tions of Rumble Areas. Report TRRL SR 292. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1978.
7. R.D. Helliar-Symons. Yellow Bar Experimental Markings--Accident Study. TRRL LR 1010. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1981.
8. R. Barkan, D. Zaidel, and A.S. Hakkert. Factors Influencing Deceleration Patterns on Interurban Intersection Approaches (in Hebrew). Road Safety Centre, Technion-Israel Institute of Technology, Haifa, 1981.
9. N. Enustun. Three Experiments with Transverse Pavement Stripes and Rumble Bars. Report STD-RD-216-72. Traffic and Safety Division, Michigan Department of State Highways and Transportation, Ann Arbor, 1972.
10. K.R. Agent. Transverse Pavement Markings for Speed Control and Accident Reduction. Division of Research, Kentucky Bureau of Highways, Frankfort, 1975.
11. G.M. Burney. Behaviour of Drivers on Yellow Bar Patterns--Experiment on Alton By-Pass, Hampshire. Supplementary Report SR 263. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1977.
12. R.L. Sumner and J. Shippey. The Effects of Rumble Strips at the Dartford Tunnel. TRRL 169UC. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1975.
13. A.J. Jobson and B.E. Fernie. Rumble Devices: Evaluation of Two Types at Park Rynie, Natal. Report RF/6/75. National Institute for Road Research, Pretoria, South Africa, 1975.
14. H.E. Pettersson. Rumble Strips Geometric Design and Behavioural Effects. Report 80. National Swedish Road and Traffic Research Institute, Stockholm, Sweden, 1976.
15. M.L. Kermit. Rumble Strips Revisited. Traffic Engineering, Vol. 38, No. 5, 1968.
16. D.W. Hoyt. In Further Support of Rumble Strips. Traffic Engineering, 1968.

Publication of this paper sponsored by Committee on Traffic Control Devices.

A Further Note on Undulation as a Speed Control Device

KING K. MAK

ABSTRACT

Conventional speed bumps have sometimes been used as a passive means of controlling speed, but there are problems associated with them, such as damaging the suspension and front-end alignment of crossing vehicles and causing loss of control for drivers of two-wheeled vehicles under certain circumstances. The U.K. Transport and Road Research Laboratory (TRRL) developed a new speed control device known as an undulation (or speed hump) that eliminates many of the deficiencies associated with conventional speed bumps. This new design has been gaining acceptance in the United States; it has been installed in a number of cities and the results so far have been favorable. The results of a research study to evaluate the effectiveness of the undulation as a speed control device are reported. The study consisted of three parts: a speed study, an instrumented-vehicle study, and a questionnaire survey. The study results indicated that that the undulation design is an effective speed control device and is more desirable and acceptable than the conventional speed bump. The study results also suggested that the level of speed control can be varied by adjusting the height of the undulation for use with various speed limits.

Speed control on residential streets has long been a concern among traffic engineers. Some drivers tend to ignore the speed limit, thereby creating a hazardous condition to pedestrians and other motorists. It may be possible to alleviate the speeding problem by increased law enforcement or a safety campaign, but the effects are mostly short lived. It is sometimes necessary to resort to some form of passive speed control device.

One commonly used passive speed control device is the conventional speed bump. Typical dimensions of a speed bump are a height of up to 6 in. and a length (in the direction of vehicle travel) of up to 3 ft.

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Although widely used, conventional speed bumps present problems in both safety and operations. A vehicle crossing a speed bump at even low to moderate speed receives a severe jolt, which could result in damage to the suspension and front-end alignment of the vehicle. On the other hand, the jolt felt by the occupants of the vehicle varies fairly little and may even lessen with speed. This results in a hazardous situation in which most drivers will come to an almost complete stop before crossing the speed bump, whereas a few reckless drivers may actually speed over the bump. In addition, drivers of two-wheeled vehicles have been known to experience loss of control under certain circumstances.

The U.K. Transport and Road Research Laboratory (TRRL) developed a new speed control device known as an undulation (or speed hump) that eliminates many of the deficiencies associated with conventional speed bumps (1-4). The undulation design, as shown in Figure 1, differs from the conventional speed bump in that it has a length (in the direction of travel) of about 12 ft, approximately 1 1/2 times the average length of a subcompact car's wheelbase, and a parabolic profile with a maximum height of 4 in. Vehicle occupants crossing an undulation experience an uncomfortable rocking motion which intensifies with speed.

The TRRL reports that the undulation design appears to be effective in reducing vehicle speed and traffic volume as well as being beneficial to safety on a residential street and is favored by the majority of drivers. The undulation design has also been gaining acceptance in the United States and undulation humps have been installed in a number of cities. The results so far have been favorable (5,6), although there are still some who oppose any kind of speed control device (7).

Two series of undulations, one with five undulations and the other with two, were installed on two separate roadways on the grounds of Southwest Research Institute (SwRI) in San Antonio, Texas. These undulations were installed in response to expressed concern over speeding on these roadways and the accompanying hazards to pedestrians and other motorists. The average free-flow speed before the installation of these undulations was in excess of 30 mph on one roadway and above 35 mph on the other despite a posted speed limit of 25 mph.

The specifications for these series of undulations were a length of 13 ft, a maximum height of 4 in. with a parabolic profile, and a spacing of 300 ft between undulations. Note that the specified length of the undulation is 13 ft instead of the TRRL design length of 12 ft, because the average vehicle in the United States is larger and longer than that in the United Kingdom.

A research study, sponsored by SwRI, was conducted to evaluate the effectiveness of the undulation as a speed control device, the results of which are presented in this paper. The research study consisted of three parts:

1. Speed study,
2. Instrumented-vehicle study, and
3. Questionnaire survey.

For comparison purposes, a conventional speed bump on a third roadway, also with a speed limit of 25 mph, was included with the seven undulations. The conventional speed bump has a maximum height of 5 in. and a length of 12 in.

SPEED STUDY

With time-lapse video photography, vehicle speed data were collected at the seven undulations and the conventional speed bump. For this study, 216 hr of data and more than 8,000 vehicles were recorded. A sampling scheme, based on time of day and vehicle type, with oversampling during hours of darkness and for vehicle types other than passenger cars, was used. Also, only free-flowing vehicles were sampled, excluding following vehicles in a platoon and turning vehicles. Overall, 1,472 vehicles were sampled for study.

For each sampled vehicle, certain descriptive data were first recorded, including vehicle type, size, and direction of travel. Vehicle speed and acceleration-deceleration data were then obtained at nine different locations for each undulation and bump. The average speed profiles for the undulations and the conventional speed bump are provided in Figure 2. Speed and deceleration data are summarized in Table 1. Note that the 50-ft point is used as the reference for all speed-change and acceleration-deceleration data. Several trends are evident from the data:

1. The approach, crossing, and exit speeds are higher for the undulation than for the speed bump, although these speed differentials may partially reflect the differences between traffic characteristics of the roadways.
2. The speed changes are much higher for the conventional speed bump than for the undulation as are the acceleration-deceleration rates. This indicates much harder braking and faster speeding up at the conventional speed bump.
3. Most of the braking and acceleration occurs within 50 ft of the undulation or speed bump. The deceleration rate is fairly constant over the 50-ft

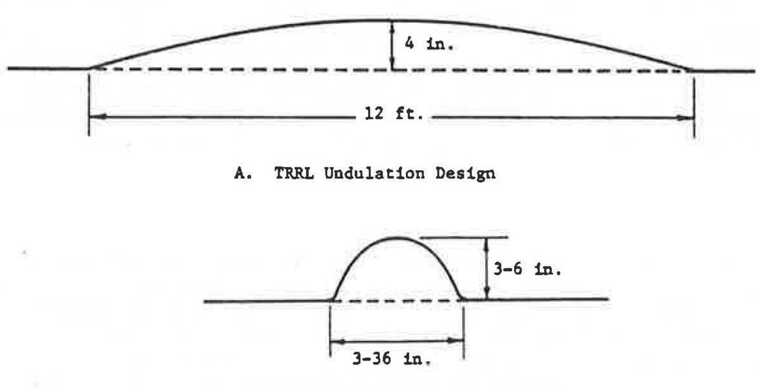

FIGURE 1 Comparison between undulation and speed-bump designs.

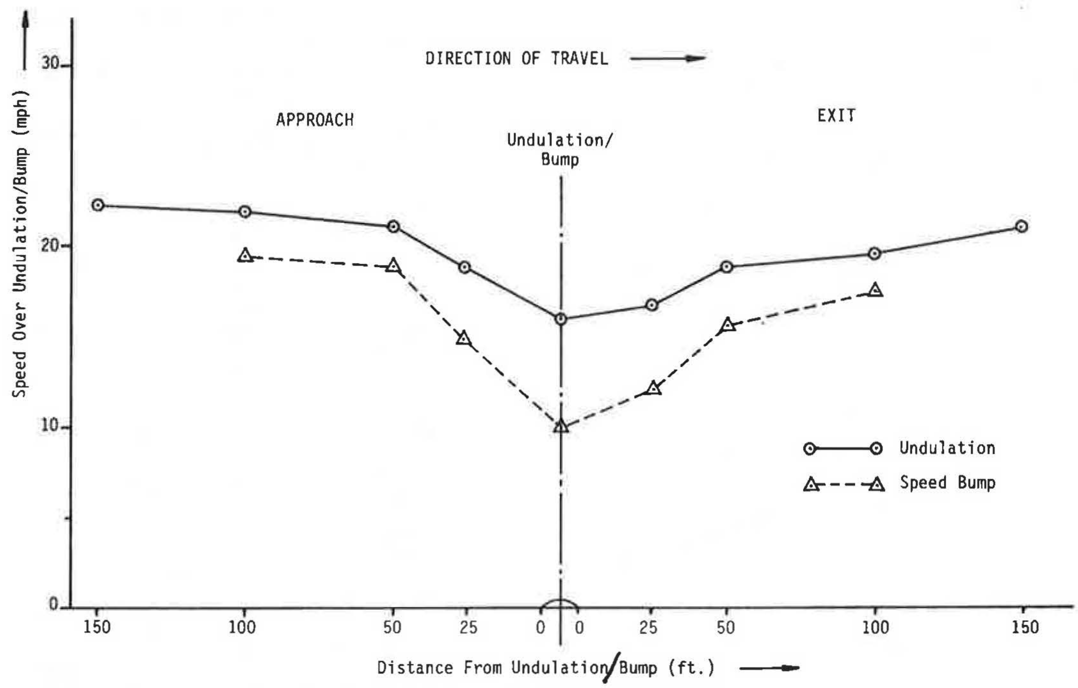

FIGURE 2 Average speed profiles for undulation and conventional speed bump.

TABLE 1 Speed and Acceleration-Deceleration Data

	Undulation	Conventional Speed Bump
Avg approach speed (mph) at 50 ft from undulation or bump	20.9	17.7
Avg crossing speed (mph)	15.9	9.8
Avg exit speed (mph) at 50 ft from undulation or bump	18.6	15.5
Speed change (mph)		
50 ft to undulation or bump	-5.0	-7.9
Undulation or bump to 50 ft	+2.7	+5.7
Acceleration-deceleration rate (ft/sec^2)		
50 ft to undulation or bump	-3.6	-5.0
Undulation or bump to 50 ft	+1.5	+2.6

Note: The minus sign denotes deceleration, whereas the plus sign denotes acceleration.

approach area. In comparison, the acceleration rate is lower in the first 25-ft exit area than in the 25- to 50-ft exit area, indicating that there is a short time lag after the vehicles cross over the undulation or speed bump before the drivers start to accelerate.

4. The highest average speed of 22.2 mph occurs in the mid-point between the undulations, as may be expected. The average speed is considerably lower than those before the installation of the undulations, indicating that the undulations are effective in controlling vehicle speeds. The 85th-percentile speed is around 28 mph, which is still higher than the posted speed limit of 25 mph.

There are marked differences in the speed profiles for the individual undulations. Some of the differences may be attributed to the location of the undulation and turning movements. However, much of the difference could be the result of variations in the physical dimensions of the undulations. The contractor did not construct the undulations according to specifications; the height ranged from 3.21 to 4.15 in. versus the specified 4 in. These variations are undesirable from the operational standpoint, but they provide an excellent opportunity to evaluate the effects of varying heights on the performance of undulations.

The undulation height, the crossing speed, and the speed change and deceleration rate at the 50-ft point are summarized in Table 2 for the individual undulations. It is evident from the data that the crossing speed decreases with increasing undulation height. Correspondingly, the speed change and the accompanying deceleration rate increase with increasing undulation height. In other words, as the height of the undulation increases, the speed of vehicles crossing it will be lower and there will be more and harder braking while approaching the undulation.

TABLE 2 Speed and Deceleration Data for Individual Undulations

Undulation No.	Height (in.)	Crossing Speed (mph)	Speed Change (mph)	Deceleration Rate (ft/sec^2)
1	3.35	20.4	-2.3	-1.96
2	4.15	14.0	-8.0	-7.87
3	3.93	17.1	-5.6	-2.40
4	3.58	15.1	-5.3	-4.79
5	3.43	15.3	-3.2	-2.70
6	3.86	14.6	-5.8	-4.42
7	3.21	18.2	-2.5	-2.51

Note: The minus sign denotes deceleration.

Linear regression equations relating the undulation height to the crossing speed, the speed change, and the deceleration rate were developed as follows and are shown in Figure 3:

Crossing speed = 35.03 - 5.13 (undulation height), $R^2 = 0.67$;

Speed change = 16.89 - 5.92 (undulation height), $R^2 = 0.92$;

Deceleration rate = 12.00 - 4.34 (undulation height), $R^2 = 0.51$.

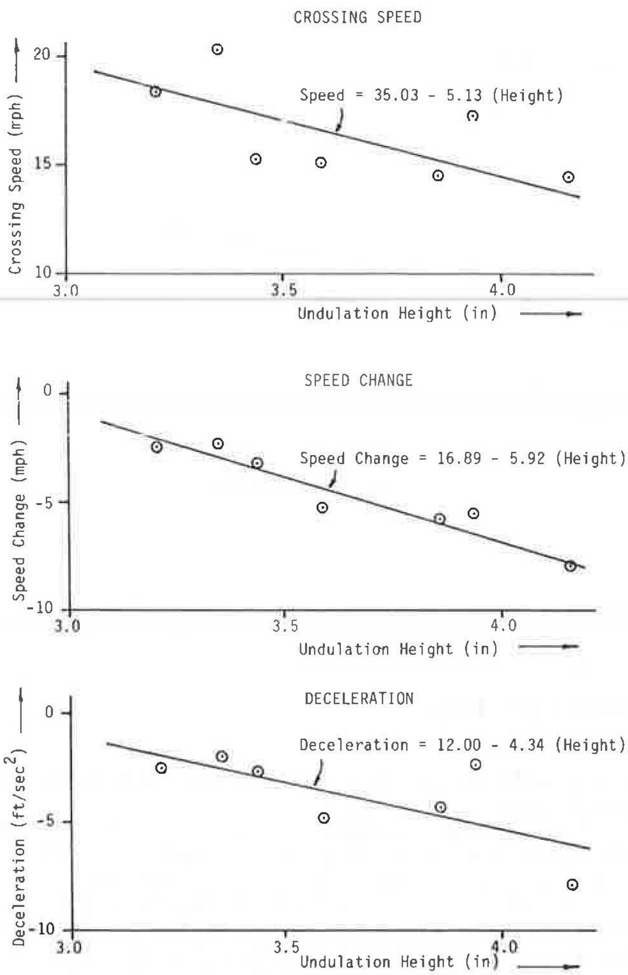

FIGURE 3 Relationships between undulation height and crossing speed, speed change, and deceleration rate.

These relationships can be used to estimate the level of speed control when the height of the undulations is varied. For example, with a undulation height of 3 in., the average crossing speed is expected to be 19.6 mph with the vehicle slowing down by 0.87 mph at a deceleration rate of 1.02 ft/sec^2. When the undulation height is increased to 4 in., the average crossing speed drops to 14.5 mph and the vehicle slows down sharply by 6.8 mph at a deceleration rate of 5.4 ft/sec^2.

Although the crossing speed is affected by the height of the undulation, the approach speed is not. In other words, the vehicle speed between undulations is not a function of the undulation height. Spacing between undulations may be a more important factor for traffic speed between undulations. However, it is not possible to evaluate the effect of spacing between undulations because a uniform spacing of 300 ft was used.

In terms of vehicle type and size, the observed differences in crossing speed, speed change, and deceleration rate are surprisingly minor for the undulation, as shown in Table 3. There are more variations for the conventional speed bump, but these are still relatively small compared with the differences between undulation and speed bump. As stated previously, the average crossing speed is considerably lower for the conventional speed bump than for the undulation, and the speed change and deceleration rate are much higher. This is best illustrated by motorcycles, which have the highest crossing speed (21.2 mph) and the lowest speed change (0.8 mph) when crossing the undulations. In sharp contrast, the crossing speed of motorcycles over the conventional speed bump is only 9.1 mph with a speed change of 10.1 mph.

TABLE 3 Speed and Deceleration Data by Vehicle Type

Vehicle Type	Crossing Speed (mph)	Speed Change (mph)	Deceleration Rate (ft/sec^2)
Undulation			
Passenger car			
Subcompact	16.3	5.2	3.49
Compact	16.2	4.6	3.51
Intermediate	16.1	5.2	4.25
Full size	15.9	5.1	3.63
Avg	16.1	5.0	3.72
Motorcycle	21.2	0.8	2.42
Pickup			
Small	15.9	5.4	3.61
Large	15.7	3.2	3.75
Avg	15.8	4.3	3.68
Van	13.8	5.6	3.00
Truck			
Single unit	15.0	4.0	2.72
Tractor-trailer	12.2	3.0	1.44
Avg	13.6	3.5	2.08
Speed Bump			
Passenger car			
Subcompact	10.6	7.4	5.70
Compact	9.7	8.0	4.07
Intermediate	10.5	7.6	5.28
Full size	11.2	8.0	4.70
Avg	10.5	7.8	4.94
Motorcycle	9.1	10.1	5.82
Pickup			
Small	7.5	9.2	5.23
Large	9.1	7.7	4.27
Avg	8.3	8.5	4.75
Van	7.8	8.7	5.39
Truck			
Single unit	6.0	11.0	6.78
Tractor-trailer	6.6	2.2	0.40
Avg	6.3	6.6	3.39

INSTRUMENTED-VEHICLE STUDY

The speed study described earlier provides information on the speeds at which the vehicles cross the speed control devices. An instrumented-vehicle study was then conducted to examine the vertical acceleration, measured in g-forces, experienced by the vehicle and its occupants while crossing the undulation or speed bump. The hypothesis is that the speed at which a vehicle crosses over the speed control device is a function of the vertical acceleration sustained by the vehicle and its occupants, which in turn is a measure of the level of discomfort experienced by the occupants.

The experimental setup took into account three major factors:

1. Speed control device type and dimension: Three undulations of high, medium, and low profiles (undulations 6, 5, and 7 in Table 2, respectively) and the conventional speed bump were selected for the study.
2. Vehicle type: Three test vehicles were used: a 1979 Ford LTD full-size car with extra-heavy-duty suspension, a 1979 Ford Pinto subcompact car with original equipment suspension, and a 1974 Chevrolet C-10 long-bed pickup truck with heavy-duty suspension.

3. Vehicle speed: The test speeds generally ranged from 10 to 40 mph in 5-mph increments. However, the upper limit of the speed range was determined also by the speed at which the vehicle suspension bottomed out in order not to damage the test vehicles.

Each test vehicle was instrumented with a biaxial accelerometer attached to the floorboard near the vehicle center of gravity and a triaxial accelerometer mounted in the head of a 50th-percentile male dummy seated, but unrestrained, on the right front passenger seat. A fifth wheel was used to monitor the vehicle speed. The test runs were also documented on 16-mm movie films for analysis of the vehicle motion.

Figure 4 shows the vertical acceleration traces of the vehicle and the unrestrained occupant for the Ford Pinto at 20 mph over the high-profile undulation and the conventional speed bump. The maximum positive (G_{max}), the minimum negative (G_{min}), and the resultant (ΣG) vertical acceleration readings are identified.

For the undulation, the vehicle moves upward as the front tires contact the undulation, resulting in a positive vertical acceleration. The vehicle comes down after crossing the undulation as indicated by the negative vertical acceleration. The vehicle then bounces a couple of times before returning to its normal position. The unrestrained occupant moves in the opposite direction to the vehicle with a slight time lag. In other words, the occupant moves downward as the vehicle moves upward. The peak vertical acceleration usually occurs when the vehicle comes down after crossing the undulation.

The acceleration pattern for the speed bump is very different from that of the undulation. The pulses are very sharp, but of relatively short duration. Also, the pulses from the front and rear axles are distinct; that from the rear axle is more severe. In comparison, the acceleration pattern for the undulation is more gradual and smooth.

Linear regression equations were developed to relate the vehicle crossing speed to the resultant vertical acceleration (ΣG_{Veh} and ΣG_{Occ}) experienced by the vehicle and the occupant (averaged over the three vehicles) for both undulations (averaged over the three undulations) and the conventional speed bump. The regression equations are as follows and are shown in Figure 5:

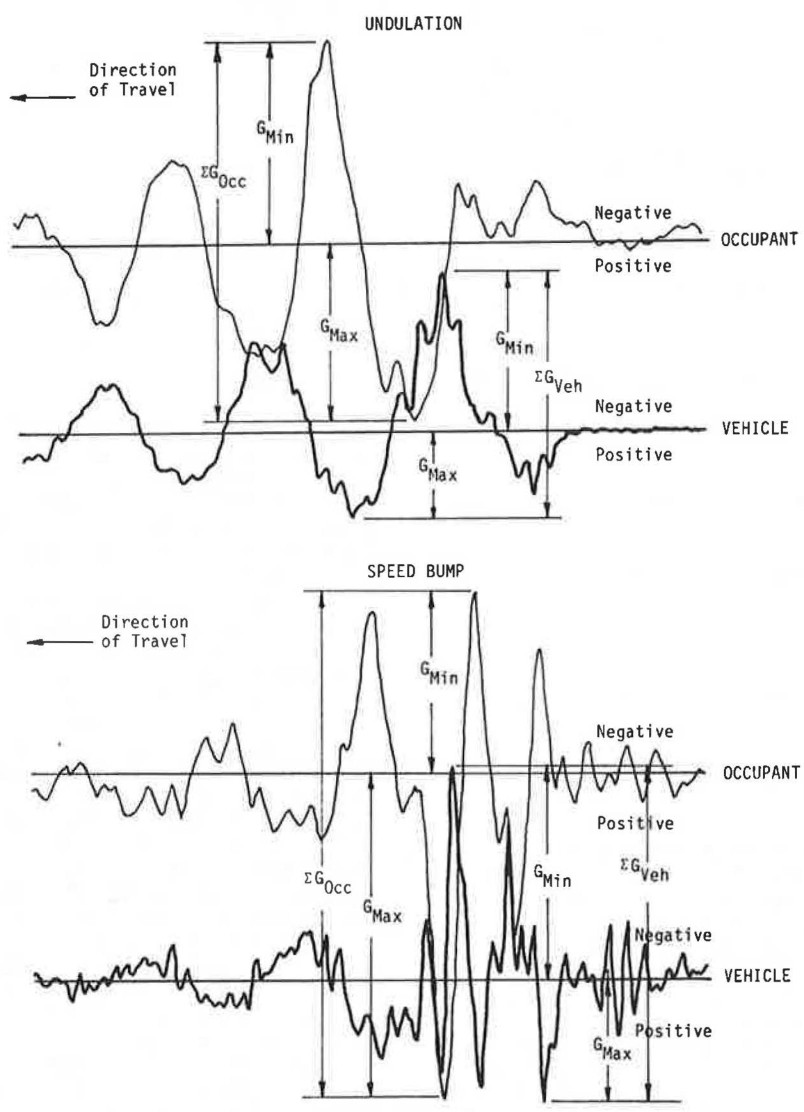

FIGURE 4 Acceleration traces of subcompact car at 20 mph.

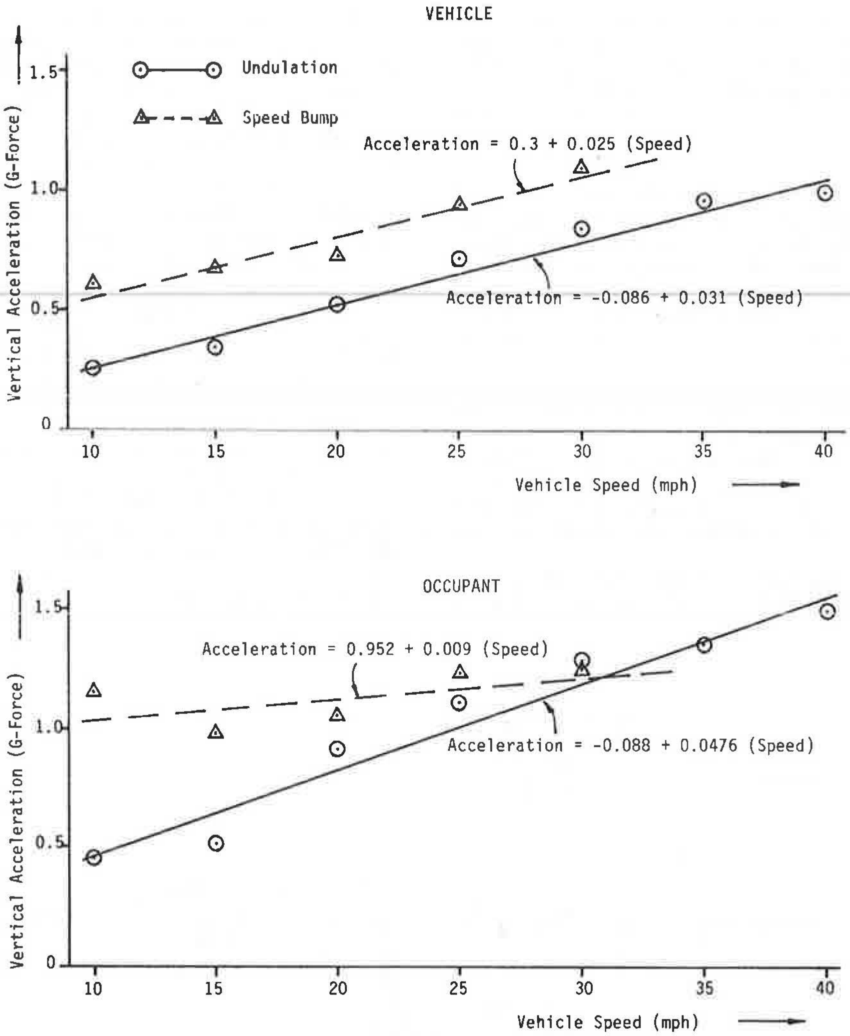

FIGURE 5 Average vertical acceleration as a function of speed.

Undulation:

Vehicle vertical acceleration = -0.086 + 0.031(speed), R^2 = 0.99;

Occupant vertical acceleration = 0.3 + 0.025(speed), R^2 = 0.94.

Conventional speed bump:

Vehicle vertical acceleration = -0.088 + 0.048(speed), R^2 = 0.94;

Occupant vertical acceleration = 0.952 + 0.009(speed), R^2 = 0.94.

The vertical acceleration experienced by the vehicle increases with higher crossing speed for both undulations and conventional speed bump. The rates of increase (as indicated by the slopes of the regression lines) are similar between the undulations and the speed bump, although the vehicle vertical acceleration for the speed bump is consistently more severe than that for the undulations.

The key difference between the undulations and the conventional speed bump is in the vertical acceleration experienced by the unrestrained occupant. Although the occupant vertical acceleration increases with higher crossing speed for the undulation, there is little change in that for the speed bump. At speeds of below 20 mph, the vertical acceleration experienced by the occupant is much higher for the speed bump than for the undulations. Then, as the crossing speed increases, the occupant vertical acceleration for the undulations catches up and eventually surpasses that of the speed bump.

This supports the contention that the undulation is a more desirable speed control device than the conventional speed bump. The undulation design provides a relatively smooth ride at low speeds and allows the drivers to maintain a somewhat constant speed. However, as the vehicle speed increases, the vertical acceleration experienced by the vehicle and its occupant(s) also increases proportionately, thus discouraging the driver from speeding.

On the other hand, vehicles crossing the conventional speed bump receive a severe jolt even at low speeds, thus fostering the pattern of hard braking before crossing the speed bump followed by rapid acceleration after crossing the speed bump. Furthermore, the vertical acceleration experienced by the occupant increases very little with higher speed so that the speed bump is not particularly effective against excessive speeding.

As for comparisons between the three undulations with high, medium, and low profiles, the data clearly indicate that more severe vertical acceleration is associated with greater undulation height, particularly for the occupant. This is in total agreement with the previous finding that lower vehicle speed is associated with greater undulation height.

Of the different vehicle types, the subcompact car fares the worst, as may be expected with the suspension bottoming out above 20 mph. The rear suspension of the unladen pickup truck tends to bounce excessively. This results in high occupant vertical acceleration for the conventional speed bump, even at relatively low speeds.

Despite the substantial differences in vertical acceleration among the three vehicle types tested, results of the speed study presented earlier indicate that there is little difference among their crossing speeds. This suggests that the drivers of small cars and pickup trucks tolerate higher levels of vertical acceleration in order to keep up with the average traffic flow.

QUESTIONNAIRE SURVEY

A questionnaire survey was conducted to solicit the opinion of SwRI employees on the appropriateness and effectiveness of the speed control devices. The questionnaire was sent to 20 percent (398) of the SwRI employees selected at random and the response rate was a high 48.2 percent (198). The questionnaire had nine multiple-choice questions with space provided for written comments. Although the respondents may not necessarily be representative of the overall population, their responses do provide some indication of the expected level of acceptance of the undulation design by the driving public. Highlights of the questionnaire survey results are as follows.

The majority (66.3 percent) of the respondents prefers the undulation over the conventional speed bump (8.9 percent), although one-quarter (24.7 percent) of them do not like either of the speed control devices and some believe that stricter enforcement of the speed limit is a better solution.

Nearly half (49.4 percent) of the respondents indicate that they usually come to a complete or near stop before crossing the conventional speed bump, and one-third (32.0 percent) indicate hard braking before the speed bump. In contrast, almost all respondents (96.8 percent) reply that they either maintain constant speed or only brake lightly while crossing the undulation.

Some of the written comments and complaints are informative and helpful to future installations of undulations. Some respondents point out that the undulations are not uniform in their behavior and that they are poorly signed and delineated and difficult to recognize, especially under adverse lighting or weather conditions. Also, some respondents complain that they were not informed in advance of the undulation installations nor advised of the proper speed at which to cross.

These comments point to the importance of advance public information and education before the installation of the undulations because the undulation design is new to the driving public. The undulation should be properly signed and delineated to advise the motorists of the presence of the speed control device and the appropriate crossing speed. Finally, care should be taken in the construction of the undulations to ensure that they are constructed according to specifications.

Overall, the respondents favor the undulation over the conventional speed bump by an overwhelming margin. They recognize the more desirable characteristics of the undulation design and have adjusted their driving behavior accordingly. However, there is considerably objection to any form of passive speed control device, as may be expected. This suggests that undulations, though superior to the conventional speed bump, should only be used sparingly, confined to locations where speeding creates an unacceptably hazardous condition and other less drastic speed control measures have failed to achieve the desired results.

SUMMARY OF FINDINGS

• The undulation design is a very effective speed control device. The average speed was reduced from more than 30 mph to approximately 16 mph at the undulations, with a high of 22.2 mph between the undulations.

• The undulation design is more desirable because it overcomes many of the drawbacks associated with the conventional speed bump. It provides a smoother ride at low speeds and allows the drivers to maintain a somewhat constant speed without hard braking and rapid acceleration while discouraging excessive speeding. It is also safer for motorcycles because it eliminates the sharp jolts to the vehicle suspension. The undulation design is also more acceptable to the majority of the drivers than the conventional speed bump.

• The level of speed control can be varied by adjusting the height of the undulation. The recommended undulation heights for various speed limits are as follows:

	Undulation Height (in.)	
Speed Limit (mph)	Minimum	Maximum
25	3.75	4.0
30	3.0	3.25

• The driving public should be advised of the undulations and the appropriate crossing speed before their installation through public hearings or the news media. The undulations should be properly signed and delineated. Care should be taken to ensure that the undulations are constructed according to specifications. These measures would help with public acceptance and minimize future complaints and liability.

• The undulation design is not a panacea to the speeding problem, but simply one of the many means of speed control available to the highway engineer. It should be used judiciously and only after other less drastic measures, such as increased law enforcement or a community safety campaign, have failed to achieve the desired result, because any form of passive speed control device will penalize the good as well as the bad drivers.

ACKNOWLEDGMENTS

The work reported here was conducted while the author was with Southwest Research Institute (SwRI). The author wishes to thank SwRI for support of the study and the permission to publish the study results. The assistance of Larry Peterson in the conduct of the study is also gratefully acknowledged.

REFERENCES

1. G. Watts. Road Humps for the Control of Vehicle Speeds. TRRL Report LR597. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1973.
2. R. Sumner, J. Burton, and C. Baguley. Speed Control Humps in Cuddelsdon Way, Cowley, Oxford. TRRL Report SR350. U.K. Transport and Road Re-

search Laboratory, Crowthorne, Berkshire, England, 1978.
3. R. Sumner and C. Baguley. Speed Control Humps on Residential Roads. TRRL Report LR878. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1979.
4. C. Baguley. Speed Control Humps--Further Public Road Trials. TRRL Report LR1017. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1981.
5. D. Smith and D. Appleyard. Improving the Residential Street Environment. Report FHWA/RD-81/031. FHWA, U.S. Department of Transportation, 1981.
6. J.P. Clement. Speed Humps and the Thousand Oaks Experience. ITE Journal, Vol. 53, No. 1, Jan. 1983.
7. P.C. Box. Letters to the Editor. ITE Journal, Vol. 53, No. 3, March 1983.
8. K.K. Mak. Evaluation of Undulation as a Speed Control Device. Final Report: SwRI Project 06-9342. Southwest Research Institute, San Antonio, Tex., June 1983.

Publication of this paper sponsored by Committee on Traffic Control Devices.

Abridgment

Analytical Warrant for Separate Left-Turn Phasing

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ABSTRACT

The development of a new volume warrant for left-turn phasing at signalized intersections is presented. The concept is to maintain a fixed volume-to-capacity (V/C) ratio for all intersection movements. Thus left-turn phasing would be warranted when the unprotected left-turn V/C ratio exceeds that of through traffic. Left-turn capacity is derived from formulas in the Highway Capacity Manual and the Australian Road Research Board Capacity Manual. The warrant also combines both signal-timing and capacity-analysis procedures. The proposed warrant has been compared with other methods found in the literature and the results are, in general, favorable. This study is preliminary in nature; its scope is limited to four-legged intersections with one through lane and an exclusive left-turn lane of adequate length on all approaches. No adjustments for trucks, buses, or pedestrian interference are considered. Finally, it is understood that traffic signal parameters are selected according to Webster's optimum settings for fixed-time signals.

The provision of separate left-turn phasing at intersections has been the subject of considerable research. The need for developing guidelines for left-turn phasing stems from an absence of uniform criteria in the Manual on Uniform Traffic Control Devices (MUTCD) (1) and the need to formulate consistent policies regarding left-turn treatments at signalized intersections.

The majority of left-turn warrants follow these general criteria:

1. Left-turn delay exceeds a prespecified threshold (e.g., 30 sec),
2. Left-turn volume exceeds a threshold [e.g., 100 vehicles per hour (vph)],
3. The product of left-turn volume and opposing traffic exceeds a prespecified threshold (e.g., 50,000 or 100,000),
4. Left-turn volume-to-capacity (V/C) ratio exceeds a threshold (e.g., 0.70 to 0.90), and
5. Number of left-turn-related accidents reaches a prespecified threshold (e.g., four accidents per approach per year).

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Methodologies for developing these guidelines have included microscopic simulation modeling (2,3), analytical models calibrated with field observations (4), and comprehensive studies of accidents, conflicts, delay, and gap-acceptance parameters (5).

Several observations are noted from the literature:

1. Although it is evident that left-turn capacity is affected by the amount of volume and green time to the opposing flow (V_0 and g/c, respectively), many studies have dealt with these two parameters independently. Yet all signal-timing methods relate signal splits (g/c) to the critical-flow ratio (V/S). In fact, Messer has shown that improved unprotected left-turn operations can be expected by optimizing the signal settings alone (6).