust emissions. The report states that "the results of the study clearly indicate that traffic calming measures increase the emissions of some pollutants from passenger cars. For petrol non-catalyst, petrol catalyst, and diesel cars, mean emissions of CO per vehicle-km increased by 34%, 59%, and 39% respectively". (Boulter and Hickman 2001)

ii. Increase noise levels where they are implemented. This includes the noise produced not just by engine and brake noise from people slowing down and speeding up, but also from trucks carrying loads that get bounced around. However, research shows that the former claim is baseless. Traffic Noise Enhancement due to Speed Bumps, a paper published in the Sri Lankan Journal of Physics assesses the effect of speed bumps on road traffic noise levels. The average additional noise created by all vehicle types (except buses) due to speed bumps is less than 5 dB(A). (Wewalwala, S.N. and Sonnadara 2011) Another study conducted by the University of Thessaly corroborates this. (Elioy, N. and Vogiatzis, C.)

iii. Cause damage to vehicle suspensions as well as the steering system. Several sports cars have a low ground clearance and cause the bottom of the vehicle to brush over the bumps.

iv. Slow the response times of emergency vehicles: According to a study done by the Bureau of Traffic Management of Portland Department of Transportation, (Bureau of Traffic Management 1996) depending on the type of fire vehicle and the desirable response speed, the speed bumps were found to create a range of delays as follows:

- 22-foot speed tables: 0.0 to 9.2 seconds of delay per speed table
- 14-foot humps: 1.0 to 9.4 seconds of delay per hump

According to ITE, there is an approximate delay of between 3 to 5 seconds per hump for fire trucks and up to 10 seconds for an ambulance with a patient. (ITE website 2015). It is important to note that, besides delay, going over the humps might also cause discomfort to patients.

v. Cause discomfort and back injury to drivers and passengers. This also includes those travelling on buses and may be walking down aisles or using the stairs, causing them to fall and injure themselves.

vi. Often divert traffic to alternative residential streets.

Besides these, speed bumps also affect other road users such as bicyclists. Bicycles are not equipped with shock absorbers capable of damping the vertical force sufficiently. Allowing a gap between the curb and the bump might cause drivers to steer their vehicles so that the wheels on one side of the vehicle may clear without having to go over the bump. Speed humps do not have this problem since there is sufficient gap between two humps to allow bicycles to pass. However, if these gaps are not present, humps with lengths shorter than the wheel base of a bicycle (3.5 feet) and heights greater than 2 inches cause the toes of bicyclists to strike the humps, as a study on speed humps by the Center for Transportation Research and Education at Iowa State University notes. (Smith and Giese, 1997)

Need for a New Design

A speed bump, or any of the similar traffic calming devices that work on the principle of creating a vertical deflection in the path of a vehicle, such as speed hump or speed ramp, speed cushion, and speed table, while providing for speed control, also has certain drawbacks; the two most crucial appear to be their impact on emergency response times and the penalizing of all drivers regardless of the speeds at which they are driving. This is because the primary objective of designing a new speed bump is to increase safety. To be in line with this objective, the new design should have no negative impact on the emergency response times. (The impact of speed bumps on emergency vehicles has already been covered in the 'Problems Description' section). This would also ensure that the new design does not meet with resistance from public officials. Also, if the bump is able to distinguish law-abiders and law-breakers, it would gain wider acceptance among the public. The two problems noted above have led to several restrictions, and in some cases prohibitions, being placed on the use of bumps as a traffic calming device.

Speed bumps are self-enforcing, in the sense that drivers are forced to slow down to avoid an uncomfortable ride, and possible damage to their cars. They can be designed to achieve a desired speed (e.g. 15 mph), which drivers are physically compelled to meet.

This research aims to provide the basis for designing and building a prototype device for traffic calming in neighborhoods with high pedestrian traffic, particularly children. This is because children are more vulnerable to crashes either due to their smaller height, inattention or inexperience in crossing streets or lesser capability to move to safety in the event of a potential threat. It focuses on modifying conventional speed bumps, which are used for calming traffic in areas with high pedestrian traffic or places that are otherwise speed sensitive.

According to a National Highway Traffic Safety Administration Traffic Safety Facts report, in 2010, 4,280 pedestrians were killed and an estimated 70,000 were injured in traffic crashes in the United States. On average, a pedestrian was killed every two hours and injured every eight minutes in traffic crashes. A pedestrian, as defined for the purpose of this Traffic Safety Fact Sheet, is any person on foot, walking, running, jogging, hiking, sitting or lying down who is involved in a motor vehicle traffic crash. (NHTSA 2010) Additionally, 618 pedal cyclists were killed and an additional 52,000 were injured in motor vehicle traffic crashes. The above figures include only those incidents that occurred within the public right of way. Each year, unfortunately, the approximately 4,000 pedestrian fatalities comprise about 12 percent of all traffic fatalities. Another 59,000 pedestrians are injured in roadway crashes annually.

There have been several studies that indicate that traffic calming is indeed beneficial in saving lives. A few of those have been incorporated in this report. These studies indicate that anything that forces vehicle drivers to slow down to the sub-15 mph speeds significantly increases pedestrian survivability in the event of a crash. The Institute of Traffic Engineers also found a 13 percent reduction in collisions at locations where speed humps were installed. (ITE website 2015)

Speed bumps continue to be used in several places despite the problems they cause (as mentioned above) and in some cases, unfavorable public opinion, too. However, pressure from public organizations often causes politicians to prevent installation of bumps, and in some cases, even remove existing bumps, at locations where their use may have been justified. This leads to unsafe conditions for pedestrians, particularly for children and the elderly. Therefore, a need exists for a device which would offer safety and at the same time solve or at least alleviate some of the public’s concerns.

Chapter 2

System Description

Basis For Design

The benefits and the concerns associated with speed bumps described in the previous sections prompt the need for development of a device that can address the issues associated with conventional speed bumps while still providing their advantages. The device should be capable of distinguishing speeding vehicles from those that are not, and should penalize only those that are not obeying the speed limit. Those obeying the law should not be penalized and should be allowed to pass undeterred. When a speeding vehicle approaches, the device should 'act' like a bump so that the driver of the vehicle may receive a physical reminder to slow down. In this way, drivers obeying the speed limit shall not be penalized, while at the same time, those breaking the law would be. The system, called the Smart Speed Bump, when installed on a roadway, would look like any other speed bump. All drivers would therefore have a clear understanding of how they are expected to react. The design should ensure that drivers are not able to change lanes to evade the bump.

Design Elements

The primary system design elements include a speed detector, a controller, a mechanism for deployment/retraction of the bump and internal communication system. The entire system may be connected by cables or wirelessly, depending on the type of detector and controls. Detailed component descriptions shall follow. Preemption would also be used to prevent the bumps from getting in the way of emergency vehicles. Figure 2-1 shows a schematic of the whole system as it would appear when installed on a street.

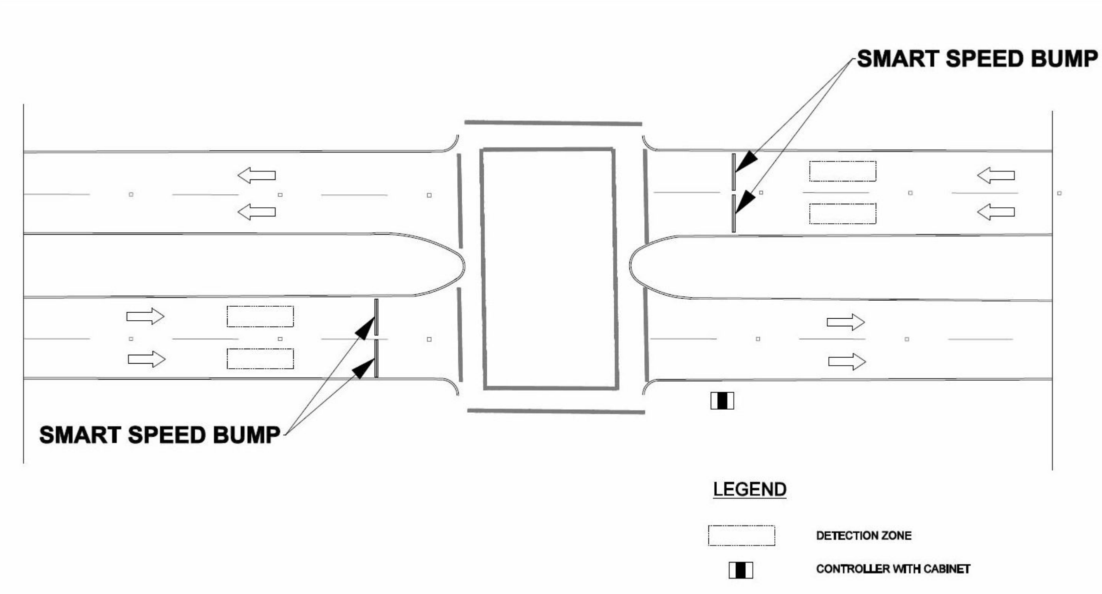

Figure 2-1 Schematic showing the components of the Smart Speed Bump system

Design Operational Requirements

When a vehicle approaches, its speed should be measured and compared with the threshold value. If the vehicle exceeds the threshold value, it should be forced to go over the bump. Otherwise, it should be allowed to pass undeterred.

However, in practice, vehicles may not always approach as isolated vehicles. A speeding vehicle may be followed by a slower vehicle and vice versa. Consider the following scenarios:

1) A vehicle travelling within speed limit followed by a speeding vehicle:
   In this case, the bump would first need to be retracted so that the first vehicle is allowed to pass. Once the first vehicle has passed the bump location, and the speeding vehicle has been detected, the bump should immediately be deployed. Assuming a headway of two seconds between the vehicles for saturated flow, the minimum time that the system would have to deploy for the speeding vehicle would be the gap between those two vehicles. In practice, the

second vehicle would actually have to slow down to adjust its speed with that of the first in order to have a safe following distance.

2) A speeding vehicle followed by a vehicle travelling within speed limit:

   In this case, after remaining deployed for a speeding vehicle, the bump needs to be able to retract once the speeding vehicle has passed. Considering the worst case scenario in which the driver of the speeding vehicle is undeterred by the bump and continues to speed through over the bump, the device would at least have two seconds (since the car behind is not speeding and assumed to be two seconds behind) to retract. In most cases, the driver of the speeding vehicle would be forced to slow down due to the deployed bump and this would lead to the following vehicle to slow down further. Thus, the bump would have a time greater than that in the previous case in order for it to retract.

3) Besides the two cases discussed above, another possible scenario is that a speeding vehicle is followed closely by another speeding vehicle. In this case the second vehicle may rear-end the first, if the vehicle ahead brakes too hard due to the bump being deployed or the vehicle behind maintains an insufficient gap. Proper signage in advance of the bump would warn the drivers of the bump ahead, and prompt them to maintain a safe following distance.

Detector

The detector must measure the speed of the oncoming vehicle and report it to the controller, which must assess whether to signal the speed bump to deploy. The detector needs to be able to detect presence and measure the speed of all approaching vehicles and report it lane wise. For this to be done, the detector needs to have separate detection zones for each of the lanes. Also, the detection zones should be located as close as possible to the bump so that no lane change occurs between detection and bump deployment. The lower limit for the location of the detection zone from the bump would be controlled by the time needed for the bump to deploy and the upper limit would be controlled by the minimum distance necessary to make a lane changing maneuver at the deployment threshold speed.

A detection technology that offers accurate detection in a relatively shorter zone shall be preferred since it would eliminate the problem of lane changing maneuvers by drivers attempting to evade the bumps. Additional measures such as markings that discourage lane changing may be required if the detection zone is too far in advance. Besides markings, yielding lane separators may be used to ensure drivers are unable to change lanes to avoid bumps. The length of the detection zones for each lane should not exceed 20 feet. This is to allow differentiating individual vehicles. Vehicles detected within a gap shorter than this shall be considered to be travelling at the same speed and would receive similar treatment in terms of bump deployment/retraction.

Existing Detector Technology

Accuracy in speed detection is vital to ensure that law abiding drivers are not penalized while at the same time speeding vehicles are given physical reminders to slow down. The Traffic Detector Handbook, a FHWA publication, has been used as the primary reference for existing detector technology. (FHWA 2006) A preliminary evaluation of each type of detector has been performed. Further research and testing would be necessary to determine the most suitable alternative prior to building a full prototype.

1. Inductive-Loop Detectors

   These are the most common type of detectors used for traffic signal actuation. Inductive-loop detectors sense the presence of a conductive metal object by inducing electrical currents in the object. The induced current decreases the loop inductance, which is sensed by the inductive-loop electronics unit. The electronics unit interprets the decreased inductance as a vehicle detection and sends an appropriate call to the controller.

2. Video Image Processors

   Video cameras were first introduced to traffic management for roadway surveillance based on their ability to transmit closed-circuit television imagery to a human operator for interpretation. Current video image processing technology allows automatically analyzing the scene of interest and extracting information for traffic management. A video image processor (VIP) system typically consists of one or more cameras, a microprocessor-based computer for digitizing and analyzing the imagery, and software for interpreting the images and converting them into traffic flow data. A VIP can replace several in-ground inductive loops, provide detection of vehicles across several lanes, and perhaps lower maintenance costs. However, additional cost is incurred in installation of mast arms or poles for mounting the video cameras if none already exists.

3. Microwave Radar Sensors

   Radar is defined as “a device for transmitting electromagnetic signals and receiving echoes from objects of interest (i.e., targets) within its volume of coverage.” Radar was originally an acronym for RAdio Detection And Ranging.

4. Active Infrared (Laser Radar) Sensors

   Laser radars are active sensors that transmit energy in the near infrared spectrum. Models are available that scan infrared beams over one or two lanes or use multiple laser diode sources to emit a number of fixed beams that cover the desired lane width.

5. Passive Infrared Sensors

Passive sensors transmit no energy of their own. Rather they detect energy from two sources:

- Energy emitted from vehicles, road surfaces, and other objects in their field-of-view.
- Energy emitted by the atmosphere and reflected by vehicles, road surfaces, or other objects into the sensor aperture.

6. Ultrasonic Sensors

Ultrasonic sensors transmit pressure waves of sound energy at a frequency between 25 and 50 kHz, which are above the human audible range. Most ultrasonic sensors operate with pulse waveforms and provide vehicle count, presence, and occupancy information. Pulse-shape waveforms measure distances to the road surface and vehicle surface by detecting the portion of the transmitted energy that is reflected towards the sensor from an area defined by the transmitter's beamwidth. When a distance other than that to the background road surface is measured, the sensor interprets that measurement as the presence of a vehicle. The received ultrasonic energy is converted into electrical energy. This energy is then analyzed by signal processing electronics that are either collocated with the transducer or placed in a roadside controller.

7. Passive Acoustic Array Sensors

Acoustic sensors measure vehicle passage, presence, and speed by detecting acoustic energy or audible sounds produced by vehicular traffic from a variety of sources within each vehicle and from the interaction of vehicle's tires with the road. When a vehicle passes through the detection zone, an increase in sound energy is recognized by the signal processing algorithm and a vehicle presence signal is generated. When the vehicle leaves the detection zone, the sound energy level drops below the detection threshold, and the vehicle presence signal is terminated. Sounds from locations outside the detection zone are attenuated.

8. Two-Axis Fluxgate Magnetometers

   Two-axis fluxgate magnetometers contain sensors that detect both the vertical and horizontal components of the Earth's magnetic field and any disturbances to them. One of the secondary windings in a two-axis fluxgate magnetometer senses the vertical component of the vehicle signature, while the other, offset by 90 degrees, senses the horizontal component of the signature. The horizontal axis of the magnetometer is usually aligned with the traffic flow direction to provide in-lane presence detection and adjacent lane vehicle rejection. Fluxgate magnetometers measure the passage of a vehicle when operated in the pulse output mode. In the presence mode, they give a continuous output as long as either the horizontal or vertical signature exceeds a detection threshold.

Comparison of existing vehicle detector technology

Table 2-1 compares each of the previously discussed technologies on the basis of its strengths, weaknesses and the approximate cost of procurement (converted to 2013 dollars). The cost has been calculated for a four lane roadway and is represented in terms of the '$' symbol where each '$' represents 5000 U.S. Dollars.

Table 2-1 Comparison of various types of detectors (Vehicle Detector Clearinghouse 2007)

Technology	Strengths	Weaknesses	Cost
Inductive Loop	• Mature, well understood technology. • Large experience base.	• Installation requires pavement cut. • Decreases pavement life. • Installation and maintenance require lane closure. • Wire loops subject to stresses of traffic and temperature.	$$
Video Image Processor	• Monitors multiple lanes and multiple detection zones/lane. • Easy to add and modify detection zones.	• Performance affected by inclement weather such as fog, rain, and snow; vehicle shadows; vehicle projection into adjacent lanes; occlusion; day-to-night transition; vehicle/road contrast; and water, salt grime, icicles, and cobwebs on camera lens. • Requires 30- to 50-ft camera mounting height (in a side-mounting configuration) for optimum presence detection and speed measurement • Reliable nighttime signal actuation requires street lighting.	$$$$$
Microwave Radar	• Typically insensitive to inclement weather at the relatively short ranges. • Direct measurement of speed. • Multiple lane operation available.	• Not suitable for dense traffic.	$$

Table 2-1—*Continued*

Active Infrared (Laser radar)	• Transmits multiple beams for accurate measurement of vehicle position, speed, and class. • Multiple lane operation available.	• Operation may be affected by fog when visibility is less than ≈20 ft (6 m) or blowing snow is present. • Installation and maintenance, including periodic lens cleaning, require lane closure.	$$$
Passive Infrared	• Multi-zone passive sensors measure speed.	• Passive sensor may have reduced sensitivity to vehicles in heavy rain and snow and dense fog. • Some models not recommended for presence detection.	$$
Acoustic	• Passive detection. • Insensitive to precipitation. • Multiple lane operation available in some models.	• Cold temperatures may affect accuracy. • Specific models are not recommended with slow moving vehicles in stop-and-go traffic.	$$$$
Two-Axis Fluxgate Magnetometers	• Less susceptible than loops to stresses of traffic. • Insensitive to inclement weather such as snow, rain, and fog	• Installation requires pavement cut. • Decreases pavement life. • Installation and maintenance require lane closure.	$$$

While microwave, inductive loop or passive infrared sensors may seem to be the low-cost choice at first glance if inductive loop detectors are not desired, a more expensive sensor such as a video image processor (VIP) may be the better choice when the number of sensors needed is taken into account. Besides, some of the sensors cannot directly measure speed (e.g., a single zone infrared sensor or a single loop detector). Consequently, if the system requires eight to twelve conventional inductive loop detectors (or ultrasonic, microwave, infrared, etc. sensors) to fully instrument a street cross-section, the cost becomes comparable to that of a video detection. However, as mentioned in the table, certain important drawbacks of video detection cannot be ignored, particularly false detection due to vehicle shadows or difficulty in nighttime detection. Thus, active infrared (laser) appears to be the most suitable technology. The only drawback listed is that of visibility, hence a laser detector may not be used in areas with frequent inclement weather that affects visibility. Furthermore, modern detectors can be mounted on a pole in the median and detect the speeds of vehicles on both sides of the road. This may also ensure minimal disturbance to vehicular traffic for maintenance.

Other factors that affect the cost and selection of sensors are the need for road closure for installation and maintenance, maturation of the designs and manufacturing processes for sensors that use the newer technologies, reduced prices through quantity buys, and availability of mounting locations and communications links at the application site.

The data obtained from detectors would serve as an input to the controller for processing. For this, the measurement needs to be as accurate as possible to avoid surprising the drivers. Besides the technologies discussed above, another technology currently being researched is the Vehicle-To-Infrastructure (V2I) Communications. This technology may offer another mode of speed measurement without the need of having dedicated detectors.

Vehicle-To-Infrastructure (V2I) Communications

An important milestone in Intelligent Transportation Systems is Vehicle-To-Infrastructure (V2I) Communications. V2I Communications is the wireless exchange of data critical to safe operation between vehicles and roadway infrastructure, intended primarily to avoid motor vehicle crashes. It is currently being researched by the U.S. Department of Transportation (USDOT) Research and Innovative Technology Administrations' (RITA) Intelligent Transportation Systems Joint Program Office (ITS JPO). (USDOT 2014)

The infrastructure already setup for collecting data can eliminate the need for a separate mechanism for vehicle speed measurement. The data gathered can be shared with the controller, which can then signal the bump to be deployed or retracted appropriately. For this to be practicable, a software interface would be needed, which would facilitate transfer of data from the infrastructure to the controller.

Controller

The controller is the central part of the system. The controller obtains speed data from the detector, processes it and sends appropriate signals to the bump deployment device.

Functionality Requirements

Since the controller is central to the system working effectively, the controller software should be capable of processing the data obtained from all the detection zones simultaneously and with high enough speed to meet the deployment speed requirements. It should also have the ability to preempt normal operation of the device when an appropriate signal is received by the preemption system from an approaching emergency vehicle. The software should also be programmable to have tolerance as well as to reduce error (as covered in the 'Tolerance and Errors' sub-section).

Comparison of Available Controllers

Several controllers are available in the market with varying functionality and costs. The most common models are the 170, 2070, NEMA TS-1 and TS-2 and the more modern Advanced Transportation Controllers (ATC). The Model 170 is the most basic and has been in used since the 1970s. It is also very low cost compared to the rest. When used for a traffic signal it can handle at most eight channels. For the Smart Speed Bump, this can be translated as the ability to serve a maximum of eight lanes, since each lane would have a separate detection zone and would require individual decision making.

Although the Model 170 is cheap and suitable for most streets with eight lanes or fewer, there are certain limitations to its use. Its processor is not as advanced as the more advanced models and not as fast. There are also limitations to its memory. Further research needs to be done regarding its capability to operate the software needed for this application. Other models are relatively more expensive but deliver better performance.

The controller can be programmed to have a certain amount of tolerance to accommodate inaccuracies in –

i. vehicle speedometers, which may trick the drivers into believing that they are travelling within the speed limit when they are actually not, and
ii. speed measurement by the detector

Tolerance and Errors

In some cases the city, county or the respective authority may choose not to penalize drivers who are fairly close to the speed limit and a certain tolerance may be added to the threshold value to allow those vehicles to pass without obstruction. Besides, some drivers may be going at a speed much higher than the speed limit. In this case, deploying the bump may be unsafe since it would cause the driver to lose control of the vehicle. Thus, the deployment speed requires a lower threshold and an upper threshold to accommodate both of these possibilities.

Inaccuracies in speed measurement by the detector can be bi-directional, that is, the detector may report a value higher or lower than the actual value of vehicle speed. Consider a statistical hypothesis wherein the null hypothesis is that the speed is greater than the lower threshold speed set in the controller. For a one-sided test, the alternate hypothesis would then be that the speed is less than the threshold.

H_0: Speed is higher than the set limit

H_1: Speed is within the set limit

This approach prioritizes the traffic calming of the Smart Speed Bump over driver convenience because the Smart Speed Bump is a safety device.

Two types of errors exist:

Type I error: To reject H_0 incorrectly (A speeding vehicle is reported as not speeding)

Type II error: Failure to reject false H_0 (A vehicle travelling within the speed limit is reported as speeding)

The result of type I error would be that a speeding vehicle would be allowed to go unobstructed. This is undesirable in speed sensitive areas such as school speed zones. The result of a type II error would be that a law abiding driver would have to suffer an unexpected speed bump. This may lead to driver frustration.

A positive correct outcome occurs when a vehicle travelling within the speed limit is allowed to pass undeterred by the bump. A negative correct outcome occurs when a speeding vehicle is made to slow down by deploying the bump. (Wikipedia - Types of Errors)

Table 2-2 Possible Outcomes of Hypothesis Testing (Wikipedia)

	Null hypothesis (H_0) is valid: Speeding	**Null hypothesis (H_0) is invalid: Not speeding**
Reject H_0: Controller judges vehicle as not speeding	**Type I error** False positive Bump retracted	**Correct outcome** True positive Bump retracted
Don't reject H_0: Controller judges vehicle as speeding	**Correct outcome** True negative Bump deployed	**Type II error** False negative Bump deployed

Choosing to decrease one type of error or the other may potentially affect driver behavior. For example, reducing type I error would lead to an increase in type II error, which would result in penalizing a higher number of cars that are close to the speed limit. This may surprise drivers and may lead to driver frustration. On the other hand, reducing type II error would lead to an increase in type I error, which means that a greater number of vehicles with speeds higher than the set limit would be unaffected by the bump and this may lead to unsafe road conditions.

Depending on the utility of the device, the system can be programmed to reduce either type of error. This may, however, be done at the expense of increasing the other type of error. In most cases, type I error should be minimized in order to maximize the safety benefits.

Bump Deployment Device

The deployment device is the central component of the system and would comprise primarily of the following:

a. Panel

   The panel acts as an interface between the vehicle tires and the support mechanism underneath. The panel should be made of a material which can deliver the load and performance requirements of the bump. The upper edge of the panel shall be curved so as to give the appearance of a conventional speed bump.

b. A mechanism to position the panel

   The mechanism deploys the panels and holds it in place or retracts it upon receiving appropriate signals from the controller.

Two alternative designs for the device are presented; the key difference between the two is the way that the position of the panel is controlled. Further research is needed to determine the most efficient design; however, any design must meet the requirements set forth under each.

Smart Speed Bump Design 1

As shown in Figure 2-2, the panel shall be split at the center and hinged towards the ends. The loose ends of the panel (the point where it is split) shall be supported by springs. The stiffness of the springs chosen should be sufficient to raise and support the panels at the designed height. At the same time, the springs shall be fully compressible under the weight of the design vehicle to provide a flattened travel surface as seen in Figure 2-2 (B). For the purpose of the Smart Speed Bump, the design vehicle considered would be the lightest compact car available in the market. This would ensure that all motorized vehicles, including those that are relatively lightweight, are able to fully depress the panels when it is in a retracted state. Two connectors, hinged close to the loose ends of the panel, are supported on a 0.15 inch thick metallic guide ring, which slides over the guide rod. Right below the guide ring is the locking mechanism, which can stop the ring from sliding down when required. Figure 2-3 shows the three positions in detail. Each bump would have a set of the support system as described above, arranged adjacently to carry the stress of traffic passing over it.

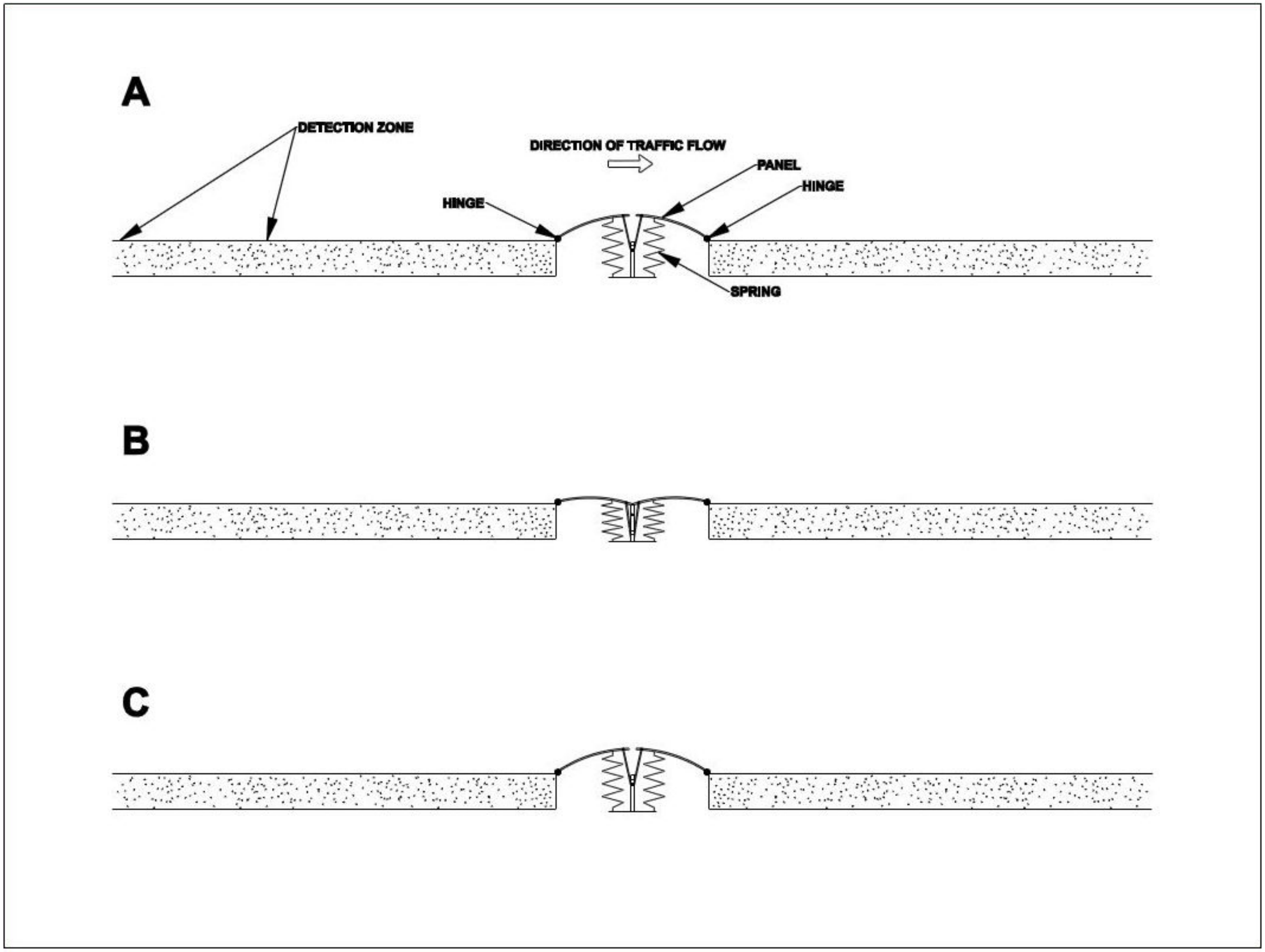

Figure 2-2 Design 1 (A) Default position of panels (Retracted state), (B) Retracted state when a vehicle passes over and (C) Deployed state

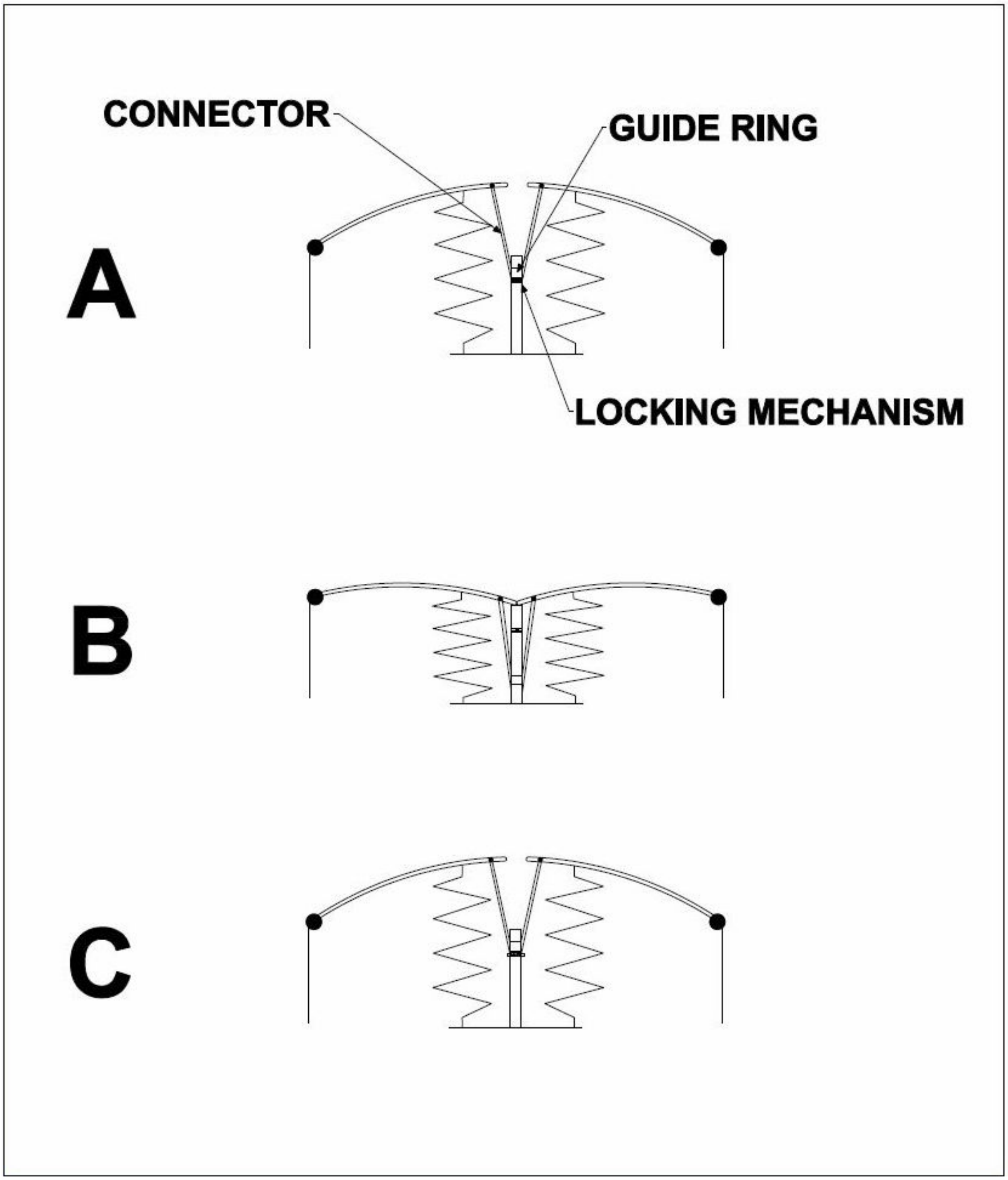

Figure 2-3 Design 1 details

By default, the panels would remain in an upright position but not deployed. This means that the drivers would see the bump in the road, but if they are driving within the speed limit, the bumps would compress into the pavement (as shown in Figure 2-2) and allow the car to pass undeterred. At the moment when the wheels of the vehicle go over the panels, it would be compressed as shown in Figure 2-3 (B). However, when a speeding vehicle approaches, the locking mechanism would prevent the rider from sliding down until the speeding vehicle has passed. The panels would then remain supported in their initial position as shown in Figure 2-3 (C). Figure 2-4 shows the dimensions of various components in order to achieve a bump height of 1" above road surface. The thickness of the panels would be based on the material chosen. The height of the bump can be adjusted as needed by moving the default position of the guide ring and the springs. The adjustable height ensures than the bump can be used on roads with different design speeds. The length of a bump would depend upon the lane width. The bumps shall span the entire width of the lane. A gap in between bumps may be needed for proper functioning of the bumps. This gap should be filled by a suitable material (such as a regular speed bump) to prevent vehicles from attempting to go around.

The material to be used to build the components for the above design would be based on its ability to deliver the structural requirements while creating minimal noise. The top surface of the panels shall be coated with a material such as vulcanized rubber to provide sufficient grip while reducing impact noise. The panel and connecters for this design, as well as the guide ring and the locking mechanism should all be able to carry the load of a fully loaded 18-wheeler, which has a legal maximum weight of 34,000 lbs. per axle. A factor of safety should also be considered while making load calculations.

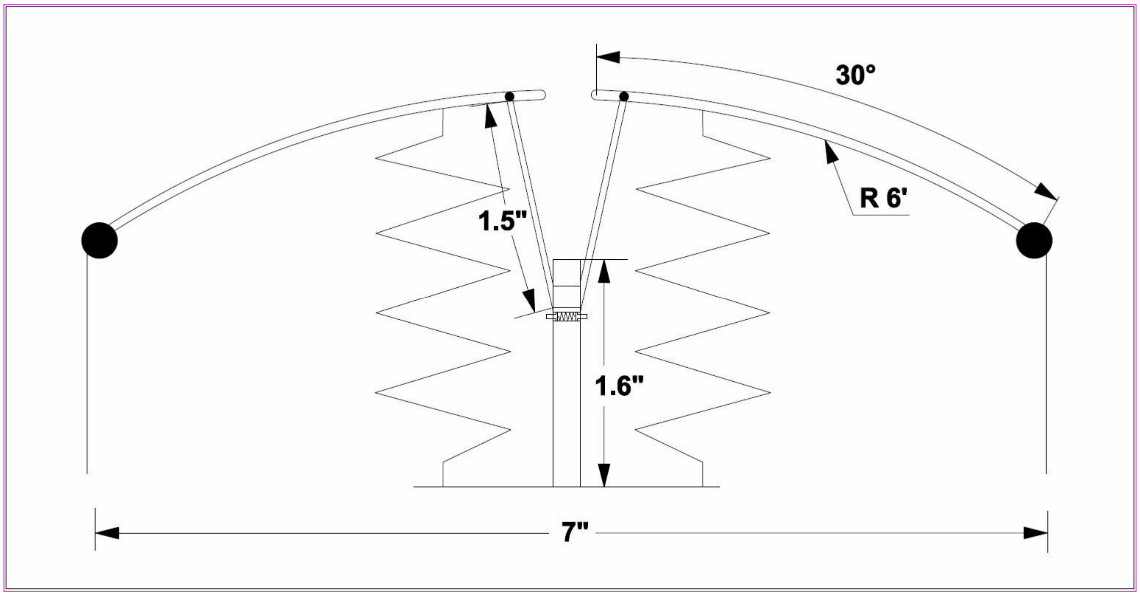

Figure 2-4 Design Dimensions for Design 1

Smart Speed Bump Design 2

As seen in Figure 2-5, the panels in this design have a different cross-section from Design 1. The panel on the upstream side is supported by a roller and the one on the downstream side is supported by a wedge made of steel or other suitable material. The wedge serves the dual purpose of supporting the panel and acting as a barrier for the roller when the bump is deployed. Unlike in Design 1, the two panels are connected by a single connector in between. The metal ball can be pushed by a hydraulic piston embedded in the pavement. The two panels in this design are directly linked by a connector between the two panels. The connector serves to transfer the upward force from the panel on the upstream side to the one on the downstream side.

By default, the top of the panels shall be flush with the road surface. An approaching driver would see only a visual delineation across the road. When a speeding vehicle approaches, the hydraulic piston forces the roller to slide up the wedge upon receiving appropriate signal from the controller. In the process, the roller pushes the upstream side panel to move upwards. The connector transfers this force to the downstream side panel. The raised panels cause a vertical deflection in the path of the passing vehicle. Figure 2-6 shows the design dimensions for a 1" high bump.

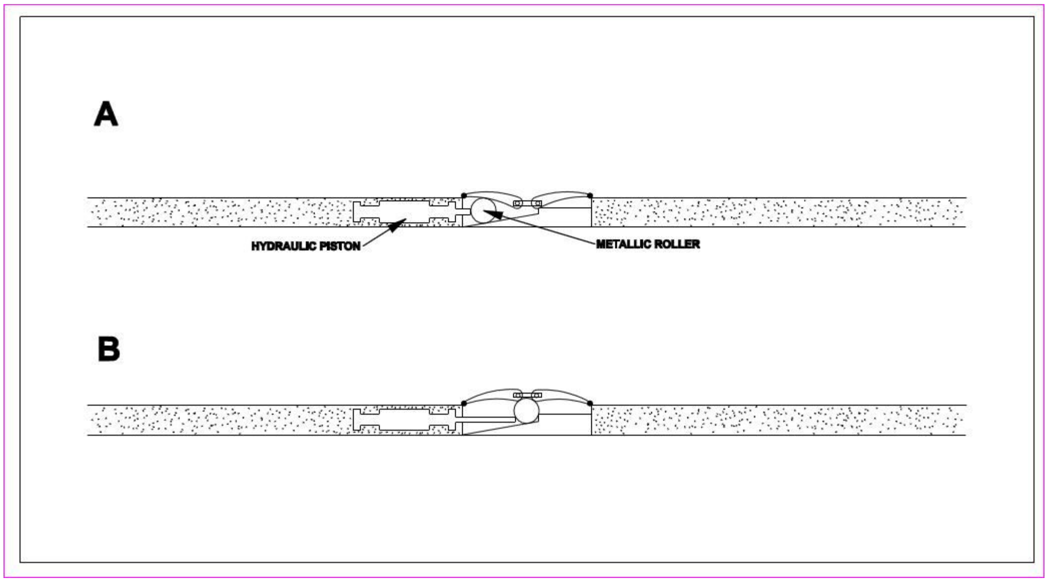

Figure 2-5 Design 2 (A) Retracted state and (B) Deployed state

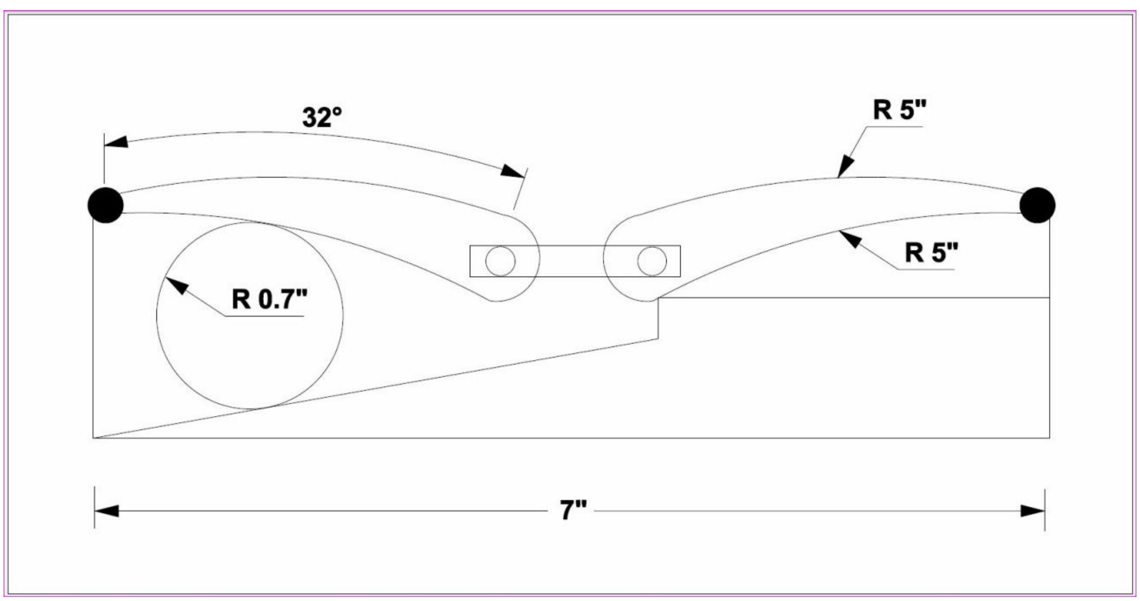

Figure 2-6 Design Dimensions for Design 2

The material to be used to build the components for the above design would be based on its ability to deliver the structural requirements while creating minimal noise. As in the previous design, the top surface of the panel shall provide the necessary grip for vehicles and prevent slippage. The bottom surface of the panel on the upstream side would be frictionless to allow smooth passage of the roller underneath. The downstream panel would be designed to create minimal noise when it returns to its original position to rest on the wedge. The design load for the components shall be the same as for the previous case, that is, the weight of a fully loaded 18-wheeler with a legal maximum weight of 34,000 lbs. per axle plus a factor of safety, in case some trucks are overloaded or travelling too fast, which may cause shock to the bump.

Design Evaluation

Each of the two designs for the device presented above must meet the functional requirements of the system. Functional requirements include speedy deployment and retraction, ability to withstand the aforementioned heavy loads and stresses and the ability to function in rough and inclement weather. Each of the designs must also be evaluated for their noise levels. If the noise is significant, sound insulation techniques should be considered. Besides performance, reliability and maintainability needs to be considered. Intrusion into the pavement might damage its structural integrity, which is another issue that needs to be considered and addressed.

Design 1 may be easier to install due to lesser pavement intrusion compared to Design 2, which requires installation of a hydraulic piston as well. In terms of noise, the main source appears be from the impact of the panels on the guide rod for Design 1 and from the movement of the roller in Design 2. If there is noise from vehicle tires coming in contact with the panels, alternate materials should be considered. Design 2 appears to be more reliable due to the use of a hydraulic piston, which can function under high stresses. The springs in Design 1 may deform over time and may no longer be able to push the panels up as needed. The pressure pipes for the hydraulic piston have the possibility of bursting under high stress. The cost of maintenance needs to be considered. The panels in Design 1 project out from the pavement surface and thus may be visible from a longer distance, giving the drivers time to respond and avoid surprising them. The height of the bumps can also be adjusted for Design 1. These strengths and weaknesses should be evaluated when testing is performed to aid in determining the suitability of each design in a given road environment.

Emergency Vehicle Preemption

Preemption systems are designed to give emergency response vehicles a green light on their approach to a signalized intersection while providing a red light to conflicting approaches. The most commonly reported benefits of using Emergency Vehicle Preemption include improved response time, improved safety, and cost savings. A study conducted by the U.S. Department of Transportation Intelligent Transportation Systems to increase awareness among stakeholders — including police, fire, rescue and emergency medical services (EMS) — about the benefits and costs of emergency vehicle preemption, states how the following jurisdictions were able to reap the aforementioned benefits:

a) Emergency vehicle preemption has allowed Fairfax County, Virginia, to reduce its response times. The system permits emergency vehicles along U.S. 1 to pass through high volume intersections more quickly with fewer conflicts, saving 30 to 45 seconds per intersection. The speed bumps would be installed at midblock locations away from intersections where there is no cross-traffic. So the time savings may not be as much. However, there would be no time lost needing to slow down for a bump. Preemption would also allow all other vehicles to clear out quickly and make way for the emergency vehicle to pass.

b) In addition, due to reduced delays at signalized intersections, the City of Plano could achieve the same response times with fewer fire/rescue and EMS stations

> than would normally be required, providing significant cost savings. The city has maintained a response time goal achievement rate of over 90 percent, contributing to its Insurance Services Office Class 1 Fire Suppression Rating - the highest possible rating on a scale from 1 to 10. (ITS 2006)

The speed bump may be equipped to receive an activation signal from a device mounted on an approaching emergency vehicle. The transmitter that is already installed on all emergency vehicles can be used to signal the speed bump preemption system of an approaching emergency vehicle.

Speed bump preemption ensures that emergency vehicles do not lose critical time slowing down at the bump. Vehicular devices can be switched on or off as needed, but in the case of emergency vehicles, they are frequently integrated with the vehicle's emergency warning lights. When activated, the traffic preemption device will cause the bump to automatically be retracted when the receiver senses an emergency vehicle approaching.

Internal Communication and Power System

The entire system needs to be connected by means of cables or wirelessly. There are two main links in the system: detector to controller and controller to the device. For the device to function properly, there links should have proper interconnectivity and uninterrupted communication.

A wireless communication system would be easier and less expensive to install due to savings in cost and efforts required for boring conduits for cables; however, the cost difference for procuring either of the systems appears trivial. Pavement invasive methods have to be used for installing cables, which may require lane closure. Also, with cables, a chance of breakage exists, which may lead to system failure and maintenance expenses. However, cables offer a higher degree of reliability and speed. The system would be exposed to rough weather conditions and thus reliability is pivotal.

The controller and the device would require external power in order to operate, and so would the detector, unless it is solar powered. Thus, there would be a need for laying cables to supply power to the system. Depending on the type of detector and controller used, the power needed would be either 24v, 12v or 5v DC, converted from 110v AC because the detectors have low voltage requirements. In some cases, such as for a laser detector, it may be more suitable to use solar power mounted on the same pole as the detector, rather than supplying external power. The bump deployment in Design 1 should not require significant power since the only power needed would be to engage the locks; however, it would be relatively higher for Design 2. More accurate power requirements can be estimated once a prototype for the design is built. An Uninterruptible Power Supply (UPS) system should be used to ensure undisrupted performance in case of a power outage.

Since cables have to be laid for supplying power, the additional cost of using a cable to link the system may not be significantly higher. If the advantage of speed and reliability are figured in, it may even be more feasible.

Key Engineering Issues

The development as well as installation of the Smart Speed Bump would involve dealing with the following engineering issues:

1. Bump being deployed for a vehicle/bicycle in front of a speeding vehicle: This can happen when the vehicle in the front has not travelled past the bump completely. This can be resolved by having a presence detector right at the bump, which would delay the detection sufficiently to allow the front vehicle to clear the bump. The bump should be split at the center with a gap adequately large for a bicycle to be able to pass unhindered.

2. Multi-lane roads: The most common application for the speed bump system would be a two lane roadway such as local streets or collectors. Other common applications would include roadways with higher pedestrian traffic or speed sensitive areas such as a school zone.

   However, there might be certain issues arising out of multi-lane use:

   i. Drivers attempting to change lanes right before the bump to avoid having to go over it. This can be resolved by having the detection so close to the bump that a lane change may not be possible between the detection zone and the bump.
   ii. For a two lane roadway, changing lanes can be particularly risky. To resolve this, there can be two possible solutions:
       a. The detection zones in such situations can be installed on both sides of the bump. This would force the vehicle attempting to avoid the bump in its lane to still be penalized by the bump in the adjacent lane.
       b. Where practicable, pylons or lane separators can be installed to disallow lane changing in the vicinity of the bump.

3. Component testing: First, each of the primary components of the speed bump system shall be evaluated and rated individually and in an isolated manner:

   a) *Detector*: The detector chosen should meet all the requirements noted under 'Detector' section, that is, it should be able to detect presence and measure the speed of all approaching vehicles from both directions and report it lane wise to the controller. Also, the detection zones should be located as close as possible to the bump so that no lane change occurs between detection and bump deployment. For this to be practical, the detector needs to be fast enough to detect the speed and report it quickly enough for the controller to process and meet the deployment or retraction time requirements. Besides the detector upstream, a presence detector downstream might be needed as discussed previously. The detectors would primarily be rated for their accuracy, swiftness and market cost. Also, observations may be made during inclement weather to understand reliability under various environmental conditions.

b) *Controller*: The primary job of the controller is data processing. Once speed data is obtained from the detector, it would be compared with the fixed threshold value of speed plus tolerances, if any. Based on the result, an appropriate signal would be sent to the deployment mechanism. The controller shall be rated primarily on its capability to take inputs from all detectors, its memory, and its processing speed.

c) *Deployment/Retraction mechanism*: This mechanism would primarily be rated on its speed, noise, robustness and the ability to deliver expected performance. The mechanism needs to be able to move fast enough to deploy the bump before a vehicle gets to it. The locking mechanism in case of Design 1 and the roller in case of design 2, needs to be able to withstand the weight of a fully loaded semi-tractor trailer. Observations should also be made during inclement weather and other environmental conditions to understand its reliability for all weather conditions.

4. Pavement Integrity: Pavement intrusion might cause pavement structural integrity issues. Heavy braking by truck drivers might cause further deterioration of the pavement surface. Prototype testing and further research would help address these issues.

Car-following Analysis

The General Motors (GM) car following model, which is a microscopic traffic flow model, can be used for analyzing approaching traffic. Its theory is amongst the most popular because of its agreement with field data. The car following model proposed by General Motors is based on follow-the leader concept. This is based on two assumptions: (a) the higher the speed of the vehicle, the greater the spacing between the vehicles and (b) to avoid collision, a driver must maintain a safe distance with the vehicle ahead. As proposed by the GM car following model, the acceleration of the follower vehicle depends upon the relative velocity of the leader and the follower vehicle, sensitivity coefficient and the gap between the vehicles.

Consider the following possible scenarios of approaching vehicles:

1) Single isolated vehicle

   For a single vehicle, the system should be able to detect the vehicle speed and deploy or retract the device before the vehicle gets to the bump. Assuming that the driver does not change lanes to avoid the bump (as covered under 'aggressive driver' scenario), the detection zone may only need to be about one car length in advance.

2) Vehicle Platoon

   For a platoon of vehicles passing the detection zone, the speed of the leading vehicle may be considered as representative of the speeds of the following vehicles. If the lead vehicle is travelling within the speed limit, the vehicles that follow it would be forced to drive within the limit, too. In this case, the bump may be retracted for all the vehicles in the platoon. However, if the lead vehicle is detected as speeding, the bump would be deployed and the vehicle would be forced to slow down and go over the bump. This would lead to a reduction in gap between the lead vehicle and the following vehicle and as proposed by the GM model, the driver of the following vehicle would decelerate to adjust his speed accordingly. The bump can then be retracted until a speeding vehicle is detected.

3) Dispersed Platoon

   In a platoon that is dispersed due to no other traffic control devices on the road for a considerable length, there might be sufficient headways for the drivers to drive at speeds independent of that of the vehicle in front of them. Drivers may even change lanes to continue at their desired speeds when vehicles in front of them are going considerably slower than them or are decelerating for the speed bump in front of them. In this case too, the required detection zone would be starting about one car length in advance, assuming that no lane change takes place between the detection zone and the bump.

4) Aggressive driver

Some drivers may attempt to evade the bump by changing lanes after passing through the detection zone. To overcome this problem, yielding lane separators should be used to prevent lane changing. The detection zone should also be extended closer to the bump if lane separators are not used. This would also ensure that once the driver moves from the subject lane to the target lane, the next vehicle in the subject lane is not unnecessarily penalized.

Once individual testing is completed, a prototype of each design shall be built. The prototypes would measure some important variables in order to gain a better understanding of the efficiency of the current design. For this, the finished prototype of the complete system may need to be installed on an actual street after obtaining all relevant permissions and installing proper signs and markings. Observations can be made using video cameras fixed at inconspicuous locations. Measurements for speeds should be taken as well. This would enable determining accuracy in bump deployment and driver response. Observation vehicles equipped with accurate speedometers may also be run along the road to collect data on detector accuracy and to understand effect on ride quality, easiness/difficulty in controlling the vehicle and driver discomfort caused. The vehicle suspensions should also be studied for possible damage after a significant number of runs over the speed bump. Some of the key variables that need to be observed have been identified below:

i. Driver response: Introduction of this system would require proper signage to inform road users of the sign. Ideally, drivers should respond exactly as they would when the encounter a conventional speed bump. A key difference, however would be that those driving within limits need not slow down further; all others must slow down or expect a bump. Another observation would be to study the effect of reducing a type of error versus the other. Does a conservative speed tolerance or threshold cause driver frustration? Road surveys may be necessary to evaluate this. Any variations in this shall be noted and studied so that the underlying cause may be determined and addressed appropriately.

ii. Accuracy in speed measurement: The primary purpose of this is to find out whether or not the bump deployed when it should have, and when it should not have. This would also help determine the most suitable detector for speed measurement. Both magnitude as well as type of error shall be measured.

iii. Detection time: this shall be defined as the time needed for the detector to sense the presence of an approaching vehicle and measure its speed. Videotaping a segment of the road with a marked point of the beginning of detection zone shall give a time stamp of the vehicles entry into the zone. Another time stamp shall be obtained from the controller firmware to check when the speed data was received. The difference between the two times shall give the detection time. Any other technique may be used to make this observation as well.

iv. Processing time: this shall be defined as the time needed for the controller to process the data obtained it and to send an appropriate signal to the bump deployment device. This would be instrumental in rating the effectiveness of the controller. The model of the controller employed shall play an important role in determining processing speeds. Model 170 (or similar) should be evaluated first for its ability and speed to process input data. More powerful models such as the 2070 may be considered as an alternate.

v. Deployment time*: this shall be defined as the time needed to bring the bump into a deployed position after receiving appropriate signal from the controller when a speeding vehicle has been detected.

vi. Retraction time*: this shall be defined as the time needed for the bump to retract after remaining deployed for a vehicle.

*Deployment and retraction time would be applicable only when a speeding vehicle is detected.

Measuring the time for each of the processes listed above is needed to determine how far in advance the detection zone needs to be.

Limitations

An important limitation of the Smart Speed Bump would be its inability to remain operational in snow conditions. If snow gets underneath the panels then it would interfere with the ability of the device to move the panels freely. Heating beneath the panels can help alleviate this problem but that would increase the overall cost of the system. Alternatively, the system can be turned off and the bumps retracted during snow conditions. This can be done by adding a WIMAX system (which is already used on many traffic signal controllers) to the controller, which would override normal system operations remotely.

Test Strategy

Two types of product development strategies are generally used: model and simulate, or prototype and test. The first involves creating a virtual model of the system and simulating its working to understand any gaps in the design using advanced computer software. The second involves building a physical model of the design and testing it on a paved surface. While sophisticated, computer-driven tools with modeling and simulation capabilities are available in the market, and in some cases prove to be a more efficient product development strategy compared to prototyping and testing, prototypes are generally more trusted. Prototyping allows for a direct observation and understanding of the design, and how well it works. In case it fails, it would be easier to identify and correct the component of the design, which is causing the failure.

In the case of a smart speed bump, the key variables previously noted need to be measured before a simulation model may be used. Thus, the most economical way to test would be to test a prototype at various locations and make several observations and then simulate for a variety of speed limits, traffic densities, driver types, lane configurations and other such conditions which may influence the efficiency of the system. Testing should also be performed for different times of day or days of week.

Each of the designs need to be tested by reducing each of type I and type II error. This means at least four different locations would be required to completely test both designs (that is all possible combinations of ‘design’ and ‘error type reduced’). The testing, as previously noted, would be done at four different locations after obtaining the necessary clearances from local authorities. The time frame for testing should be long enough to gather data for a sample size that may be considered representative of the annual average daily traffic (AADT) on the given roadway. Longer time frame would also give a better understanding of the reliability of each design. The springs in Design 1 and the hydraulic pressure pipes in design 2 need to be tested for fatigue under repeated stresses of traffic. The system should continue to operate in inclement weather such as heavy rain. Roadside surveys would help gain a better insight into driver behavior.

Chapter 3

Conclusion

Pedestrians need to be a prime consideration while designing streets. This would ensure greater safety for non-motorized road users and particularly for older adults, children and people with disabilities. The Smart Speed Bump is one of those elements that can contribute to increasing pedestrian safety.

Smart Speed Bumps would prove to be a pivotal innovation in pedestrian safety, especially in school zones and roads with heavy pedestrian or vehicular traffic. The implicit speed enforcement and the savings in public spending thereby shall offset part of the costs associated with the installation of a new bump.

The bump acts as a deterrent to speeding vehicles, which serves the purpose of its design. Perhaps more important, its effectiveness as a traffic calming device is independent of driver obedience. The selective deterrence ensures that law abiding drivers are not punished and thus keep from antagonizing them. The systems installation would thus be met with no or lesser public resistance compared to conventional bumps. The preemption system eliminates concerns related to bumps affecting emergency response times. The bump would cause fewer vehicles to brake and accelerate thereby reducing the pollution any other traffic calming device may create.

Further Research

There is scope for further research in designing the ideal traffic calming solution for urban areas.

i. Using V2I as ‘Virtual Speed Bumps’: The V2I technology may also be used to create virtual speed bumps when the technology matures sufficiently. A Virtual Speed Bump is one that does not exist physically, yet has the effect of a traffic calming device (by means of giving warning signals to the driver, causing him to slow down). In the future, a separate module similar to V2I but in the reverse direction, that is Infrastructure to Vehicle communication may be used as a virtual speed bump. In locations where it is desired, the infrastructure can be programmed to communicate the speed limit on a particular street to all vehicles using that street. There can be two different ways of using the speed information when any vehicle exceeds the speed limit on that road:

a. It can be used to warn the vehicle driver of over speeding by means of a beeping signal inside the vehicle or some other on-dash communication systems. This would provide the driver of the vehicle with a reminder to slow down. This is important particularly in school zones when the driver may have not noticed the school zone speed limit warning sign.

b. The second approach would be to compel the vehicle to slow down rather than just warning the driver of over speeding. The infrastructure can signal the Engine Control Unit (ECU), which is already built into almost all cars on the roads today. The ECU is designed to limit a vehicles speed by restricting the flow of air and fuel to the engine and even the sparks that cause combustion. The speed would be limited after the vehicle exceeds the tolerance threshold, for example, in a 20 mph speed zone the Virtual Speed Bump may be invoked when the speed exceeds 25 mph. This would eliminate the need to use any other traffic calming device and would help enforce speed limit particularly in school zones. However, compelling drivers to slow down might be considered as intrusive and might result in possible public resistance.

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Biographical Information

Mohammed Shakir Rajani was born March 21, 1991 in Mumbai, India. He earned his Bachelor in Engineering in Civil Engineering from University of Mumbai in 2012. In 2013 he joined the Master of Science in Civil Engineering at the University of Texas at Arlington.

Mohammed has received scholarships and grants during his graduate studies at the University of Texas at Arlington. He was awarded the *Transportation Research Center for Livable Communities (TRCLC)* grant for research on smart speed bumps. While pursuing his degree, Mohammed served as the Vice President of the student chapter of the Institute of Transportation Engineers (ITE) at his college. He interned at Ergonomics Transportation Solutions, Inc., a traffic engineering firm in Houston, Texas and is currently a full time engineer.

Mohammed plans to pursue his research further and build a prototype based on it. He would like to continue his research in the field of transportation to help improve the safety and efficiency of the entire transportation system.