TEXAS
TRANSPORTATION
INSTITUTE

STATE DEPARTMENT
OF HIGHWAYS AND
PUBLIC TRANSPORTATION

COOPERATIVE
RESEARCH

THE INFLUENCE OF ROADWAY SURFACE HOLES ON THE POTENTIAL FOR VEHICLE LOSS OF CONTROL

RESEARCH REPORT 328-2F
STUDY 2-18-81-328
PAVEMENT EDGES

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-83/ +328-2F		

4. Title and Subtitle	5. Report Date
The Influence of Roadway Surface Holes on the Potential for Vehicle Loss of Control	August, 1983
	6. Performing Organization Code
	8. Performing Organization Report No. 328-2F
7. Author(s) Richard A. Zimmer and Don L. Ivey	
9. Performing Organization Name and Address: Texas Transportation Institute, The Texas A&M University System, College Station, Texas 77843	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. 2-18-81-328
12. Sponsoring Agency Name and Address: State Department of Highways and Public Transportation, Austin, Texas 78701	13. Type of Report and Period Covered: Final - September 1982 August 1983
	14. Sponsoring Agency Code

15. Supplementary Notes

Research preformed in cooperation with DOT, FHWA.
Study Title: Pavement Edges, Roadway Discontinuities and Vehicle Stability

16. Abstract

Holes in pavement or 'Potholes' have long been a source of aggravation for the motoring public and possible causes of accidents. It is the safety related aspect of potholes that has been investigated by Texas Transportation Institute, sponsored by The Texas Department of Highways and Public Transportation. The research concentrated on establishing baseline data from four typical passenger vehicles impacting holes of various lengths and depths with square edges. The study involved field tests, test track work and computer modeling. Various controlled experiments were conducted at the TTI Proving Ground to establish the drop rate of different vehicle suspension systems. These drop rates or trajectories were then used with observed tire deformation effects to determine limits of safety.

The stability of the vehicles striking relatively large potholes was found not to be affected, in that the path was not changed. The only safety related influence of holes identified in this study was damage to tires and rims, with the associated potential for an air-out. The incipient points of potential safety related damage in terms of hole length, depth, vehicle speed and vehicle type has been defined and presented in this study.

17. Key Words	18. Distribution Statement
pavement edges, edge drops, maintenance safety, vehicle stability	No restrictions. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	41	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

THE INFLUENCE OF ROADWAY SURFACE HOLES ON THE POTENTIAL FOR VEHICLE LOSS OF CONTROL

by

Richard A. Zimmer
Head, Proving Grounds
Texas Transportation Institute

and

Don L. Ivey
Research Engineer
Texas Transportation Institute

Research Report 328-2F
Research Study Number 2-18-81-328
Pavement Edges, Roadway Discontinuities and Vehicle Stability

Sponsored by the

State Department of Highways and Public Transportation

August 1983

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

IMPLEMENTATION STATEMENT

The results of this study can be implemented immediately as the foundation for pothole maintenance guidelines relative to the safety. These guidelines would be formulated by the State Department of Highways and Public Transportation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

"Holes in the paving have to be a foot or more long and wider than a tire to be hazardous. If a driver claims his vehicle was thrown out of control by a small hole, treat this statement with suspicion and look for driver actions which may be contributing factors, such as cutting back into lane after overtaking.... A vehicle can be turned over by hitting a chuck hole without signs on either the tire or the hole, especially when the edges of the hole are rounded."

With the statements above, J. Stannard Baker (1), the widely acknowledged authority on traffic accident investigation gives credence to the danger of holes, one of the most prolific of the so-called pavement discontinuities that flourish in this time of unmerciful highway loads and merciless maintenance funding problems. There is no doubt a hole "by any other name" is still a pothole, chuck hole or unprintable colloquialism. The nature of such a hole is to be hard on tires, vehicles and drivers' tempers, but are they really a significant direct threat to safety, or is their influence on safety highly inflated by many accident reports reflecting driver frustrations and excuses.

Accident reports state "holes" are a causative factor in many accidents. In 1976, Ivey and Griffin (2) reported a rank ordering a roadway disturbances based on 15,968 accidents in North Carolina. Of these, the narratives of 566 stated that the accident was either caused or aggravated by some kind of roadway disturbance, e.g. holes, ruts, soft shoulders, water, etc. "Hole" was mentioned in 59 reports ranking "hole" fifth of 19 disturbances behind the key words water, dropped, soft, curb and edge. In a Delphi ordering developed by the same authors, "holes" ranked 18th of twenty disturbances. It may be noteworthy that "holes" seemed more important to the drivers of wrecked vehicles in North Carolina than they did to the engineers involved in the Delphi study.

In 1977 Klein, Johnson and Szostak (3) completed a study of the influence of roadway disturbances on vehicle handling. The accident data cited were difficult to interpret because of extremely small sample size from each source. As part of this study, a questionnaire was sent to the membership of the Automobile Club of Southern California. Twenty-eight percent (1,412 individuals) responded. Holes ranked third of thirteen identified disturbances in terms of hazard. It seems clear, whether justified or not, holes are perceived to be a significant threat to safety.

It is also clear that the perception of the public is not shared by many engineers with significant knowledge of vehicle handling and stability characteristics. One way of more accurately defining the problem is by controlled vehicle-hole interactive tests. The experiments reported here reflect an effort to separate folklore, personal perceptions and societal opinion from fact.

TEST PROGRAM

A comprehensive test program was developed to evaluate the safety related effects of roadway surface discontinuities in the form of holes in pavement, commonly referred to as potholes. Since there is an infinite number of pothole shape, area and depth combinations, and a large number of vehicle suspension system and tire combinations, a program to look at all conceivable combinations was deemed impractical. The research approach here was to determine a worse case condition, or a condition that would produce a definite safety hazard. This condition was defined as an upper bound and sublimit tests were performed to evaluate the potential influence on safety.

Potholes

In order to evaluate the effect of various pothole diameters and depths, three round holes were cut in the existing PCC test track at the TTI Proving Ground. These holes had diameters of 1 ft, 2 ft and 3 ft, with an initial depth of 7 inches, to be adjusted by filling with sand to the desired test depth. The 3 ft diameter hole is shown in Figure 1. The edges were intentionally left square to simulate a worse case condition, similar to the typical pothole shown in Figure 2. In addition to the fabricated potholes, two other test facilities were constructed. The first being a six-inch deep trench into which one side of the test vehicle could drop. The trench was twelve feet long, in order to allow wheel drop trajectory to be measured. The other test facility consisted of a three-inch high piece of lumber attached to the test track and a rubber bump strip with sloping sides. These fixtures allowed the measurement of tire/suspension characteristics in response to two different force inputs, as might be encountered when the vehicle strikes the far edge of a pothole.

Figure 1. Research Pothole

Figure 2. Typical Square Edge Pothole

Vehicles

To evaluate the effect of various weights, suspension systems and wheel sizes, a mini-compact, an intermediate, and a full size automobile were tested, along with a standard size pickup truck. These vehicles, described in Table 1, provide an adequate range of vehicle weights, varying from 1668 lbs to 4713 lbs. The wheel sizes varied from 12 to 15 inches. Before testing, each vehicle was set up to manufacturer's specifications with respect to the suspension and steering system, and periodically inspected during the course of the testing. Each vehicle was equipped with a roll bar and racing lap and shoulder belts to provide an added margin of safety for the test driver.

Test Trailer

To quantify some of the more critical factors involved with a vehicle tire impacting the edge of a pothole, a series of runs were made using the TTI Proving Ground general purpose research trailer. This trailer which conforms to ASTM E274, (Ref. 4) Figure 3, is capable of measuring wheel forces in three directions and the three moments developed by the test tire.

Tires

The tire sizes and construction types are shown in Table 1 for each vehicle, with the passenger automobiles using radial tires and the pickup truck using bias ply tires. The tire pressure was adjusted to the vehicle manufacturer's recommended cold pressure prior to testing for the major portion of the project. A study of the effect of low tire pressure was conducted early in the project. The results of the low pressure study are discussed separately in this report.

Photo-Instrumentation

The majority of data were gathered by means of a high speed cine camera operating nominally at 400 fps, with precision time marks recorded

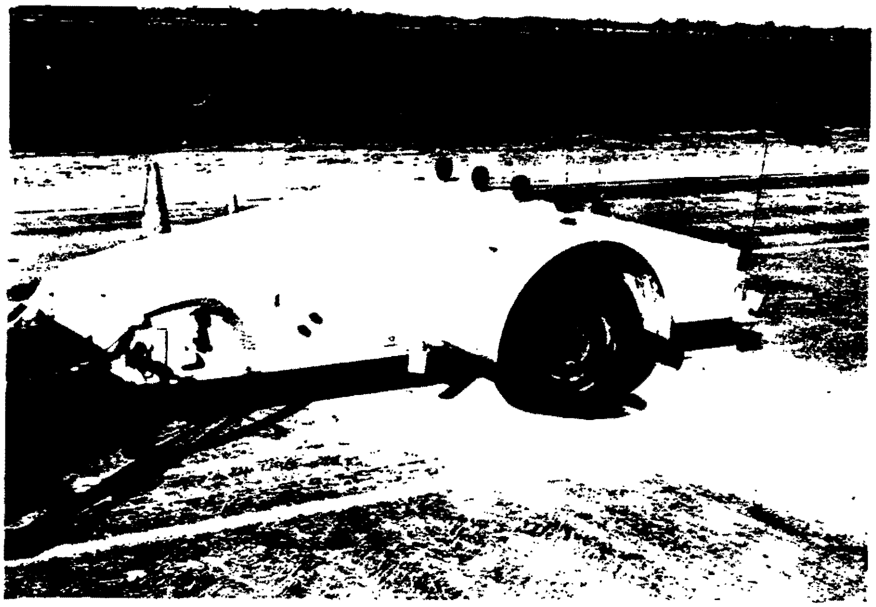


Figure 3. Instrumented Test Trailer

simultaneously on the film. The film was then analyzed on a Vanguard Motion Analyzer, one frame at a time, to determine X and Y coordinates vs. time. These coordinates were converted to inches by an HP-85 computer system using calibration measurements from a reference target on the test vehicles. Over 600 individual frames were analyzed to arrive at the various trajectory plots shown in this report. In addition to the high speed photography, standard speed film was used to document selected test runs at both the Proving Ground and on area roads.

Test Driver

Only one driver was used throughout this study, since only the influence of the pothole on the vehicle was being evaluated. This study made no evaluation of driver performance as related to pothole avoidance. Preliminary tests, made on area roads, showed that striking a pothole has very little effect on vehicle stability so that special driver skills are not required.

TEST METHODOLOGY

Field Tests

To obtain insight into the reaction of a vehicle striking a large pothole, initial tests involved transversing a typically large pothole in a local road with two vehicles at various speeds. The pothole transversed is shown in Figure 4, with dimensions listed below. The vehicles chosen for this initial test series were a subcompact automobile (Honda Civic) and a standard size pickup truck (Ford F150) to cover each end of the range of passenger vehicle weights and tire sizes. The runs were documented by both standard speed and high speed cine with the high-speed camera viewing the pothole area and the standard speed camera proving an overall view of the runs. Test speeds were incremented from 20 to 60 mph for each vehicle with the right side of the vehicle contacting the hole toward the center and near the edges (in separate runs).

A total of 12 runs were performed, none of which resulted in tire, rim or suspension damage. Further, no directional stability problem was observed on film or reported by the driver.

In addition to the single hole tests, several subjective runs were performed and documented on a section of roadway with many consecutive potholes. It was found, as could be expected, that the speed at which this road could be driven was quite low due to the induced discomfort to the driver. Also it was noted that there were no problems in directional stability other than the driver being bounced around, which somewhat affected the steering wheel input. This test finding is concurrent with that of a previous study which considered the multi-pothole situation (Ref. 3).

To observe the forces that are created by various edge shapes a square edge piece of lumber 1.5 inches high and a rubber bump strip 1.5 inches high,

Figure 4. Field Test Pothole

POTHOLE #2039

Location - Center of Roadway
Maximum Width - 40 in.
Maximum Length - 33 in.
Maximum Depth - 6 in.

LONGITUDINAL PROFILE

Distance Back From Trailing Edge (Inches)	Depth (Inches)
0	0.0
3	3.75
5	5.0
7	5.25
9	5.75
13	6.0
19	5.25
25	4.0
27	3.5
31	0.75
33	0.0

with 26° sloping sides, were struck with the instrumented test wheel, on which was mounted a standard tire (ASTM E501, Ref. 5). The results of these runs, made at speeds from 10 to 40 mph, are shown in Figure 5. These data show that the vertical forces, the forces required to get the tire up and out of the pothole, are relatively independent of speed. Thus at higher speeds the axle remained at the same level for a longer distance after contacting the far edge, producing the higher horizontal forces as a portion of the tire is wrapped over the edge. The sloped edge produced a horizontal force reduction of about 66%, compared with the force at the square edge. Even though the peak forces are quite high the duration is very short resulting in horizontal force impulse values ($\int Fdt$) between 3 and 7.5 LB-SEC and vertical impulse values between 1 and 2 LB-SEC including both square and sloped edges.

The peak force vectors for the square edge input are inclined approximately 22 deg to the horizontal at 10 mph and 12 deg at 40 mph. For the sloped edge input, the peak force is inclined 37 deg at 10 mph and 24 deg at 40 mph. These force vectors are shown in Figure 5.

Low tire pressure experiments were conducted, using the test trailer, by impacting the 3-foot test pothole at 20 mph with a A78-13 tire. Three high speed filmed runs were performed with the tire pressure set at 10, 15 and 24 PSI. The digitized results of these runs are presented in Figure 6. At zero inches on the horizontal distance scale the wheel starts to drop into the pothole from its normal rim bottom height. At the point marked 'Tire Contact' the tire first touches the far edge and at the point marked 'Hole Edge' the axle or lowest part of the rim is directly over the far edge. It may be seen that the closest point between the rim and the pothole edge is approximately 1.25 inches regardless of tire pressure.

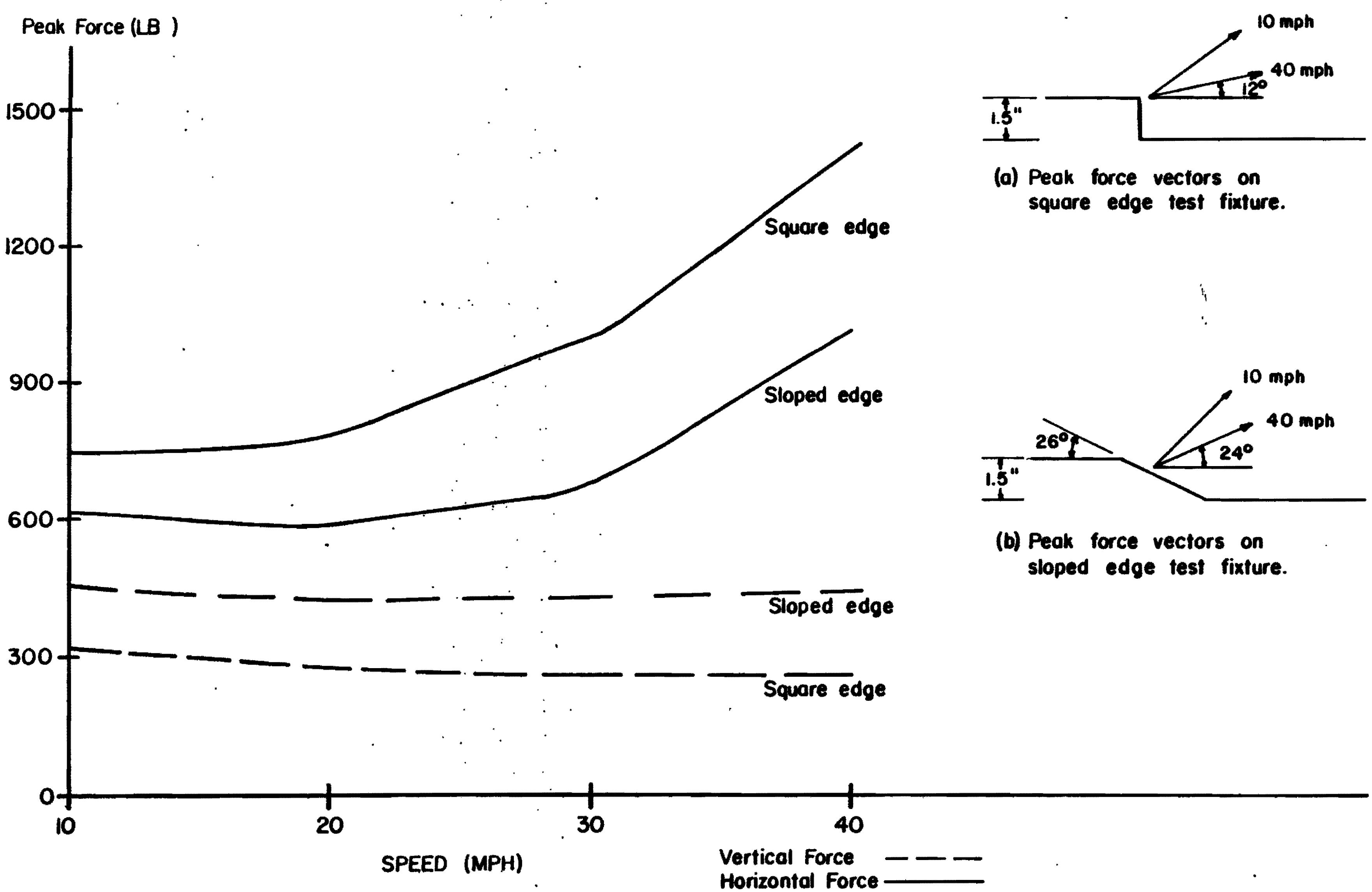


Figure 5. Wheel Forces Produced by the ASTM Standard Tire Striking a Square Edge and a Sloped Edge. Instrumented Trailer Test.

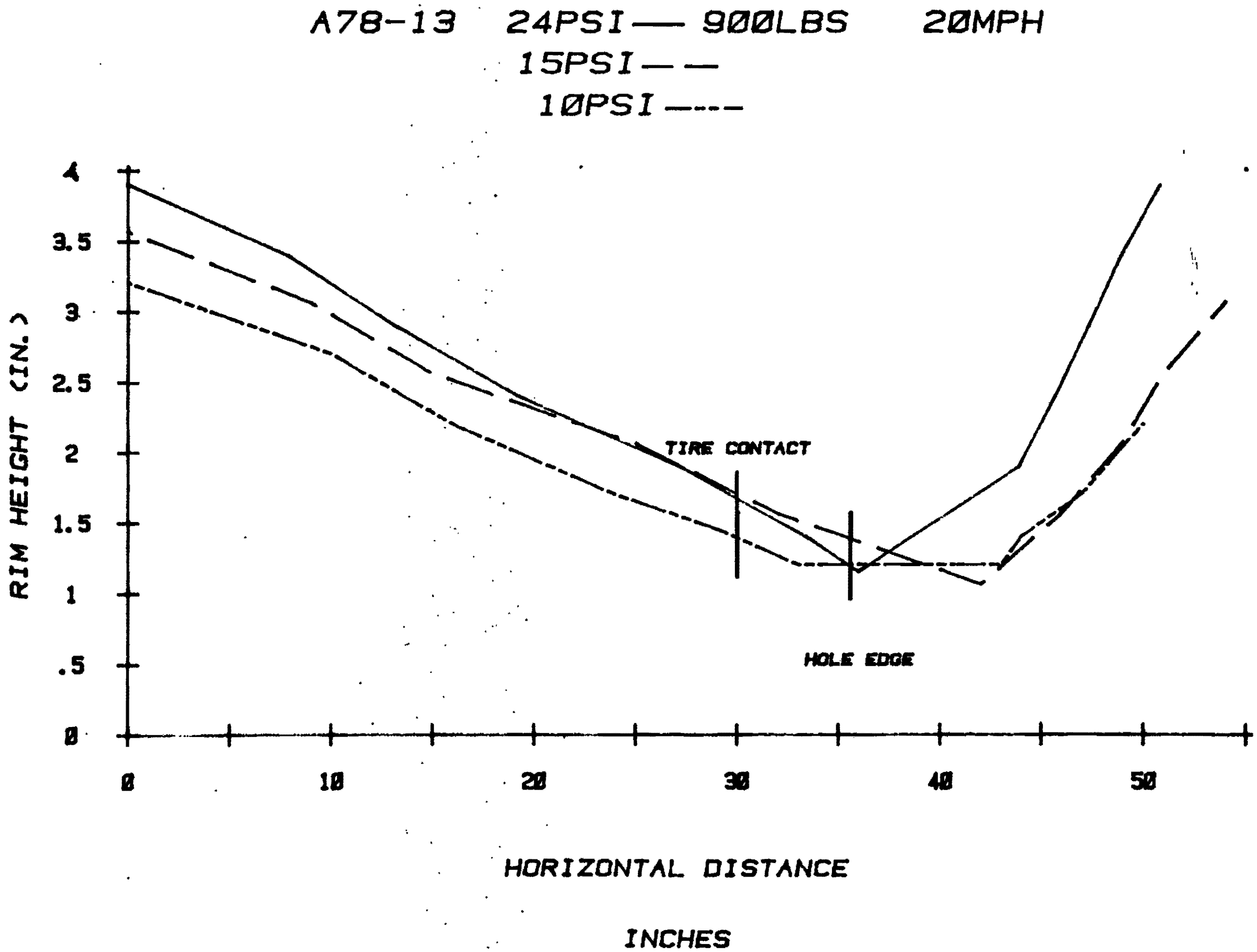


Figure 6. Tire Pressure Effects

Several high-speed photo data runs were made with the test trailer to measure wheel drop and rebound rates and axle trajectories. These measurements provided insight into the mechanics of a tire impacting a pothole but were found to be of limited use since the construction of the suspension system of the test trailer did not fully represent the suspension characteristics of the passenger vehicles.

Passenger Vehicle Tests

To accurately evaluate the effect of suspension and weight differences in standard passenger vehicles, the four vehicles described in Table 1 were chosen as representative and were used throughout the test program. The two major areas of concern were (a) the wheel drop trajectory, or the path of the axle as the wheel drops into a pothole, and (b) the rebound trajectory, or the path of the axle as the wheel exits the hole. It was decided to measure each of these trajectories independently which would allow the two functions to be combined so as to produce a specific reaction to any size hole desired. To provide the drop, a trench 1 foot wide was dug which was 6 inches deep for a longitudinal distance of 6 feet starting at the edge of the concrete test track. This trench rose to ground level in a longitudinal distance of 12 feet to avoid an exit jolt. As each vehicle was driven at 20 mph into the trench, the paths of the front and rear wheels were recorded by high speed photography. By using a known size calibration target on the side of each vehicle, and a small tracking target at the center of the wheel, the trajectory of the wheel was plotted. This was done frame by frame on a Vanguard Motion Analyzer and converted to X and Y coordinates as functions of time by a HP-85 computer.

The results of these wheel drop tests are shown in Figure 7 for the front wheels and in Figure 8 for the rear wheels. These trajectories are determined by a complex combination of interrelated influences of the sprung and unsprung

SIZE	MINI COMPACT	INTERMEDIATE	FULL SIZE	PICKUP TRUCK
YEAR	1977	1974	1977	1976
MAKE	HONDA	CHEVROLET	PLYMOUTH	FORD
MODEL	CIVIC	NOVA	GRAND FURY	F150 CUSTOM
MASS[a] FRONT	L 519 R 514	859 883	L 1347 R 1323	1259 1289
MASS[a] REAR	L 306 R 329	773 731	1019 1024	872 889
MASS[a] TOTAL	1668	3246	4713	4309
ENGINE DISPL.	75.5 CID	250 CID	440 CID	390 CID
SHOCK ABSORBERS	TELESCOPING	TELESCOPING	TELESCOPING	TELESCOPING
SUSPENSION	STRUT	BALL JOINTS	BALL JOINTS	KING PINS
POWER STEERING	NO	NO	YES	YES
STEERING RATIO	18.2:1	36:1	21.2:1	21.8:1
BRAKE TYPE/POWER	FT DISC REAR DRUM/NO	DRUM/NO	FT DISC REAR DRUM/YES	FT DISC REAR DRUM/YES
AIR CONDITIONER	NO	NO	YES	YES
TIRE SIZE	P155/80R12	P195/75R14	PZ25/75R15	L78-15
AND TYPE	GOODYEAR TIEMPO	GOODYEAR POLY STEEL	GOODYEAR VIVA	GOODYEAR POLYGLAS
AVE. TREAD DEPTH	LF 9/32 RF 9/32	LF 11/32 RF 11/32	LF 10/32 RF 10/32	LF 11/32 RF 11/32
	LR 9/32 RR 9/32	LR 11/32 RR 11/32	LR 10/32 RR 10/32	LR 11/32 RR 11/32
RECOMMENDED TIRE PRESSURE	FRONT 24	FRONT 24	FRONT 30	FRONT 30
	REAR 24	REAR 24	REAR 30	REAR 36
WHEELBASE	86.5"	111.25	122	132.75
FRONT TRACK	51.5"	59.25	63.875"	65
REAR TRACK	50.75"	59.5	63.625"	64.5
MILEAGE	70122	07077	78651	65270
MINIMUM GROUND CLEARANCE mm	5.25"	6.25"	7.25"	8.75"

(a) Mass Less Driver and Instruments

Table 1. Vehicle Descriptions

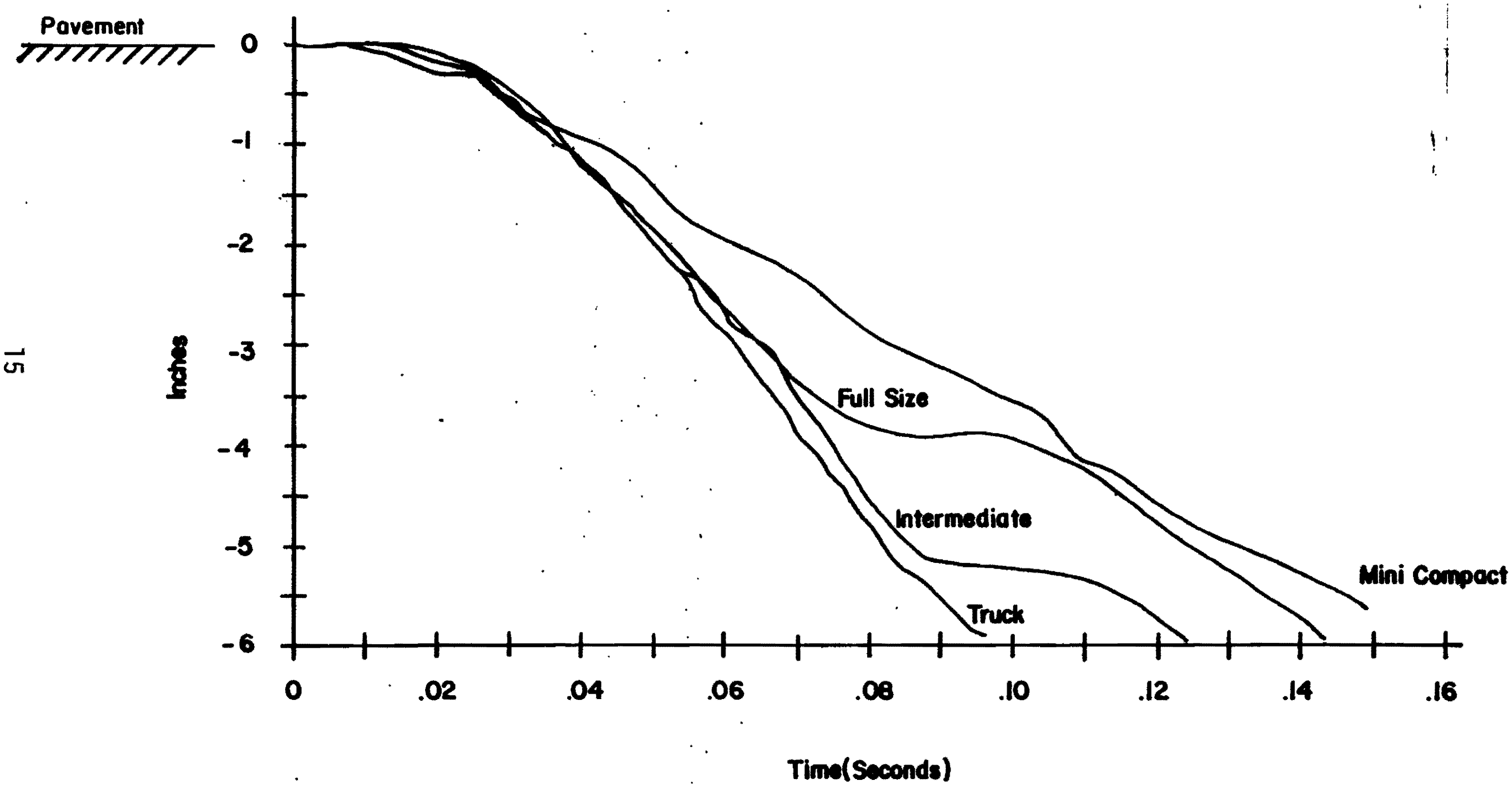


Figure 7. Front Wheel Drop Trajectories

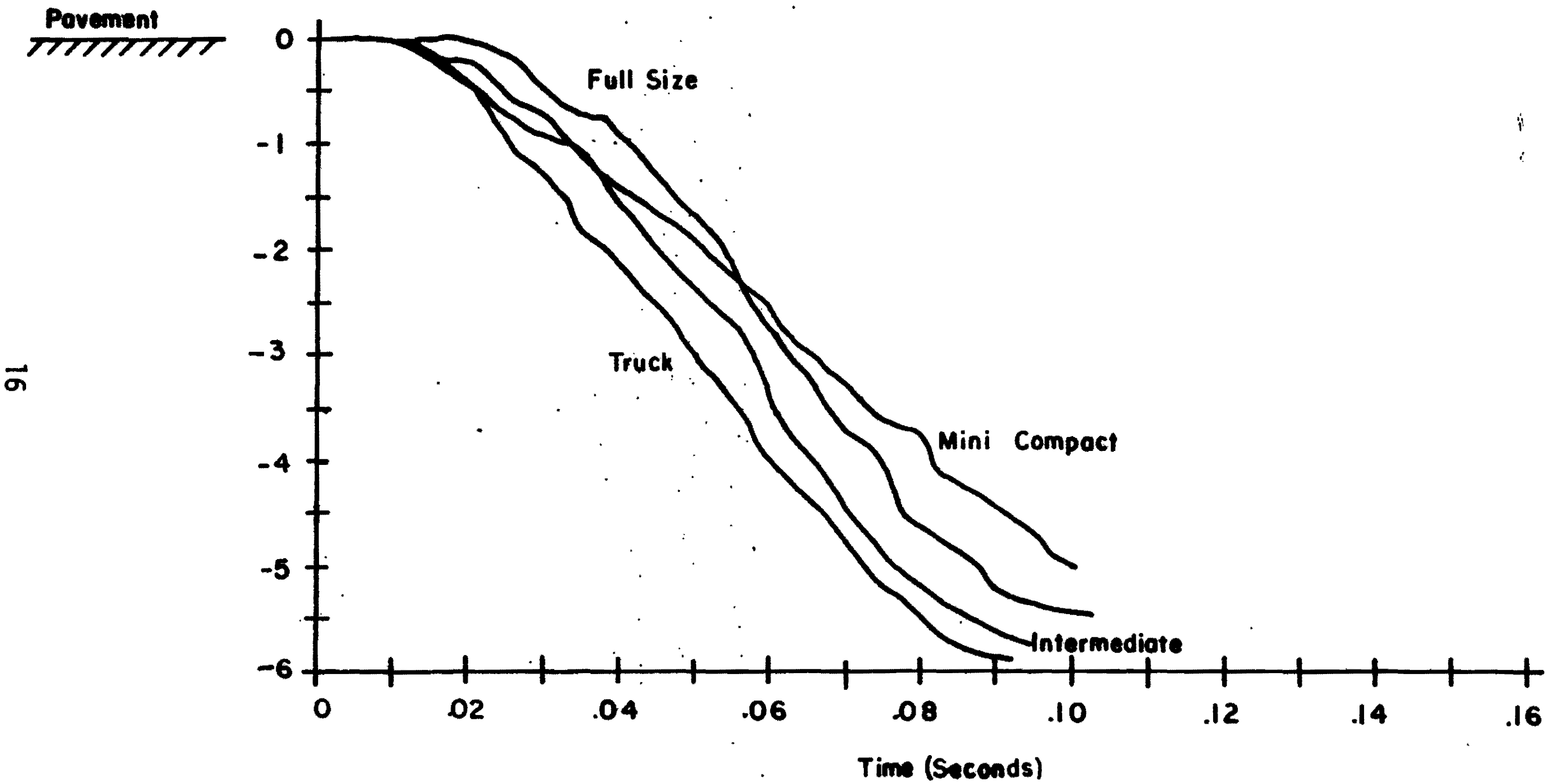


Figure 8. Rear Wheel Drop Trajectories

moments of inertia, spring rates, shock absorber damping, and suspension limit stops. As can be seen in the front wheel drop curves these variables can cause unusual results as in the case of the full size and intermediate size automobiles.

To measure the rebound trajectories, a square-edge step 3 inches high was created by attaching a piece of lumber 1 foot wide and 3 feet long to the test track. As with the drop tests, high speed film documented the path of the front and rear wheels as they impacted the step at 20 mph.

The results of these runs are shown in Figure 9 for the front wheel and Figure 10 for the rear wheel. An interesting result of these tests was the finding that for the first 0.005 seconds of contact the wheel did not change height. Should the tire be well in the hole at 40 mph, 0.005 seconds would result in 3.5 horizontal inches traveled which compresses the tire bringing the rim near the hole edge.

In the majority of the filmed 20 mph runs, the axle height did not significantly change between the time the tire touched the edge and the time that the center of the wheel was over the edge. This then simplifies the prediction of a hazardous condition by allowing the simplification that the tire will be compressed to the extent that if the rim is at the same height or lower than the edge, at time of impact, there is a strong possibility that the rim will impact the edge. The rim impacting the edge does not necessarily mean there will be a blowout or tire deflation, but does point to the possibility of this occurrence.

Hazardous Condition Determination

It has been found that knowing the drop rate of various wheel/suspension systems and the initial ride height of the rim (bottom of the rim to the ground distance), it is possible to predict the minimum length and depth of a pothole

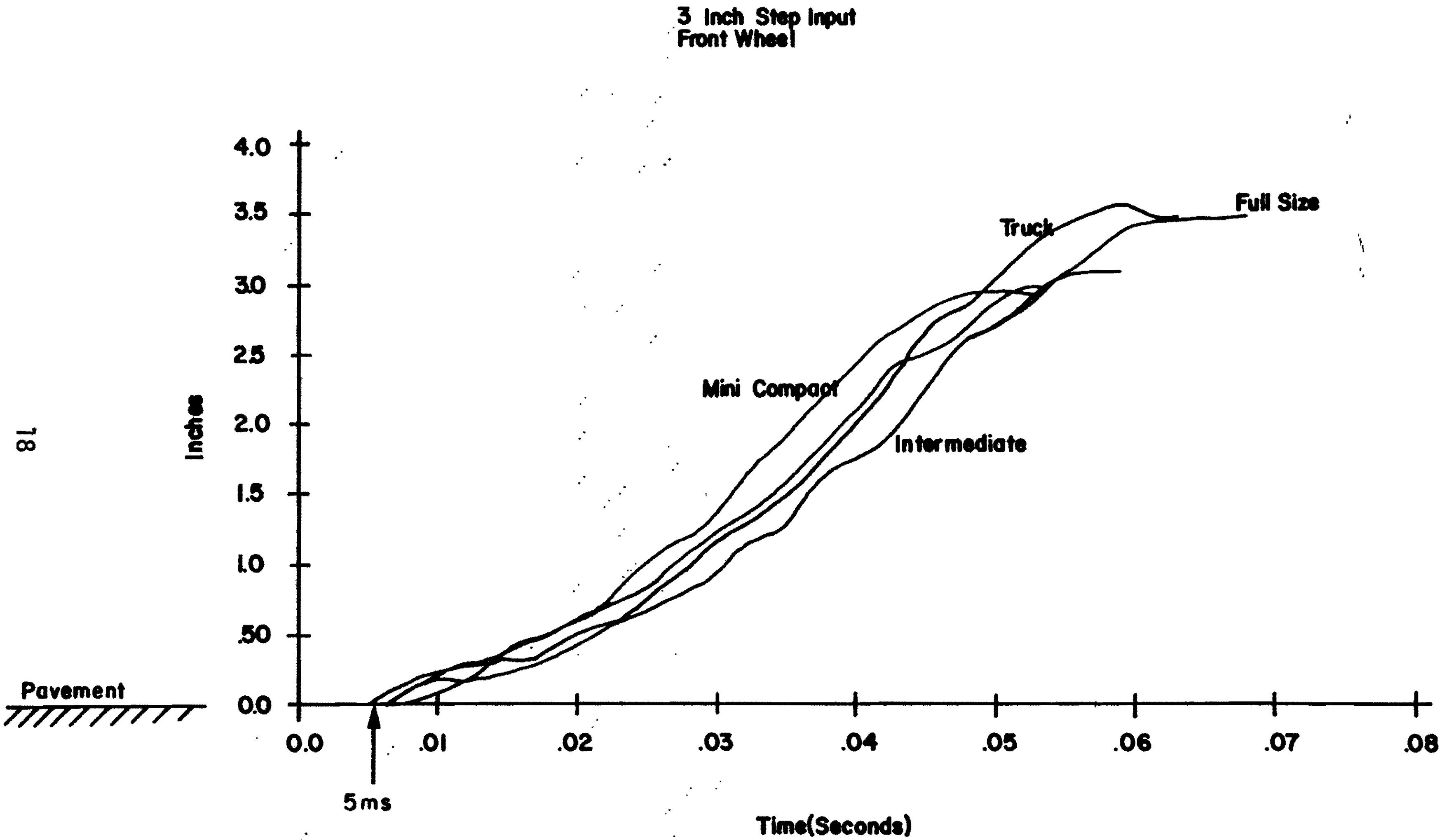


Figure 9. Front Wheel Rebound Trajectories
Striking a Square Edge Step

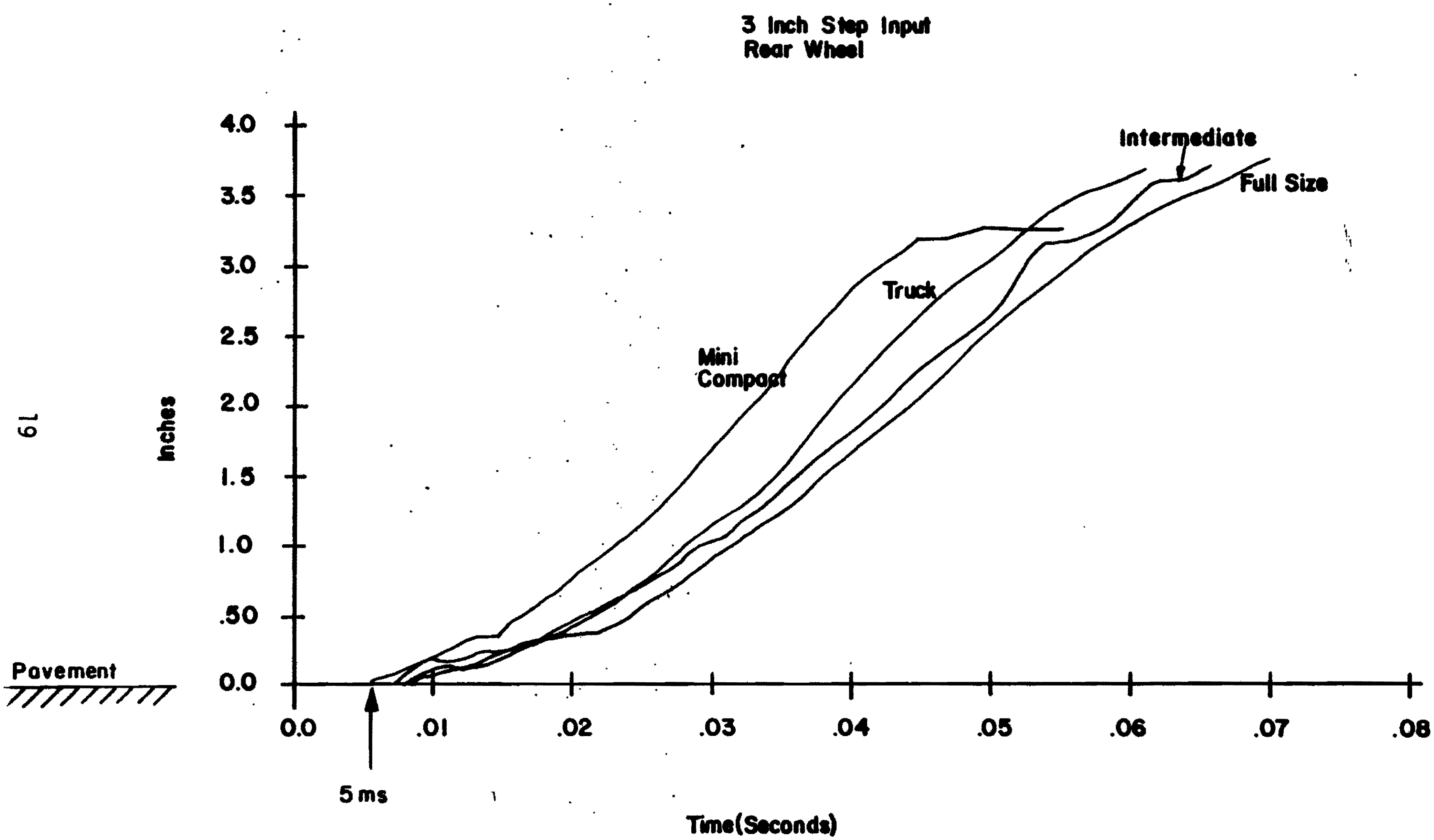


Figure 10. Rear Wheel Rebound Trajectories
Striking a Square Edge Step

(with a relatively square edge) that will produce a possible hazardous condition at any particular speed.

In developing the prediction, the rim ride height is measured for the particular vehicle. From the wheel drop trajectory plot for this vehicle, the time for the wheel to drop a distance equivalent to the rim ride height is obtained, 'A' in Figure 11. The travel distance at the desired speed is then found by multiplying the drop time by the forward velocity in inches per second, 'D' in Figure 11. If, at this distance, the tire just touches the far edge of the pothole, it is very likely that the rim will be at the same height when directly over the edge. This impact is highly dependent on vehicle characteristics, since the downward motion of the wheel must be stopped and an upward motion begun. To find the maximum safe pothole size, the horizontal distance from the bottom of the rim to the tread (at point of initial contact), 'C' in Figure 11, must be added to the longitudinal distance previously determined. Table 2, illustrated by Figure 11, was developed using this method for the front and rear wheels of the four test vehicles at 20, 30, 40, 50 and 60 mph. Column 'E' indicates the theoretical maximum safe pothole size assuming a relatively square edge. The results of this table are graphically illustrated in Figure 12. A point for a particular vehicle and speed combination is first located and then a line is extended up and to the right from that point. The area encompassed by the two arrows (i.e. The area of the chart above and to the right of the intersection of arrows) represents those combinations of length and depth that could produce a potentially hazardous condition. Conversely, the area to the left and/or below the intersection of arrows indicates relatively safe hole sizes.

To test the theoretical method of determining maximum safe pothole sizes, several runs were made at 20 mph using the mini-compact and intermediate size

	(A) Rim Height	(B) Time to Drop to DIST. (A)	(C) Horz. Dist. to Rim	V = 20 mph		V = 30 mph		V = 40 mph		V = 50 mph		V = 60 mph	
				(D)	(E)	(D)	(E)	(D)	(E)	(D)	(E)	(D)	(E)
Mini-Compact	3.25		8.0										
Front Wheel		.092 s		32.3	40.3	48.6	56.6	64.8	72.8	81	89	97.2	105
Rear Wheel		.085 s		30.0	38.0	44.9	52.9	59.8	67.8	74.8	82.8	89.8	97.8
Intermediate	3.75		10.3										
Front Wheel		.057 s		20.0	30.3	30.1	40.4	40.1	50.4	50.2	60.5	60.2	70.5
Rear Wheel		.061 s		21.5	31.8	32.2	42.5	42.9	53.2	53.7	64	64.4	74.7
Full-Size	4.6		10.5										
Front Wheel		0.12 s		42.0	52.5	63.4	73.9	84.5	149	105.6	116	127	137.5
Rear Wheel		0,083 s		29.2	39.7	43.8	54.3	58.4	68.9	73	83.5	87.6	98.1
Pickup Truck	5.3		11.5										
Front Wheel		0.078 s		27.4	38.9	41.2	52.7	54.9	66.4	68.6	80.1	82.4	93.9
Rear Wheel		0.080 s		28.2	39.7	42.3	53.8	56.4	67.9	70.5	82	84.6	96.1

(D) = Distance Traveled during time to Drop Dist. (A)
(E) = Distance (D) plus Dist (C), Maximum Safe Hole Length at Speed (V)
All Measurments in Inches

Table 2. Development of Recommended Maximum Pothole Size Criteria.

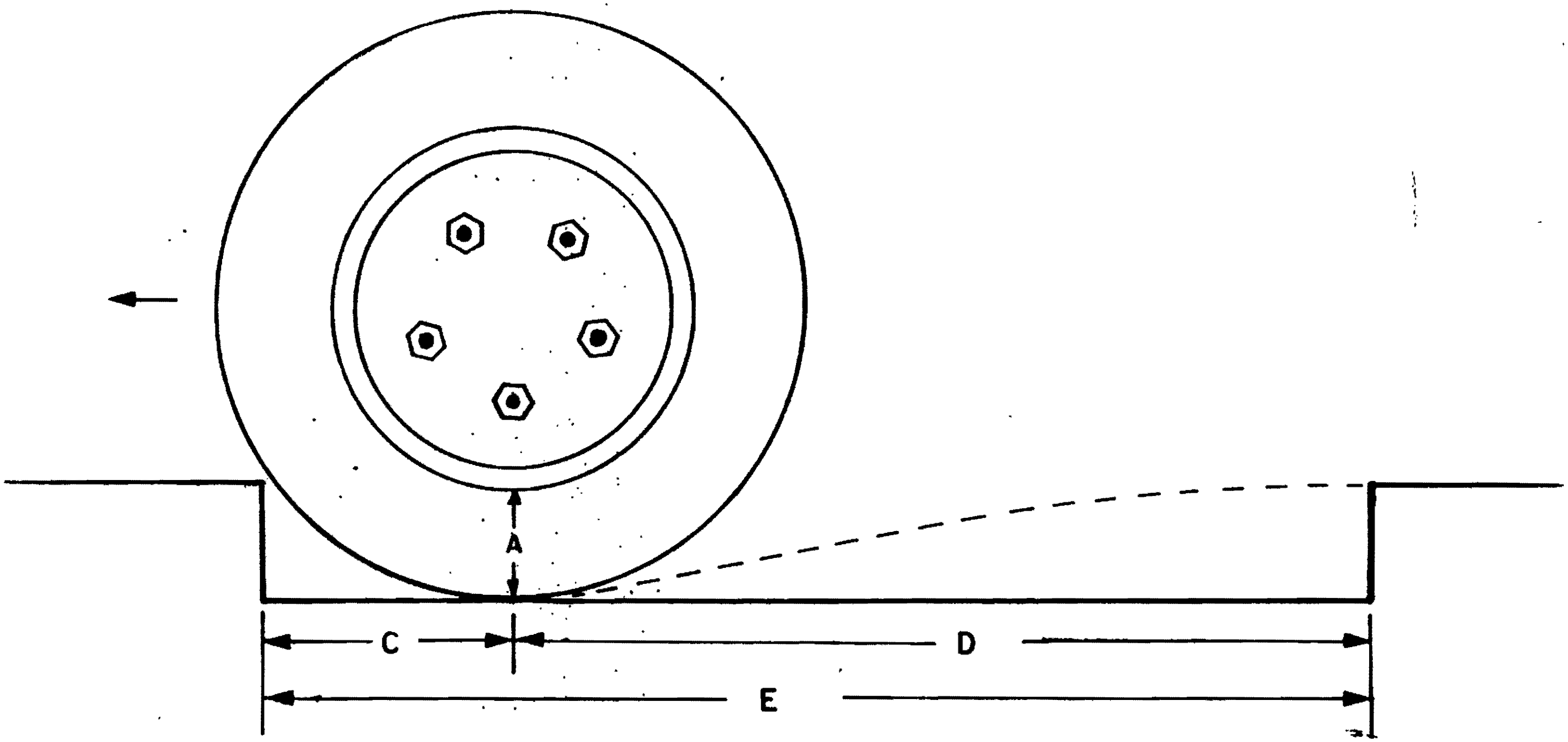


Figure 11. Illustration of Table 2

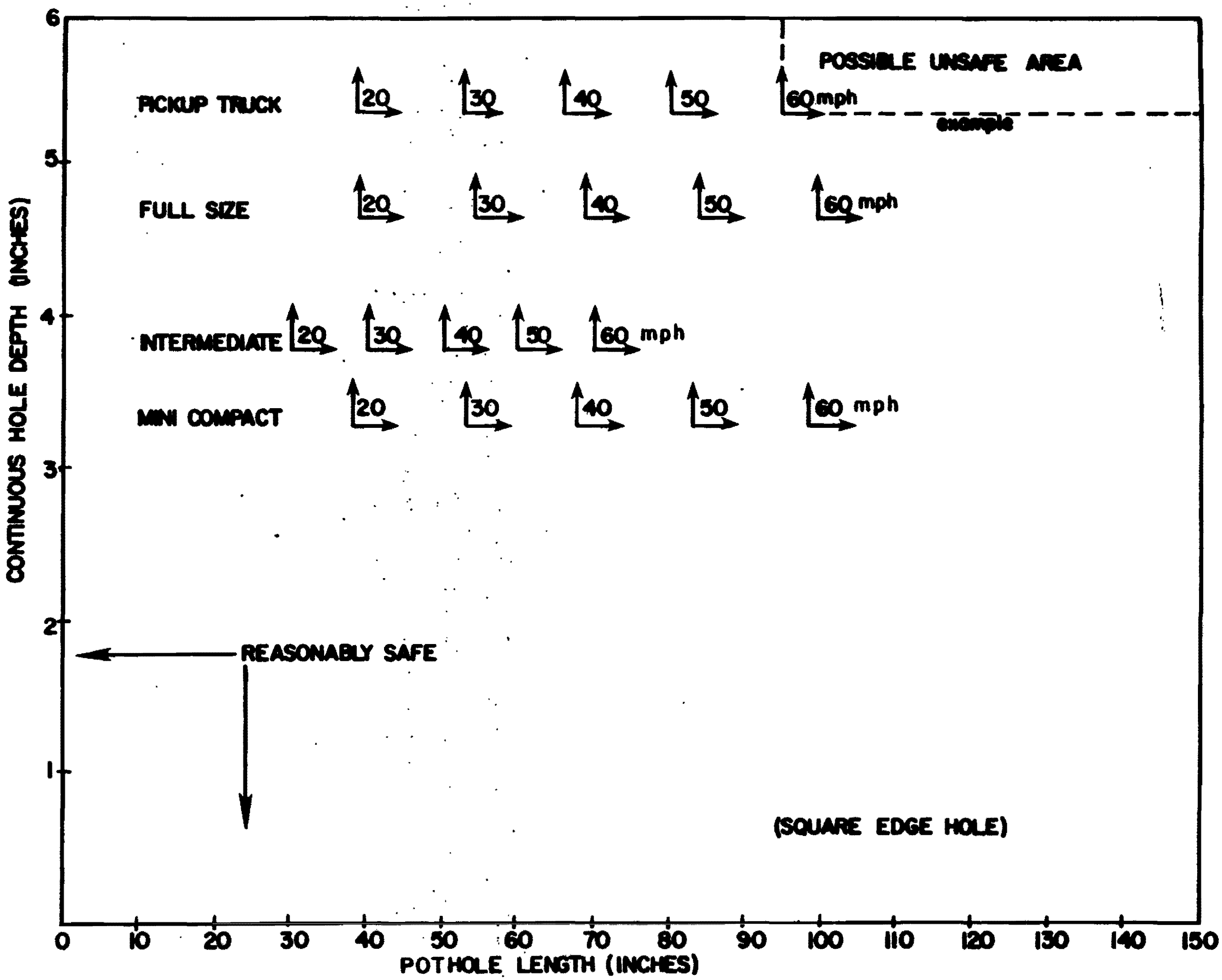


Figure 12. Safety Limits As a Function of Pothole Size, Vehicle Speed, and Vehicle Type.

vehicles, dropping the left wheels into the 36-inch diameter hole set to a depth of 6 inches. The speed of 20 mph was arbitrarily selected as a lower limit, for this study, since any lower speeds should not produce safety related problems. This speed then becomes the worse case condition if lower speeds do not produce significant problems and higher speeds do not allow the wheels to drop as far for a given length.

The trajectories for the front and rear wheels of the mini-compact are shown in Figure 13. This vehicle had a rim height of 3.25 inches above the ground, which is its critical drop distance. As can be seen in Figure 13, the critical drop was never reached since the maximum drop was only 2.8 inches. The prediction for this vehicle at 20 mph was a maximum safe hole size of 38 inches which was confirmed by the fact that the 3.25 inch rim height was never reached in the 36-inch hole. Once initial contact was made the path of the wheel continued downward but at a much slower rate and the rebound was slightly faster than predicted. This would be expected since the vertical distance was greater than the step and ramp tests producing higher forces. This trajectory difference shows there will be some small variability in predicting the exact point of rim contact since it is due to the suspension characteristics of each type of vehicle.

To determine the effectiveness of relating wheel drop data and wheel rise data from an initial steady state condition to an actual pothole test a composite plot of a 36-inch pothole was created on an HP-85 graphics computer and is shown in Figure 14. This trajectory curve for the front wheel is quite close to the actual trajectory, dashed line, although there is a slightly different slope on the rebound. It is felt this is due to the higher compressive forces generated as the downward travel of the wheel is stopped at the hole edge and to the difference in spring compression.

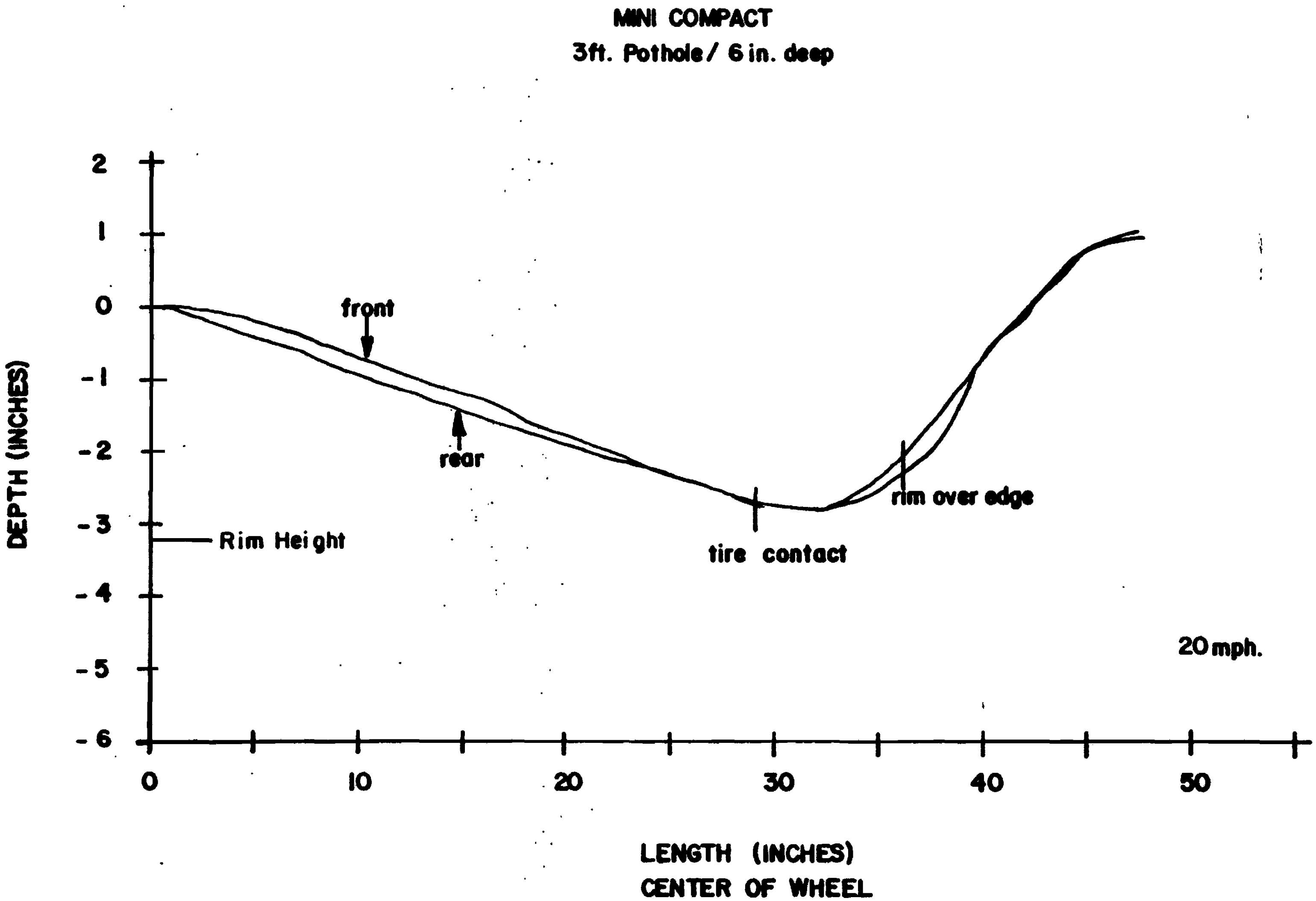


Figure 13. Wheel Drop Trajectories (mini-compact)

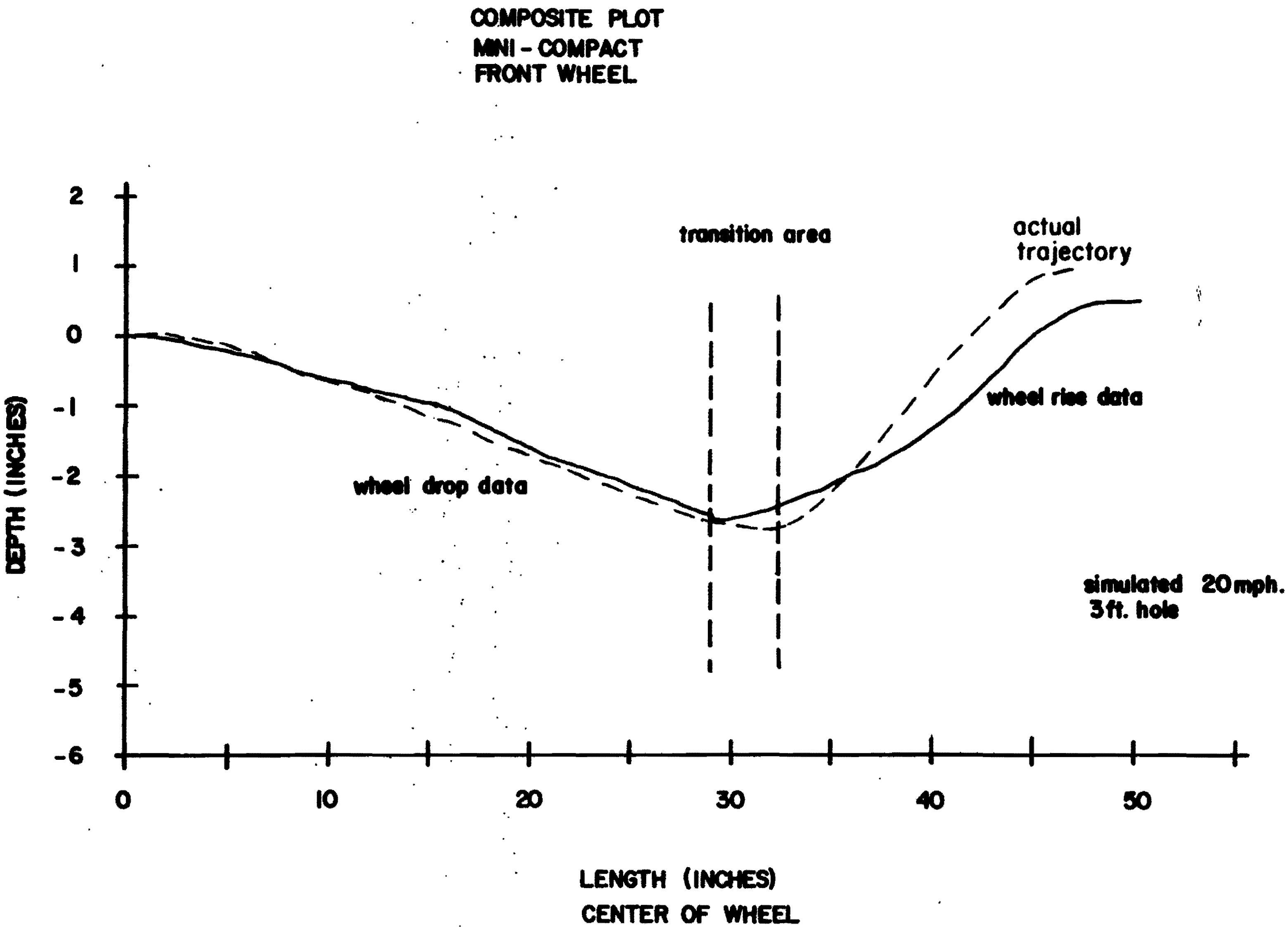


Figure 14. Computer Generated Wheel Trajectory (mini-compact)

The intermediate vehicle was run over the same hole at 20 mph with the resulting wheel paths shown in Figure 15. It is seen that the front and rear wheels dropped at a higher rate than those of the mini-compact, and reached a depth of 3.8 inches at time of tire contact for the rear tire and 4.8 inches for contact of the front tire. Once contact was made the front wheel started rising after 4 inches of forward travel while the rear wheel continued to drop until the rim contacted the edge. Even though the front wheel dropped further than the rear it did not sustain damage, though the tire was fully compressed to the rim. The rear rim was damaged, as seen in Figure 16; the metal was bent, but not enough to deflate or cut the tire.

The maximum safe pothole size prediction for the intermediate vehicle was 27 inches long and 3.75 inches deep. Figure 15 shows that the rim was indeed below the road surface at 27 inches. Based on the continued downward path of the rear wheel it would have made contact with the far edge.

It was found during field and test track testing that directional stability was not affected by impacting single holes up to and including 3 feet diameter and 6 inches deep. According to the test driver even the run which bent the rim of the intermediate vehicle did not change the vehicle path or force the steering wheel to turn.

In Figure 12 a hazardous condition is defined as an increase in the hole length and/or depth beyond the point shown by the intersecting arrows. This chart is conservative in that the square edge hole, profile C in Figure 17, is the most critical of the hole edge geometries. This chart is further generalized by Figure 18 where three bands of safety are shown based on the four test vehicles evaluated. The first band, left and lower, defines hole length and depths referred to being Reasonably Safe or where a prudent driver of a reasonably maintained vehicle would experience no significant problem in

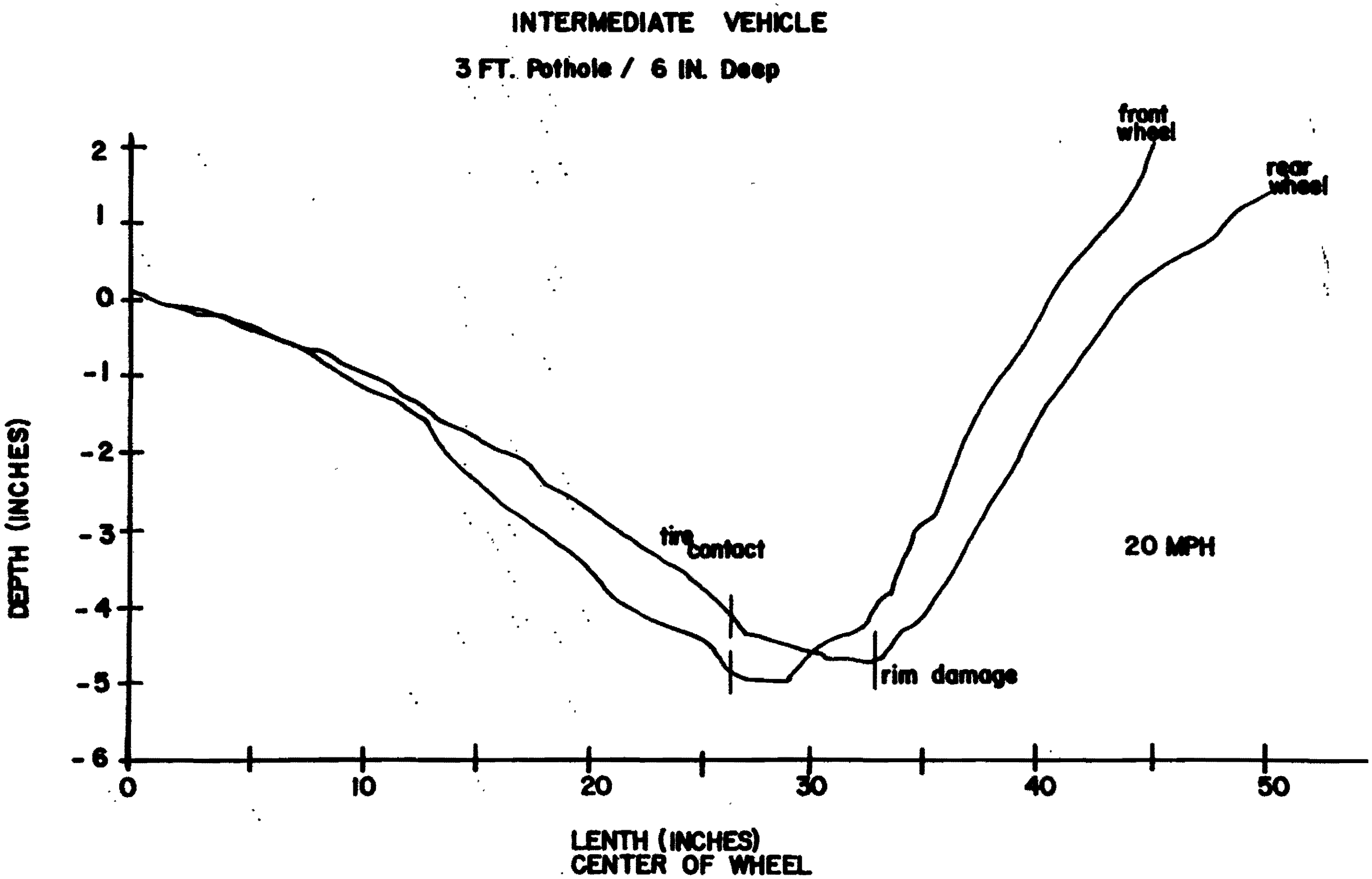


Figure 15. Wheel Drop Trajectories.
Intermediate Vehicle

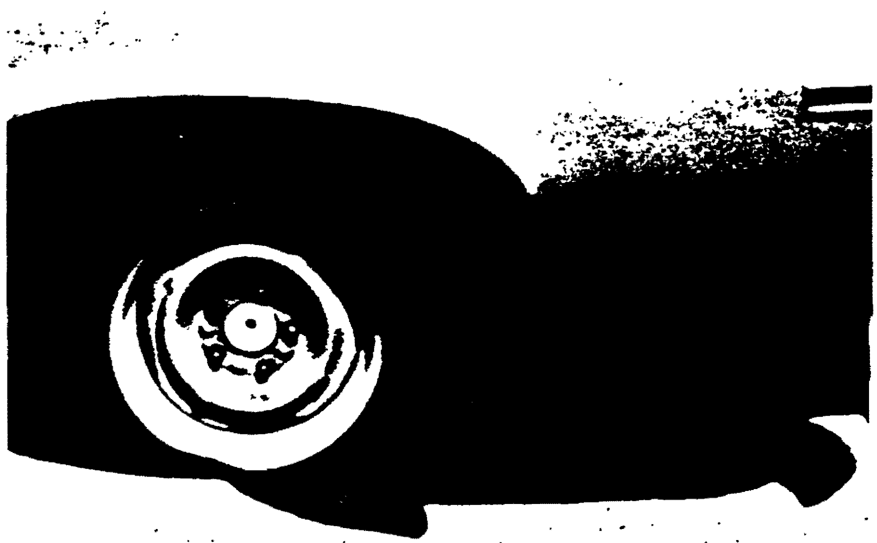
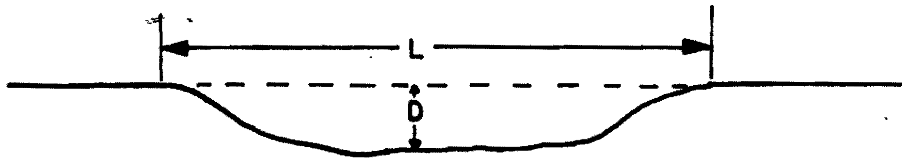
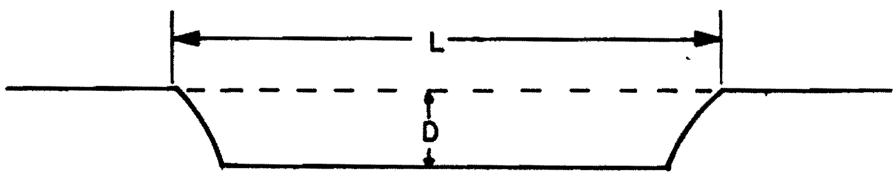


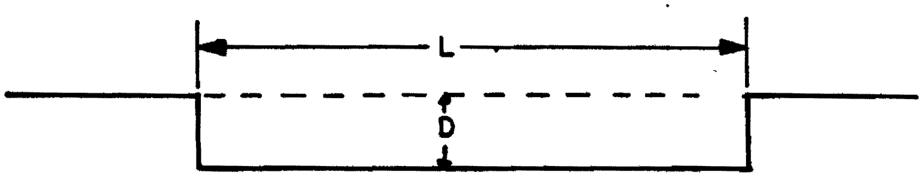
Figure 16. Rim Damage (Rear wheel, Intermediate Vehicle, 20 mph).



Profile A , Common



Profile B, Common



Profile C, Rare but most critical

Figure 17. Typical Hole Profiles.

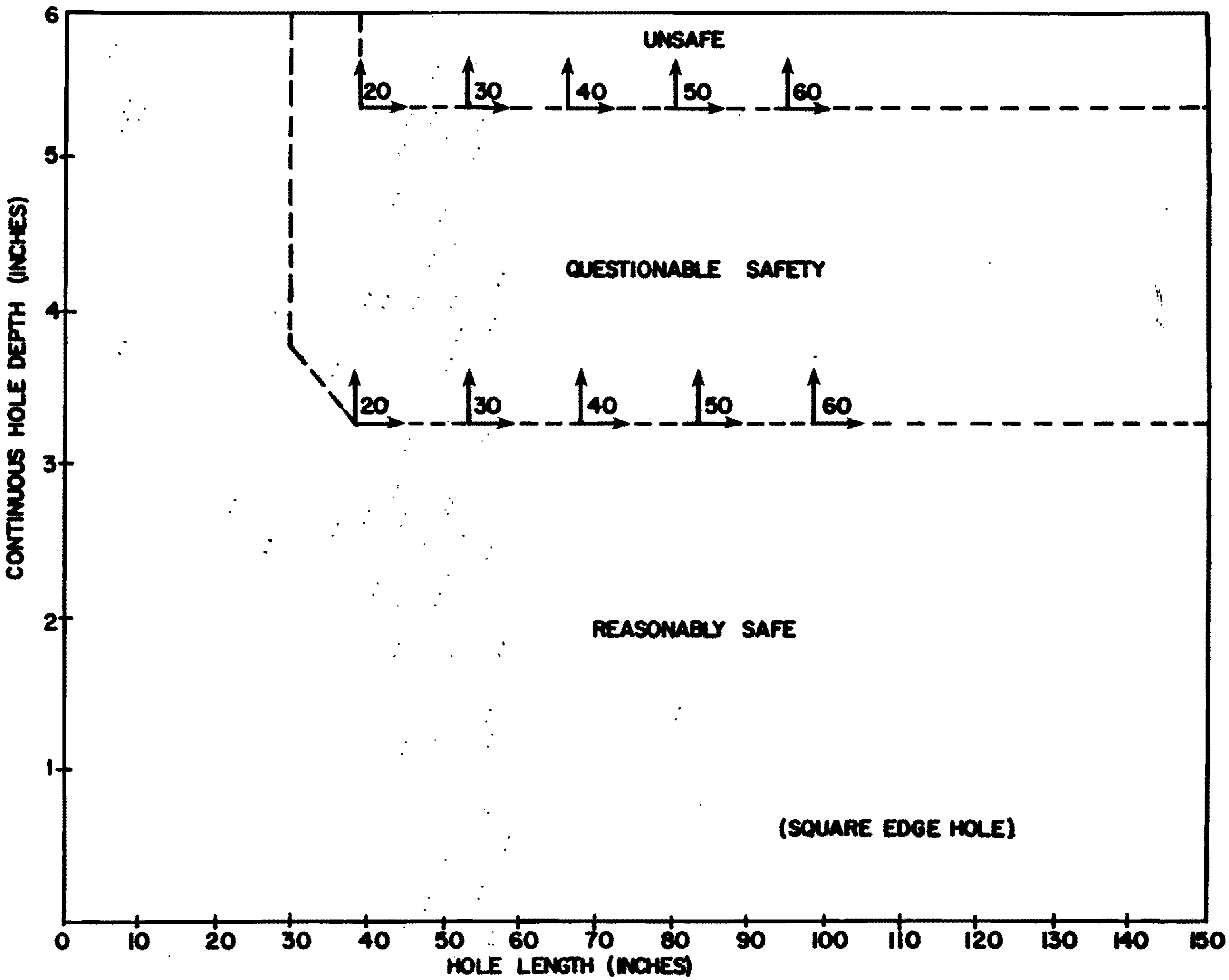


Figure 18. Pothole Safety as a Function of Size and Speed.

traversing the hole. The middle band which is bounded by the upper and lower extremes of vehicles tested represents a Questionable Safety area where a vehicle could sustain tire, rim or suspension damage when traversing a hole with the defined dimensions. Finally the Unsafe band defines length depth combinations which could produce a hazardous condition for any of the four vehicles tested. If a particular speed for evaluation above 20 mph is to be considered the upper two bands may be modified by locating the desired speed on the band baseline and extending a line vertically to redefine the zones. The band label would then be valid for all the area to the right of the speed line and the area to the left of the speed line would assume the label of the next lower band.

Limitations of Test Program

Although the choice of vehicles would seem to be adequate to define a fairly wide spectrum of vehicle characteristics, this has not been experimentally verified. Parameters such as inertial properties, spring stiffness and tire stiffness should be considered in order to objectively evaluate the spectrum of vehicles encompassed. Other factors such as vehicle loading, and the influence on vehicles other than four-wheeled passenger vehicles were not considered. As with snowflakes, there are probably no two potholes alike in terms of shapes, edge slopes and bottom contours. This study utilized a definable edge which was square, with vertical sides, and a level bottom. This approach provided insight into a worse case situation which may encompass only a small number of real world potholes. It does, however, permit, conservative safety predictions, since any sloping of the sides will only produce a safer condition for a given size hole.

CONCLUSION

It is apparent that a hole must be relatively large to constitute a significant safety influence when rim or tire damage are the guiding criteria. At common highway speeds, in excess of 40 mph, a hole must be in excess of 60 inches long and three inches deep to constitute a threat to the smallest automobiles. On urban streets, with traffic speeds as low as 20 mph, holes must still be over 30 inches in length and over three inches deep to have the potential of damaging tires and/or rims.

Damage to tires and rims, with the associated potential for an air-out, is the only significant safety related influence of holes identified in this study. Holes are atypical of most highway surface discontinuities in that they have a greater potential to cause damage the lower the vehicle speed. At the same time, following the usual trend, a vehicle with an air-out is obviously much easier to cope with at 30 mph than at 60 mph. The result of these two effects is that the usual size hole a driver encounters is not likely to be a major problem when struck directly.

Problems can arise if a driver reacts to the hole inappropriately. For example, it is counter-productive to react with braking or extreme cornering to a hole in the vehicle's path. In general, a given size hole is more likely to cause damage if speed is reduced. Losses of control can occur if extreme braking is produced at highway speed. Extreme cornering can have two results. First, if a driver reacts with a large steering input to avoid a hole he may produce a loss of control on a low friction surface. Second, he may put his vehicle in a hazardous position with respect to other traffic. In the writer's opinion, it is probably the latter that accounts for most of the accidents where holes are identified as have influence.

The influence of holes encountered when cornering deserves further attention. A cornering (turning) vehicle transfers weight from the wheels on the inside of the turn to the outside wheels. The springs on the heavily loaded side are compressed. When one of these tires encounters a hole, it goes down faster due to the acceleration of the higher spring force. Thus, it gets in position to be damaged somewhat more quickly (down farther in a given length of hole for a specific speed) than is represented by Figure 12. A second and potentially more hazardous situation is if a tire is moving laterally and encounters the side of a hole. A trip and roll could possibly occur in this situation, but it would required the car to be in an extreme lateral drift (skid). This lateral drift would need to be so extreme that it would be associated with intemperate vehicle control or a loss of control that preceded contact with the hole. It could be that first-hand knowledge of an event such as this, even though it is likely to be rare, stimulated Mr. Baker (1) to say "A vehicle can be turned over by hitting a chuck hole..."

The purpose of this work is certainly not to conclude that holes in highway surfaces should be tolerated. The many disadvantages of these flaws dictate their elimination within the bound of financial constraints. In this day of highways that are "past maturity and in future shock" (6), it is unlikely that the public will choose to afford the maintenance funding required to make holes an endangered species. The purpose is to put the safety influence of holes into a reasonable perspective, so that maintenance activities can be appropriately prioritized.

REFERENCES

1. Baker, J. Stannard, "Traffic Accident Investigation Manual", The Traffic Institute, Northwestern University, Evanston, Illinois, 1976.

2. Ivey, Don L. and Griffin, Lindsay I. III, "Driver Vehicle Reaction to Road Surface Discontunities and Failurers", International FISITA Conference, Tokyo, 1975.

3. Klein, Richard H., Johnson, Walter A., and Szostak, Henry T., "Influence of Roadway Disturbances on Vehicle Handling", Contract DOT-HS-5-01223, Final Report, October 1976.

4. "Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire", American Standard Testing Material, Volume 04, 03, ASTM E 274-79.

5. "Standard Specification for Standard Tire Pavement Skid-Resistance Tests", American Standard Testing Material, Volume 04, 03, ASTM, E 501-76.

6. Ivey, Don L., McFarland, W. F., Lytton, R. L., Burke, Dock D., Gallaway, Bob M., and Wootan, C. V., "Highway Pavements, Past Maturity and in Future Shcok", A report prepared for the Congressional Research Service of The Library of Congress, Texas Transportation Institute, August 1980.