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This report describes developments toward an improved system for accomplishing the desired results. The system employs a cleated belt supported by dual wheels in the configuration of a V-belt which carries the instruments. A pneumatic hammer which delivers an impulse of energy to the pavement and its supporting linkage is also described.

A bibliography of previous reports on impulse techniques of pavement testing is included.

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PAVEMENT DEFLECTION MEASUREMENT - DYNAMIC
PHASE III
SECTION II (VEHICLE)
FINAL REPORT

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Prepared for
Washington State Highway Commission
Department of Highways
in cooperation with
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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Washington State Highway Commission, Department of Highways or the Federal Highway Administration.

(Transportation Systems Section Publication H-38)

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ABSTRACT

Implementation of automatic data acquisition using impulse techniques requires the development of a mechanical device to set an instrument package on the pavement, deliver an impulse of energy, and retrieve the instrument package. This is to be accomplished automatically with the vehicle proceeding down the highway.

This report describes developments toward an improved system for accomplishing the desired results. The system employs a cleated belt supported by dual wheels in the configuration of a V-belt which carries the instruments. A pneumatic hammer which delivers an impulse of energy to the pavement, and its supporting linkage is also described.

A bibliography of previous reports on impulse techniques of pavement testing is included.

SUMMARY

Progress has been made toward the development of a vehicle for automatically logging the structural condition of highway pavements at speeds considerably greater than any previously available method. The goal of the development is a vehicle which will travel at a comfortable speed and make measurements while in motion, automatically recording the data collected on digital magnetic tape for manipulation by modern methods of high speed electronic data processing. The entire state highway system could be logged at planned intervals of time. The resulting data bank would be useful for assistance in many management decisions such as establishments of priorities, budgets, and maintenance schedules.

The development which has made such a vehicle possible is the impulse technique of pavement testing. The impulse technique was first described in a report entitled "Pavement Deflection Measurement-Dynamic-A Feasibility Study, Final Report, June 1970" by Frank W. Brands, P.E. and John C. Cook, P.E., prepared for the Washington State Highway Commission, Department of Highways, in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

Subsequent work and results of various field tests using the technique are reported in the references listed in the bibliography attached to this report.

The implementation of the use of the impulse technique for automatic data acquisition requires that a system be developed for mounting on a vehicle which will deposit an instrument package on the pavement, permit it to dwell there for a short period of time such as a half or a quarter of a second, and then retrieve the instrument package. This cycle must be repeated at intervals as the vehicle proceeds along the highway with a constant forward velocity. In addition, while the instrument package rests on the pavement an impulse of energy must be delivered to the pavement at a precise position relative to the instruments.

It was recognized that this is a rather challenging mechanical problem, and a test model vehicle was built to investigate various schemes for achieving the desired results and to assist in the developmental process.

The test model vehicle has an outer frame equipped with road wheels and an inner frame which can be raised clear of the pavement for traveling, or lowered to the pavement for making measurements. The construction of the entire vehicle is sufficiently large and sturdy to permit various systems to be installed on the inner frame for tests and experimentation.

The first scheme to be installed employed a large flat belt supported by pulleys and wheels. The belt contacted the pavement in a manner similar to the track of a crawler tractor. The instruments were built into a carriage attached to the edge of the belt by a shaft. As the belt rotated, the instrument carriage would be set down on the pavement by the belt and remain there until it was picked up by the motion of the belt going over the rear supporting pulley, and carried to the front of the vehicle where the cycle would repeat. A problem existed of keeping the belt from running off its supports, especially when the vehicle negotiated turns.

This report describes an improved system which has overcome the problem of the belt running off its supports. By changing the supports to two sets of dual motorcycle wheels and securing a row of aluminum cleats onto the belt, the advantages of a V-belt are realized and the belt cannot now run off.

The new design permits the instruments to be mounted directly on the belt. The space between the dual wheels provides sufficient clearance so the instruments can pass around the belt supports.

A radio telemetering link transmits the signals from the instruments located on the moving belt to receivers located conveniently on the main frame of the vehicle or other convenient location.

A pneumatic hammer provides the impulse of energy and a hammer support linkage positions the hammer appropriately so the impulse is positioned correctly with respect to the instruments.

Test results have shown this cleated belt system to be a considerable improvement over the flat belt configuration. The hammer is synchronized with the belt and directs an impulse of energy into the pavement properly. The impulse is of proper magnitude and the signal from the transducers is telemetered to the receivers where it is reproduced with good fidelity.

Only slow speeds were attainable at this time because of limited ruggedness in the design of the transducers and the synchronizing cleat of the belt. In addition,at speeds approaching 8 miles per hour vibrations became excessive.

Remedies are suggested for all of the aforementioned problems, but the termination of the time allotted for the project prevented their being pursued. There does not appear to be any major impediment to the cleated belt scheme being refined into a working design, although additional evaluation tests should be made, especially on the suggested modifications.

While observing the machine in action, an alternate scheme was conceived which appears to have several advantages over the cleated belt. The hammer support linkage operates so effectively that it seems reasonable to install the instruments directly on the hammer support also and eliminate the belt completely. The resulting mechanism would be simpler than the cleated belt configuration and would not require that the hammer location be synchronized with a specific point on the belt with each cycle as required by the cleated belt design.

CHAPTER I

INTRODUCTION AND REVIEW OF PREVIOUS WORK

The Impulse Deflection Profile and Impulse Index as a measure of pavement condition were developed at Washington State University and were first described in a report entitled "Pavement Deflection Measurement-Dynamic-A Feasibility Study, Final Report, June 1970" by Frank W. Brands, P.E. and John C. Cook, P.E., prepared for the Washington State Highway Commission, Department of Highways, in cooperation with the U.S. Department of Transportation, Federal Highway Administration Project No. Y-1205. Results of additional developmental work and experimentation are reported in the series of publications listed in the bibliography attached to this report.

The First Report

The first report[1] of the series describes the initial experimentation, measurements, and tests that went into the search for an improved method of determining highway pavement condition.

A number of new concepts for evaluating pavement condition were explored, and their qualities were compared with established techniques. Results of the tests and explorations performed under this initial feasibility study phase of the work revealed several important matters relevant to the problems of pavement testing.

Tests performed at Washington State University indicated that the structural parameters of pavements are linear, or sufficiently linear, over a broad enough range that the energy or force utilized in testing need not always be as great as previously accepted methods used.

Literature[4] reveals that other investigators have made supporting conclusions on the matter of linearity. The direct consequence of this reasonable linearity is that pavement testing equipment need not intrinsically be large and heavy.

A second important fact reported is relevant to the limitations of testing methods developed previously elsewhere that use a steady state sinusoidal single frequency driving function.

Standard textbooks on linear circuit theory (6,7,8) thoroughly present the theoretical background indicating the necessity of utilizing a broad frequency range when investigating system response. Single frequency excitation risks the hazard of response being very dependent upon the locations of the s-plane poles of the system transfer function with respect to the poles of the single frequency driving function. A unit impulse, on the other hand, contains an equal amount of all frequencies, and the response of a system to a unit impulse is determined only by the parameters of the system under test and not by a response to a specific single frequency selected for the driving function which may or may not coincide with self-resonant frequencies of the system under test.

Tests were conducted on various pavements using an impulse of energy for system excitation. Various transducers were positioned at several locations on assorted pavements, and their outputs examined for correlation of parameters with known pavement condition. The final product of the research was the development of a system using two accelerometers whose outputs were full wave rectified and then integrated. This quantity from each accelerometer can be used for plotting a profile of the pavement deflection under impulse loading. Correlations are shown for the deflection profile obtained using the new low energy impulse technique and the profiles obtained using commercially available single frequency steady state sinusoidal type equipment as produced by a Dynaflect.

In addition a mathematical formula is introduced which reduces the profile information into a single number referred to as the Impulse Index. An evaluation of the usefulness of the Impulse Index as a measure of pavement condition was presented and results compared with those obtained using other criteria, including Dynaflect and Benkelman Beam measurements.

Two important advantages of the new method over any previous method are the very short length of time required for the data acquisition (a fraction of a second) and the light weight of the necessary equipment. These two features make it feasible for the impulse technique of pavement testing to be applied from a moving vehicle.

It is anticipated that when this advantage is fully exploited, the data will be automatically acquired from a moving vehicle and recorded on magnetic tape, facilitating the rapid logging of the conditions of the complete highway system at planned intervals of time. Such a logging system will be a valuable aid in the management of highway maintenance, providing an accurate log of the state of deterioration as well as the rate of deterioration for every increment of highway pavement. Being on magnetic tape, the format of the data would be easily handled in short time with great flexibility of format and at extremely low cost using modern computer data processing methods. Sections of pavement could, for example, be easily categorized according to their relative condition, and all sections whose conditions is worse than a threshold criteria could be identified thereby rapidly providing the information necessary for documenting budgetary requirements and establishing priorities and work schedules.

The capability to present documentary evidence of the rate of deterioration of a highway would greatly strengthen requests for the funding necessary for prudent maintenance and management decisions.

Second Report

The second report[2] of the series describes the initial work on a test model vehicle whose function is to provide a means for acquiring information necessary to design a completely mechanized unit for automatic data acquisition and logging of pavement condition utilizing the impulse technique.

One of the most challenging problems involved is designing a device which will deposit an instrument package on the pavement, permit it to dwell for a finite period of time on the order of a quarter or a half of a second while the instrument package performs its measurements, retrieve the instrument package, advance it down the road a reasonable distance and again deposit it on the pavement to repeat the cycle. All this should be accomplished with the vehicle maintaining comfortable forward velocity.

The instrument package contains two accelerometer type transducers. The transducers must be placed on the pavement a fixed distance apart, (eighteen inches is satisfactory) and then a hammer blow must be struck on the pavement near the front of one of the transducers. The electrical signals from the transducers must then be acquired for the next 50 milliseconds.

The aforementioned report describes a roadworthy vehicle which carries an inner frame capable of being lowered to the pavement for use, or raised clear of the pavement for traveling. The inner frame is large enough and sturdy enough to permit experimentation with various schemes to perform the required function.

The first scheme attempted employed a flat belt which contacted the pavement similar to the track of a crawler tractor. An instrument carriage was attached to the belt by means of a pinion as shown in Fig. I-1. As the vehicle progressed along the road, the instrument carriage would be deposited on the pavement and remain there while the vehicle advanced until the rear belt support picked it up. It would then be carried by the belt to the front of the vehicle and the cycle would repeat.

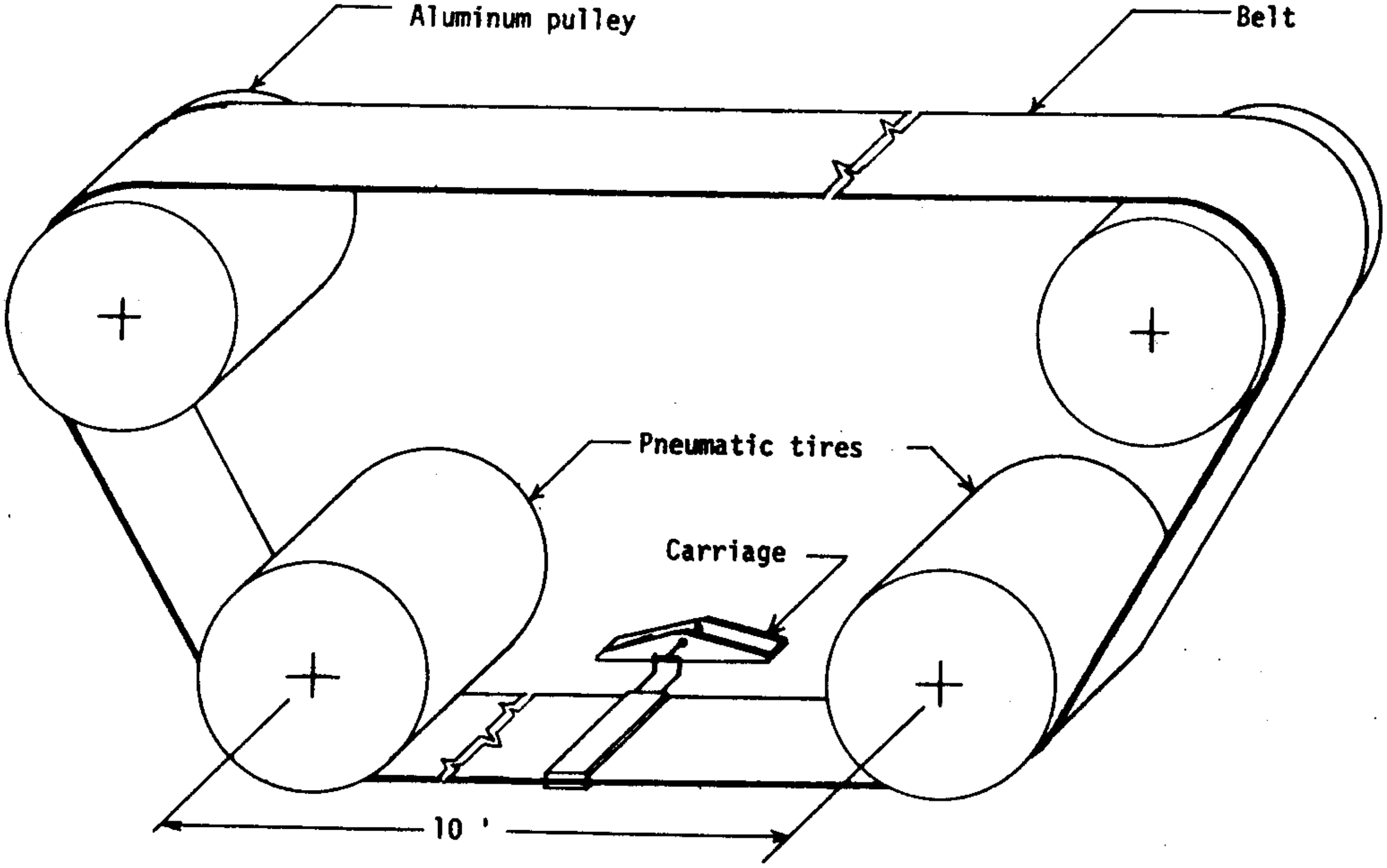


FIGURE I-1

Flat Belt Mechanism

Figures I-2, I-3, and I-4 are a photo sequence showing the carriage being deposited on the pavement at the front of the vehicle. Fig. I-5 is a photo of the entire vehicle as it appeared with the flat belt, and the inner frame raised for traveling when measurements are not being made. When tests were to be made, the inner frame was lowered so that the belt contacted the pavement, and the friction of the pavement set the belt in motion in synchronism with the pavement. As the belt moved, the instrument carriage would be deposited on the pavement as shown in Figs I-2, I-3, and I-4. At a particular point in the cycle while the carriage dwelt on the pavement, a pneumatic hammer would strike a vertical hammering pin located on the carriage a precise distance from the first transducer. This provided the impulse of energy required for the measurement.

While the flat belt scheme did operate, certain mechanical problems existed and were reported. Various improvements were subsequently made and are reported herein in later chapters of this report.

The Third Report

The third report[3] describes a hand carried suitcase sized package with which the impulse technique of pavement testing can be easily applied. With this compact and highly portable instrument, designated "The Impulse Index Computer", measurements can be rapidly made on flexible pavements giving an indication of their condition. The measurements made with this hand carried device are the same as the measurements that are planned to be made from the moving vehicle. The moving vehicle is planned to

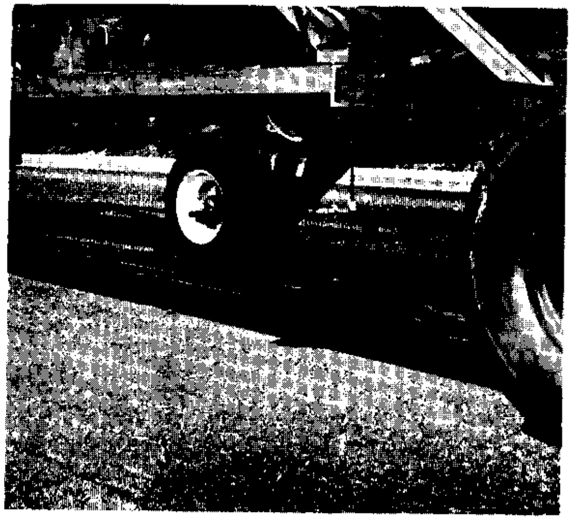


FIGURE I-2

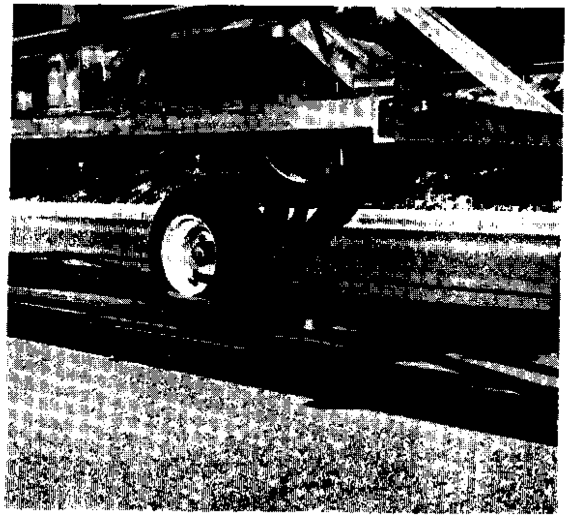


FIGURE I-3

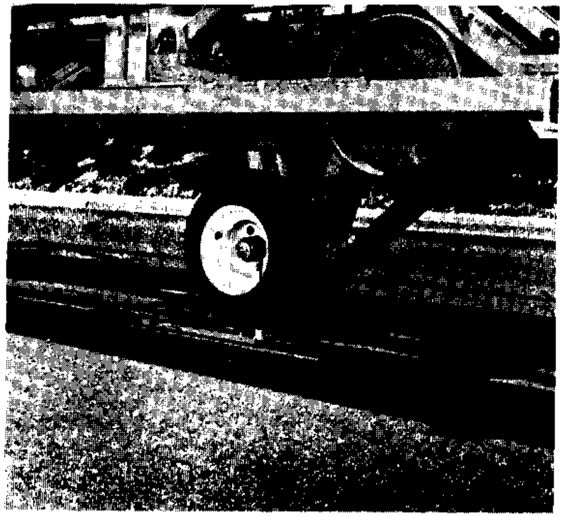


FIGURE I-4

Sequence Indicating Manner in Which Instrument Carriage is Set
on Pavement
With Flat Belt System

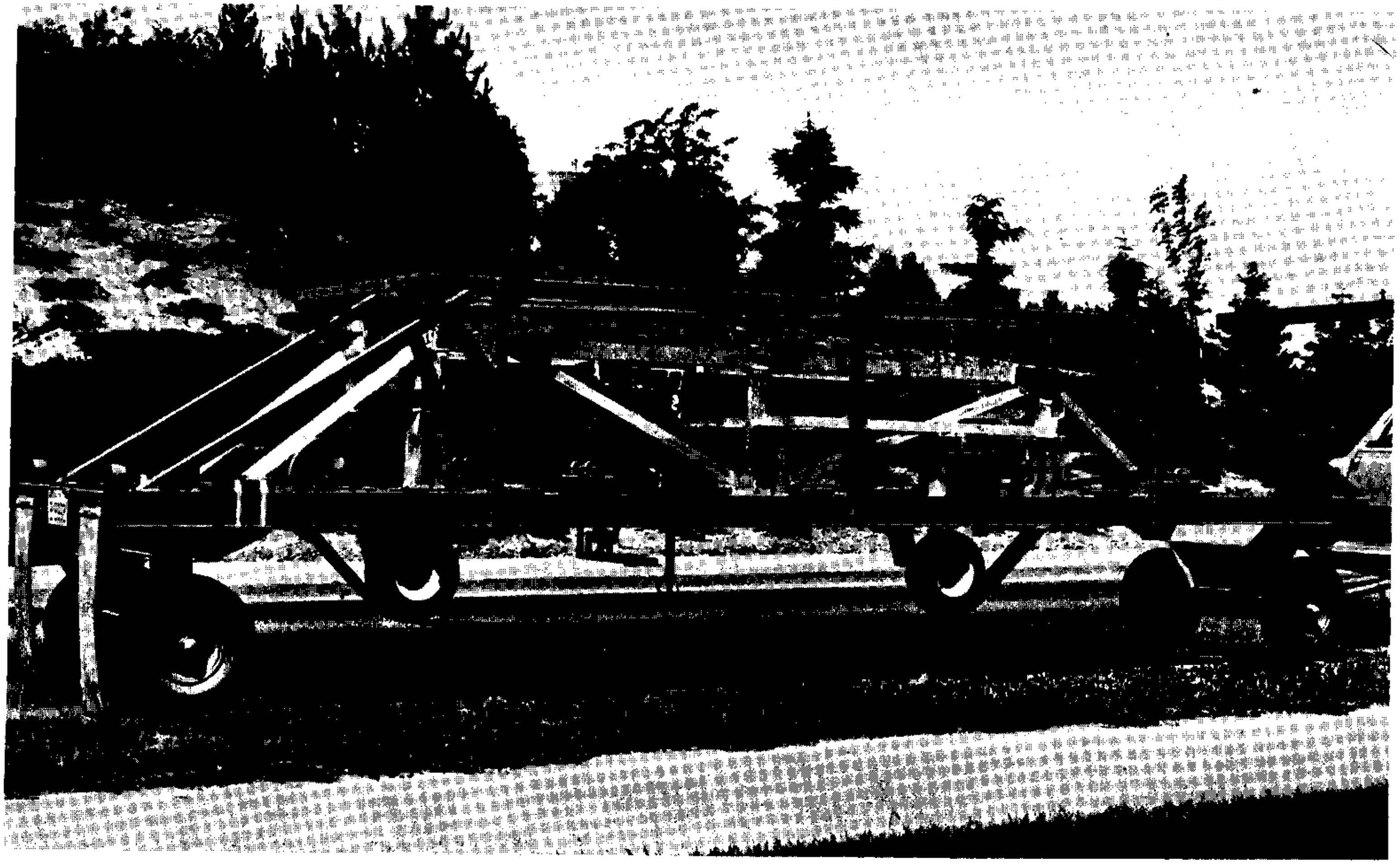


FIGURE I-5

Test Model Trailer Vehicle
With Inner Frame Raised for Traveling
Showing Flat Belt System

automatically test a great number of locations and record the data in computer readable format. The hand carried version was primarily designed to be useful for spot testing local detail work, experimentation, demonstration, and acquiring additional experience and knowledge of the impulse technique of pavement evaluation. The report describes the operation of the instrument and results are presented of tests conducted on various pavements using the Impulse Index Computer. With the limited experience accrued it appears that the device is by far the fastest method yet devised anywhere for determining subsurface conditions of flexible pavements.

Report of Current Work

The purpose of the work done which is described in this report was to overcome some of the mechanical problems encountered in the test model vehicle and in the mechanization scheme. Specifically, a different belt configuration was to be tried which would eliminate the previously encountered problem of the belt slipping off its supports. The outrigger instrument carriage was to be eliminated and the transducers mounted directly on the belt for better dynamic balance.

A telemetering system was to be designed to transmit the signals from the transducers to receivers located on the vehicle main frame. The results of this work are reported in the following chapters.

CHAPTER II

THE FLAT BELT AND THE CLEATED BELT

Several mechanical difficulties encountered with the flat belt were eliminated by the change to a cleated belt design.

The Flat Belt

The most serious problem of the flat belt was its tendency to run off its pulleys if they were only slightly out of alignment, and also when the vehicle was negotiating turns.

Although the pulleys and road wheels were crowned, the lateral forces produced on the belt when it was in contact with the pavement were too great when the vehicle was negotiating turns. At times, it was possible to change traffic lanes successfully, but at other times the belt would be dislodged with only slight provocation.

Even when the belt did not come completely off its pulleys, it would wander laterally. This lateral motion jeopardized the outrigger instrument carriage, threatening to smash it against the pulley or under a wheel if the belt wandered too far. Ultimately, in the evaluation tests of the flat belt scheme, the instrument carriage did lodge under the front supporting wheel of the belt while the vehicle was in motion and was damaged.

The Cleated Belt

To correct for the problems encountered with the flat belt, a modification of the system was made using a cleated belt. Fig. II-1 is an overall view of the test model vehicle with the new system installed.

Forty-eight metal cleats were formed from one eighth inch 6061-T6 aluminum stock as shown in Fig. II-2. The cleats were bolted to a four inch wide rubber and fabric belt on eight inch centers in a configuration of a V-belt. The rubber and fabric part of the belt is narrow enough so that it can flex laterally somewhat. The purpose of designing in this lateral flexing capability was so that when the vehicle turns, the belt will track an arc instead of skidding and dragging the transducers on the pavement. To support the belt, dual motorcycle wheels were mounted near the front and rear of the inner frame of the vehicle. The cleats ride between the dual motorcycle wheels similar to the manner in which a V-belt rides in a pulley. The cleated belt and motorcycle wheels can be seen in Fig. II-3. The wheels are movable fore and aft with lead screws to permit the belt tension to be adjusted. Because it is desirable to have the belt somewhat slack in order to permit the lateral motion required in tracking an arc, parallel rails were installed to support the upper part of the belt in the region between the forward and rear sets of dual wheels.

Performance tests of this cleated belt configuration have shown it to be reliable with no major annoyances except vibration as reported in Chapter V, and it has completely eliminated the problem of running off its

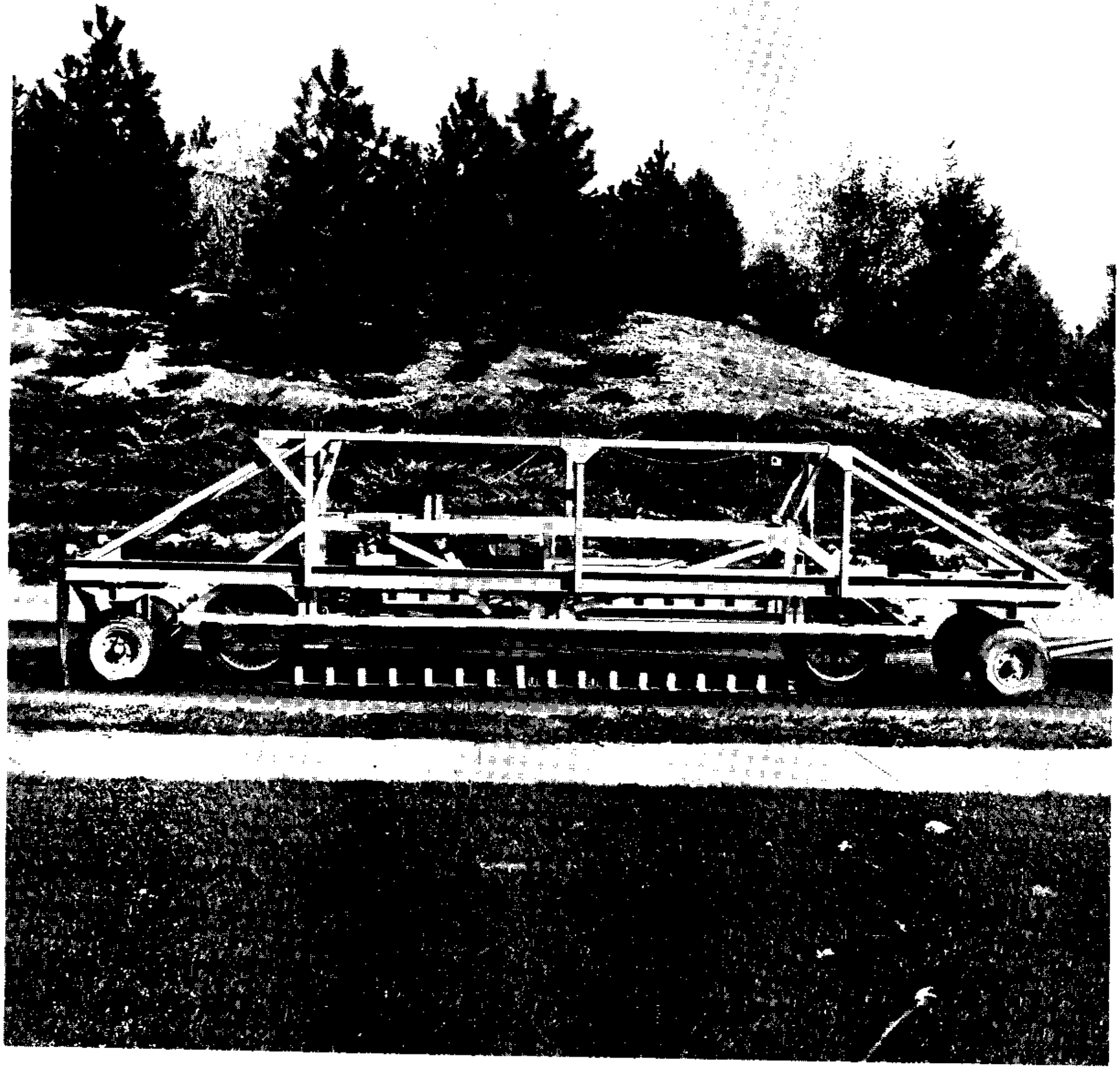


FIGURE II-I

Overall View of Test Model Vehicle
With Cleated Belt System Installed

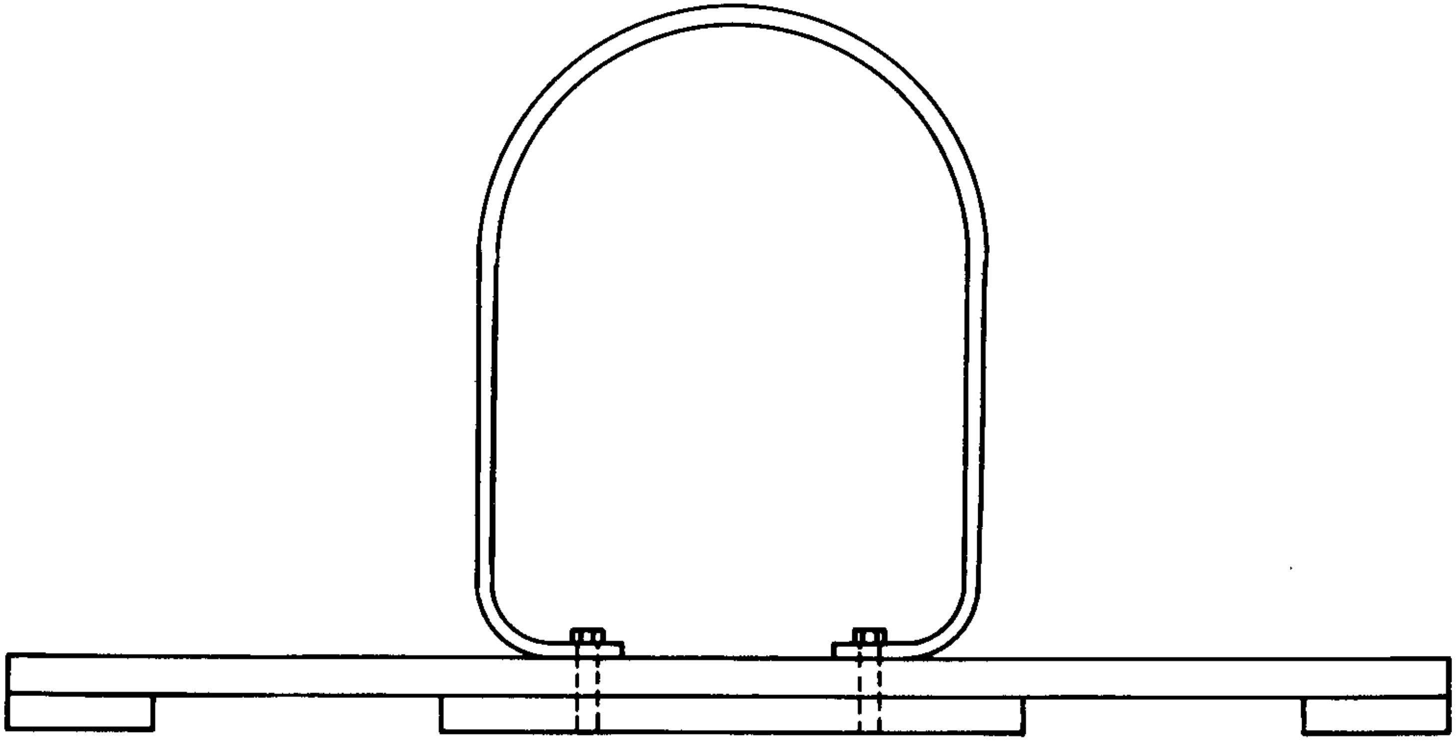


FIGURE II-2

Aluminum Cleat Mounted on Rubber & Fabric Belt

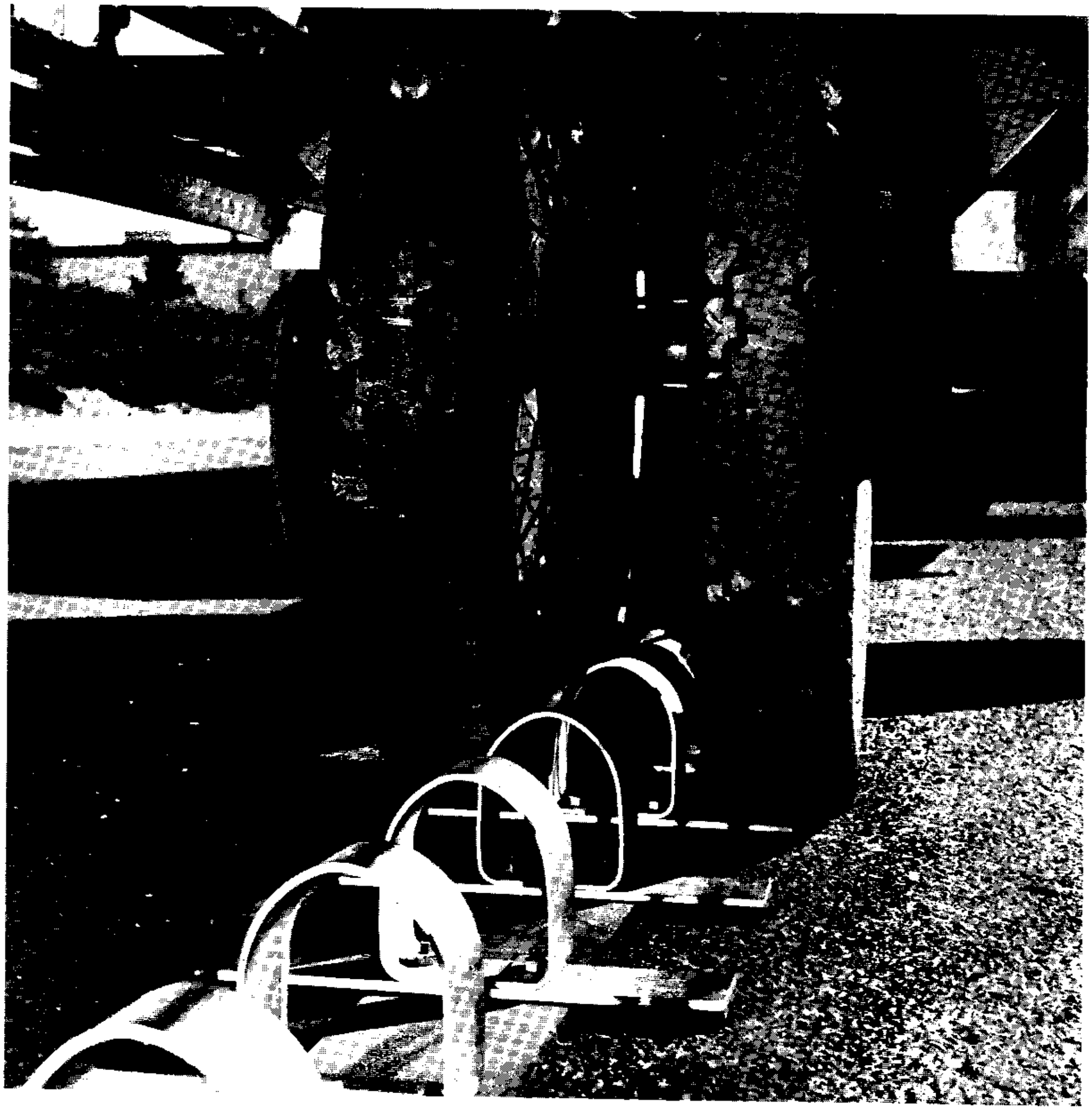


FIGURE II-3

Cleated Belt and Forward Supporting Wheels supports as was experienced with the flat belt configuration. The vibration is considered correctable as described in Chapter V.

Instrument Section of Belt

A five foot long section of the belt is different from the rest of the belt. This section of belt can be seen in Fig. II-4. The rubber and fabric part is tapered out to an eight inch width. Two spring steel straps provide additional stiffening of this region of belt.

On this section of the belt are mounted an extra tall cleat with a hammering pin, two accelerometers, and two telemetering transmitters.

The Tall Cleat with the Hammering Pin

One of the cleats on the instrument section of the belt is higher than the rest of the cleats. It is the same width as the others but is six and one half inches high. A one-half inch diameter hardened steel pin is inserted vertically through holes at the top and bottom of the cleat and it is held captive by two collars. Fig. II-5 is a drawing of the large cleat. The bottom end of the pin rests on the pavement and the top end of the pin is to receive the hammer blow from a pneumatic hammer. The purpose of the pin is to transmit the impulse from the hammer blow to the pavement at a point accurately located from the first transducer. This cleat is taller than the others in order to accurately synchronize the motion of the hammer during each cycle of operation. This will be explained in more detail in Chapter III which describes the action of the hammer linkage and which will make reference to this tall cleat with the hammering pin.

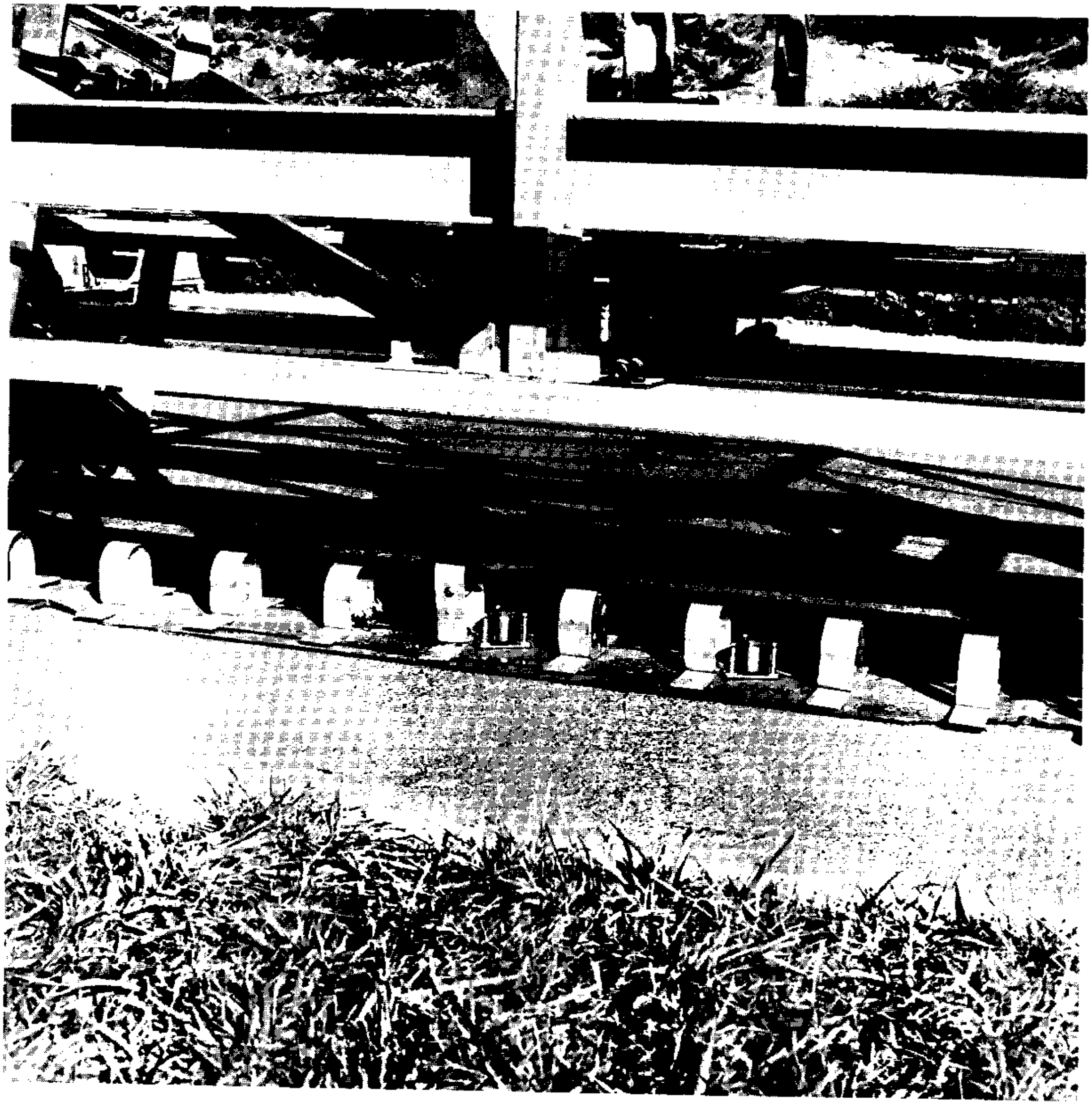


FIGURE II-4

Instrument Section of Belt

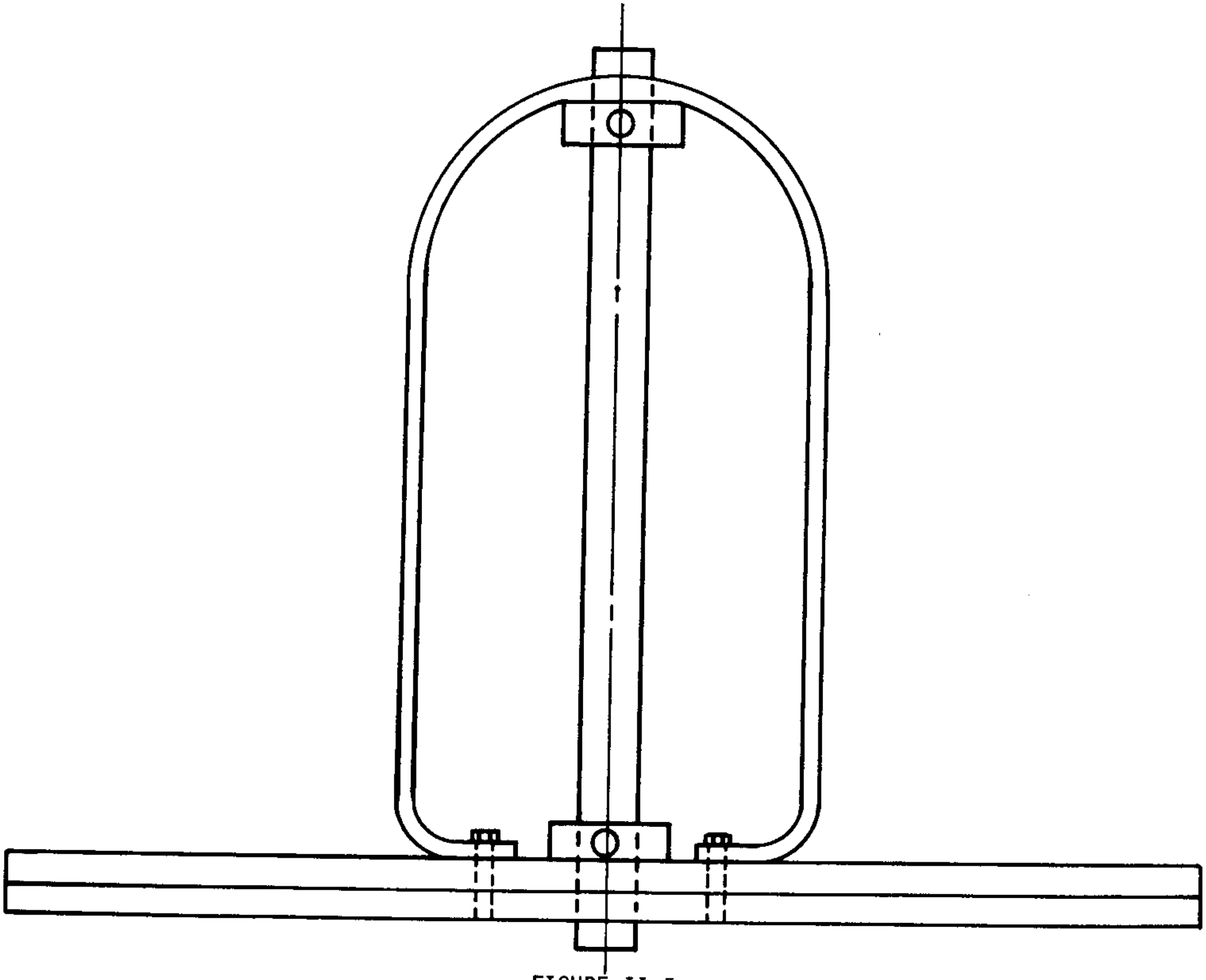


FIGURE II-5

Tall Cleat and Hammering Pin

Transducer Locations and Mounts

The first transducer is mounted on the belt immediately adjacent to the tall cleat and the second transducer is mounted eighteen inches away. These mounting locations preclude the necessity of having a separate cantilevered instrument carriage, as was required with the flat belt. Because the transducers are located on the center line of the belt the dynamics are much better behaved than with the cantilevered instrument carriage. The space between the dual wheels supporting the belt permits easy passage of the transducers around the wheels as the vehicle advances.

The transducers are mounted with specially fabricated air cushion shock absorbers as shown in Fig. II-6. The air cushions are to prevent damage to the transducers as they contact the pavement. When the section of belt bearing the transducers comes around the forward set of supporting dual wheels, the transducers would receive a severe mechanical shock when they hit the pavement were it not for these air cushion shock absorbers.

The shock absorbers each consist of a piston fitted to a cylinder with a needle valve for controlled escape of air. The needle valves are adjusted so that it requires about one half second for the air to bleed out. After this period of time, the weight of the transducer has forced the pistons to the end of their travel and the transducers are then in firm contact with the pavement and ready to perform when the hammer strikes. When the section of belt bearing the transducers comes over the rear supporting wheels to the top of its travel the transducers and their supports are upside down and

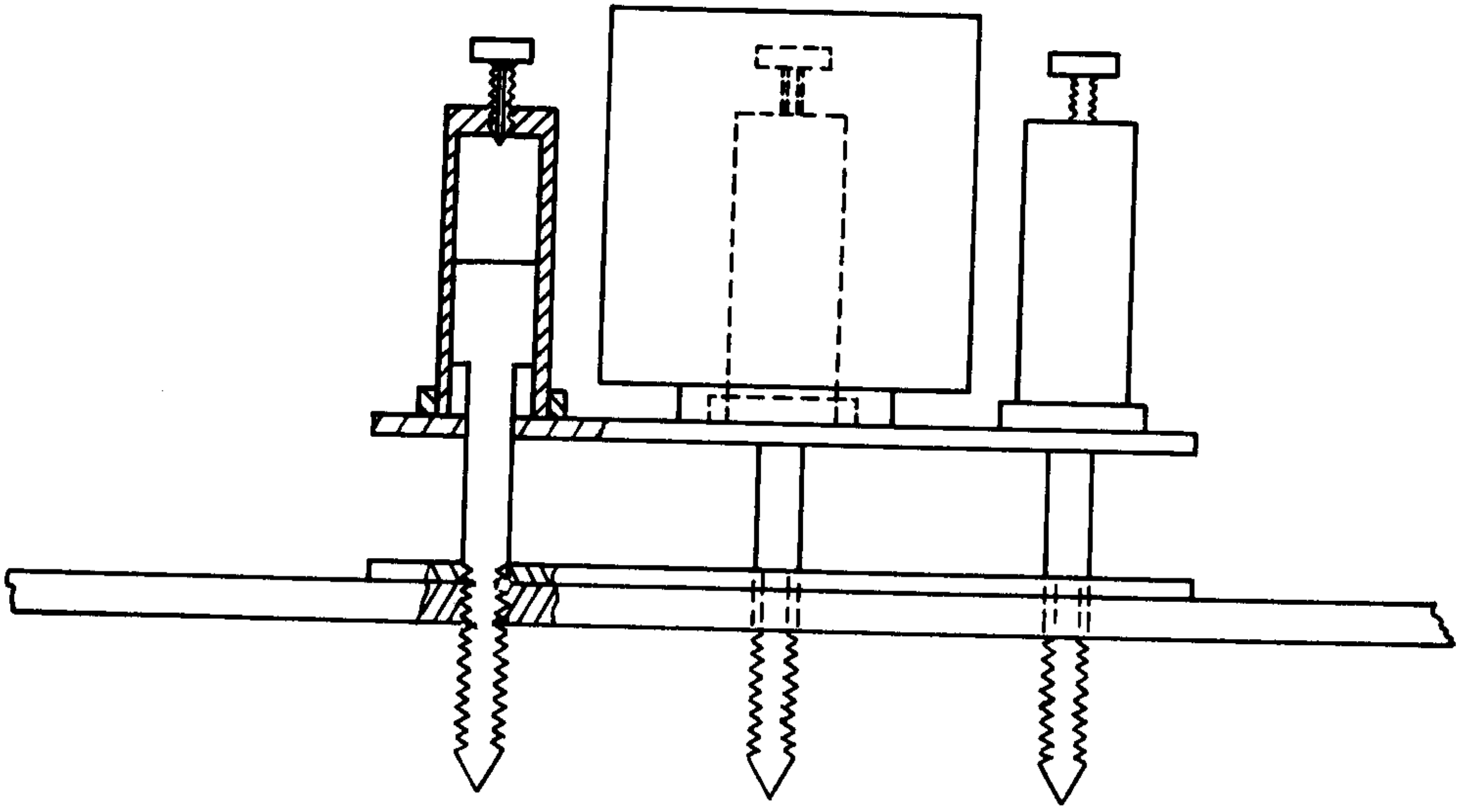


FIGURE II-6

Transducer Mount Showing The Shock Absorbers the weight of the transducers pulls the pistons to the other extreme of their travel so that the cylinders are again charged with air in readiness to repeat the cycle.

Telemetering Transmitter Mounts

Adjacent to each transducer a cleat is enclosed to house a telemetering transmitter. The transmitters are wrapped in shock absorbing material inside the cleat enclosures. The antennas are secured to the belt. The telemetering transmitters are more thoroughly described in Chapter IV.

CHAPTER III

PNEUMATIC HAMMER AND LINKAGE

After the belt has placed the transducers on the pavement, an impulse of energy of controlled magnitude must be delivered to the pavement at a point accurately located with respect to the transducers. The energy required in the impulse is not critical, but it should be between 5 and 50 foot pounds. A pneumatic hammer is used to provide the impulse. Because of its size and its energy requirements, the pneumatic hammer is not mounted on the belt, but is secured to the inner frame of the vehicle. Because the vehicle and its inner frame have a constant forward velocity with respect to the pavement, the hammer supporting linkage must give the hammer a relative velocity toward the rear of the vehicle during its stroke so that the hammer blow is vertical.

The cleated belt is rather slack in order that, when the vehicle is negotiating curves, the belt tracks an arc rather than skidding laterally and dragging the transducers. As a result of this degree of freedom of motion between the belt and the vehicle, the location of the transducers with respect to the frame is not precisely predictable. The amount of freedom is limited however, and the lateral uncertainty is taken to be less than plus and minus four inches. The impulse must be delivered with much more locational precision than four inches however.

Requirements

The hammer was designed to fulfill the following requirements.

(1) Locate the position of the hammer blow within a one-half inch circle of error as measured from the transducers whose location is predictable within a less accurate four inch circle of uncertainty.

(2) Deliver the impulse vertically and in such a manner as to not jostle the transducers through any path other than the pavement.

(3) Deliver an impulse of energy of 5 to 50 foot pounds but with a high degree of repeatability in its magnitude.

(4) Deliver the impulse on command from an electrical contact closure.

Hammering Pin

To locate the position of the impulse accurately, a one-half inch hardened steel hammering pin was mounted in the cleat nearest to the first transducer. This cleat is taller than the others, and the hammering pin protrudes through holes in its top and its bottom so that the lower end of the pin rests on the pavement and the upper end is in position to receive the hammer blow.

The pin is accurately located with respect to the transducers and is held captive in the cleat by a pair of collars. Fig. II-5 is a drawing of the tall cleat with the hammering pin, and Fig. II-4 is a photograph showing the relative locations of the hammering pin and the transducers.

The hammer is built with an eight inch wide foot, so that the hammer will contact the hammering pin regardless of the relatively large potential lateral displacement between the two.

The fore and aft relative positions of the hammering pin and hammer are handled by the synchronizing feature of the hammer linkage, described in the following section.

Hammer Support Linkage

To deliver a vertical stroke to a stationary hammering pin from a moving platform requires that the hammer be supplied with compensating motion toward the rear of the vehicle during its stroke. A twin four bar linkage was designed on which to mount the hammer and to operate in such a manner that during a portion of its cycle the hammer is in exact synchronism with the tall cleat of the belt. Fig. III-1 and III-2 are schematic diagrams and Fig. III-3 is a photograph of the linkage.

In operation, the rotation of the rear belt support wheels provides the power to operate the hammer linkage. Referring to Fig. III-2 a sprocket on the support wheel drives a chain which powers an idler shaft through a Dodge Torque Tamer. The Torque Tamer is to prevent destructive forces in the event of some interference with the motion of the linkage. The idler shaft turns two additional sprockets, one for each of the twin four bar linkages. Each of the twin four bar linkages has an arm with one end secured to the center of its drive sprocket and the other end projecting radially so that as the drive sprocket is rotated, the projecting end

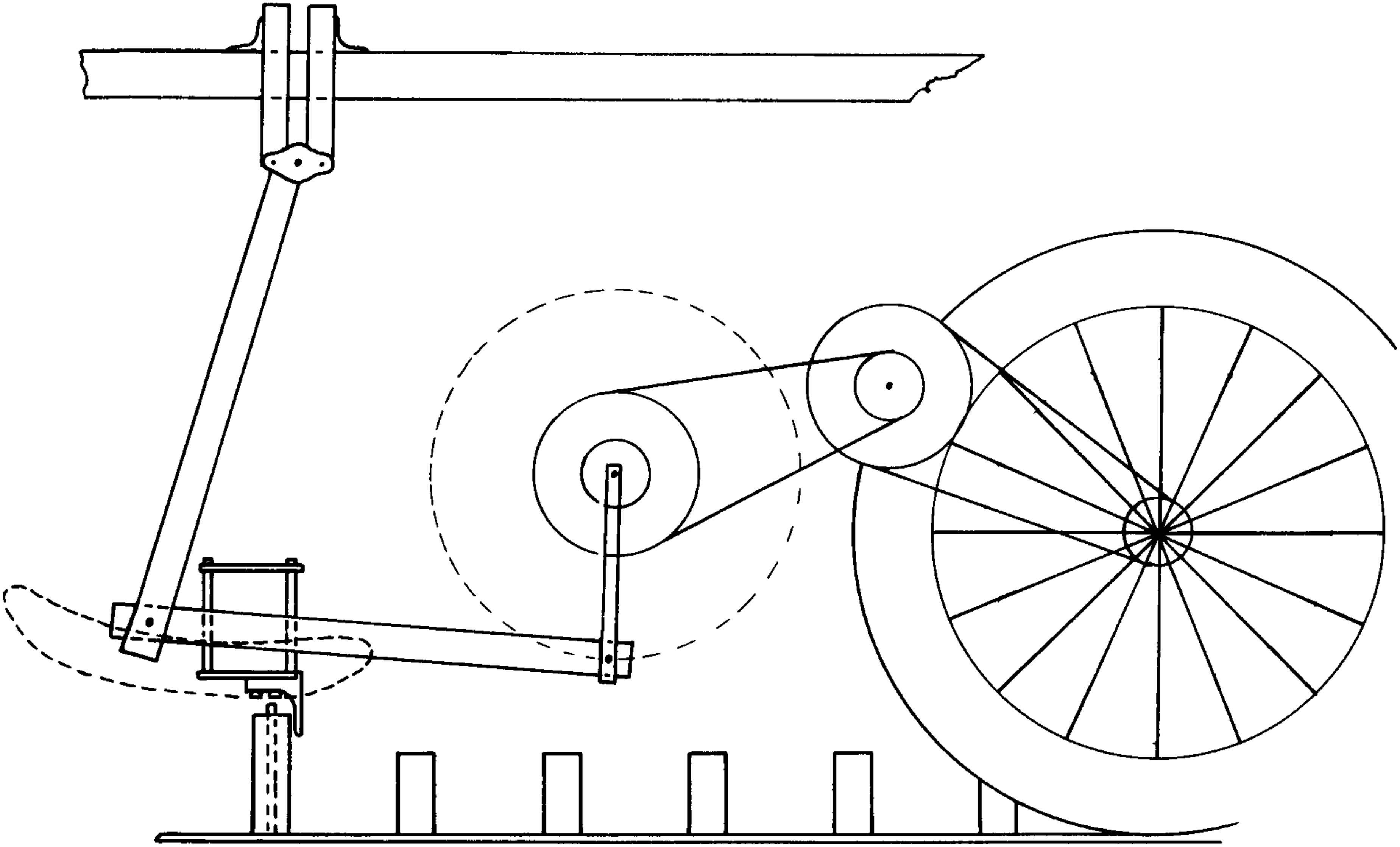


FIGURE III-I

Schematic Diagram of Hammer Support Linkage
Showing Path of Motion of Hammer

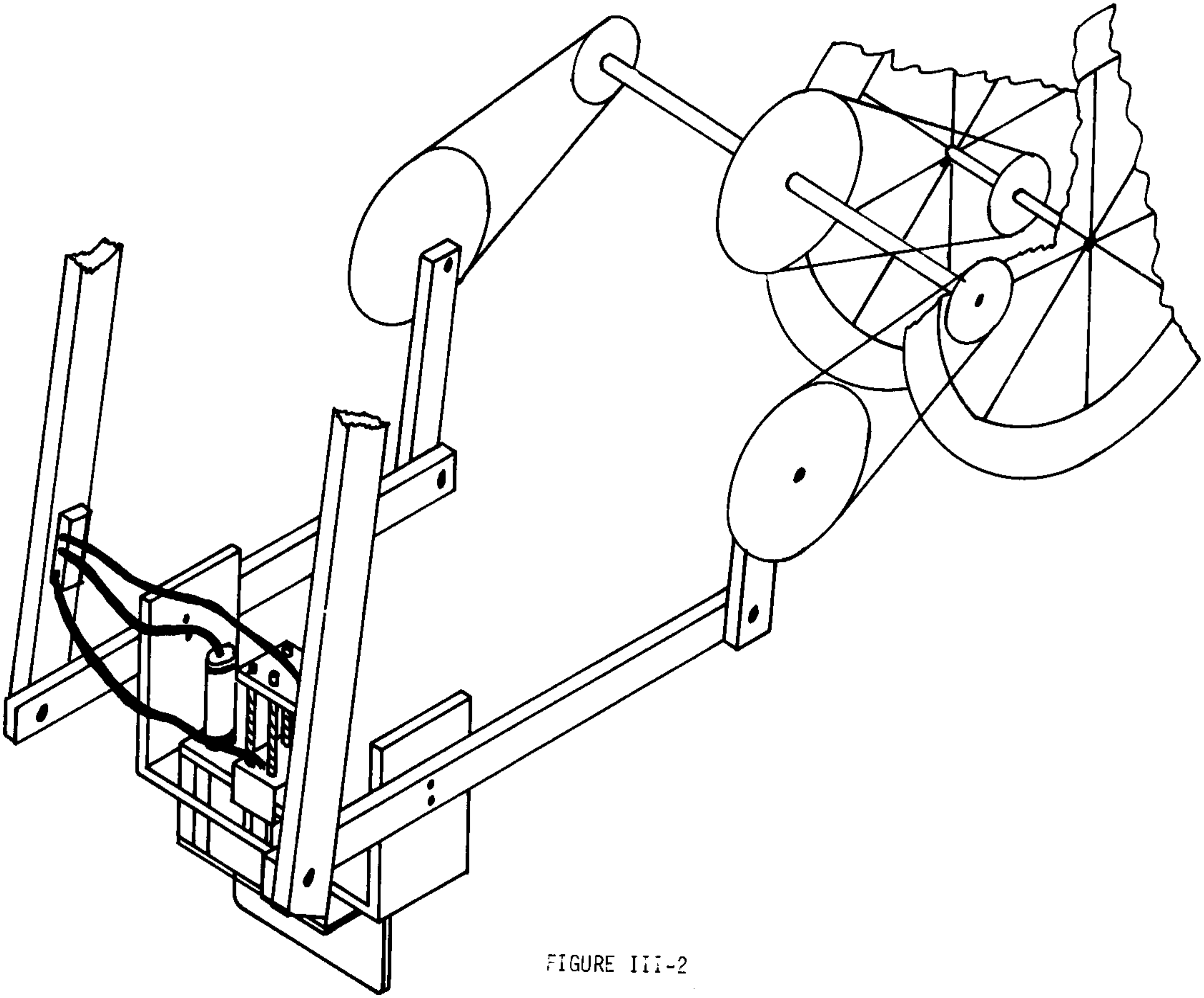


FIGURE III-2

Perspective Diagram of Hammer Support Linkage

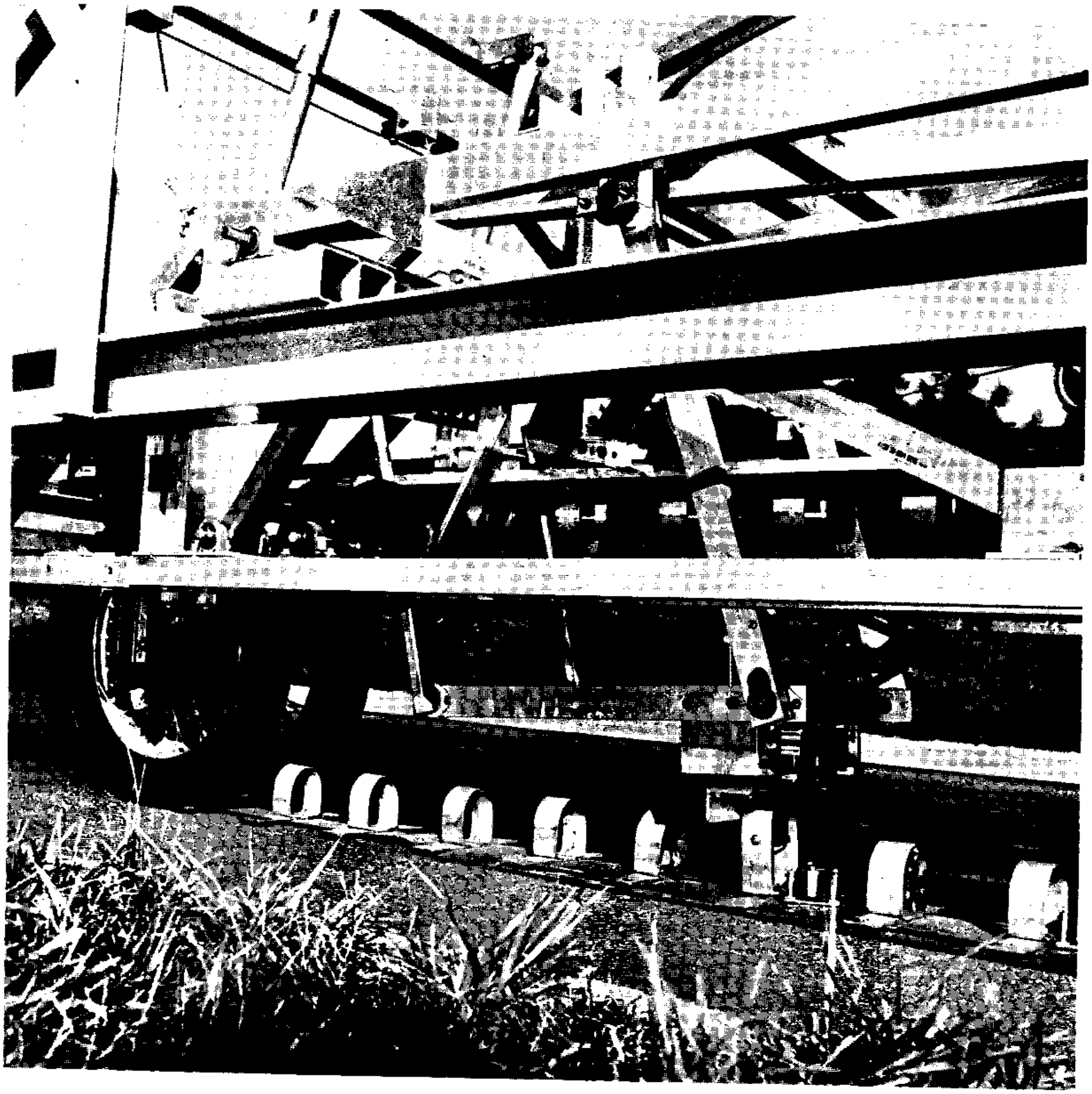


FIGURE III-3

Photograph Showing Hammer Support Linkage describes a circular path. This radius arm drives a coupler arm, the opposite end of which is pinned to a rocker arm. The other end of the rocker arm is connected to the vehicle inner frame with a pivot bearing. The hammer is attached to the two coupler arms and the resulting path of the hammer can be seen in Fig. III-1.

The lengths of the arms of the four bar linkage were determined using an IBM 360 to yield the straightest path for the hammer possible within the space provided in the lowest region of its travel, in which region it must engage the tall cleat on the belt and deliver its blow.

The lower part of the hammer mount path is not actually a straight line, but does have a large radius of curvature. The hammer is mounted to the coupler arms with a spring suspension to provide the final flattening of this path. The spring loading thereby provided on the tall cleat and hammering pin has an additional advantage in serving to hold the cleat and pin firmly in place laterally while it is struck with the hammer.

Linkage Drive

The drive speed ratios for the sprockets were selected so that for each revolution of the cleated belt, the hammer support linkage makes slightly less than one complete cycle. A synchronizing scheme then causes the differences in the two cycles to be eliminated when the hammer engages the tall cleat.

To facilitate the synchronization each of the final sprockets in the power train to the four bar linkages drives through an over-riding clutch.

A force applied to the hammer can advance it in its cycle but cannot retard it. As the hammer moves into the vicinity of the belt at its most forward position, the tall cleat on the belt engages it and over-riding the powered drive, drags it through the part of the cycle during which the cleat and hammer are in contact. Exact fore and aft positional accuracy is thereby maintained as well as exact synchronism of hammer and cleat during the critical part of the cycle.

When first assembled the over-riding clutches permitted the weight of the hammer to cause undesired over-riding during part of the cycle. Counter balancing was added to correct for most of this. In addition to the counter balances, small caliper type drag brakes were installed in parallel with the over-riding clutches. In order to over-ride the drive, the drag brakes must also be over-ridden. The tension on the brakes is adjustable so their drag can be set to the minimum required to prevent over-riding due to unbalance but yet permit over-riding by the tall cleat.

The tall cleat must provide the force to cause the over-riding and produce synchronism of the belt and hammer. To hold the cleat vertical while delivering this force, guy wires are attached from the top of the cleat to the lower part of the adjoining cleat. To provide additional stiffening, spring steel straps tie five of the cleats together in the region which includes the tall cleat. The photograph of the linkage shown in Fig. III-3 shows the tall cleat just coming into contact with the hammer initiating its over-riding action.

The Hammer

Fig. III-4 is a schematic diagram and Fig. III-5 is a close-up photograph of the hammer. The hammer itself is driven by two short stroke double acting pneumatic cylinders. The air supply is a high pressure storage cylinder mounted on the main frame of the vehicle. An adjustable regulator reduces the pressure to the desired amount. The air is then passed through a filter and a four way pilot operated high speed valve with three eighths inch NPT ports. The valve is electrically actuated and when the power is off air is connected to the lower chambers of the pneumatic cylinders, holding the hammer in the up position. The large ports on the valve were found to be necessary for a fast stroke of the hammer. When electric power is supplied to the four way air valve, the air pressure is routed to the upper chambers of the pneumatic cylinders, the lower chambers are exhausted to the atmosphere, and the hammer delivers its stroke. The pneumatic cylinders are mounted on a movable frame which is positioned on top of the hammering pin and tall cleat when it is poised for action. The blow of the hammer impinges on the upper surface of the bottom plate of the movable frame and the energy is transmitted through the plate to the hammering pin and thence to the pavement. The movable frame is eight inches wide so that the hammering pin is engaged by the hammer even if the tall cleat is laterally displaced up to four inches from the center line of the vehicle. Lateral displacement of the tall cleat occurs when the vehicle negotiates curves in the road and the belt tracks an arc.

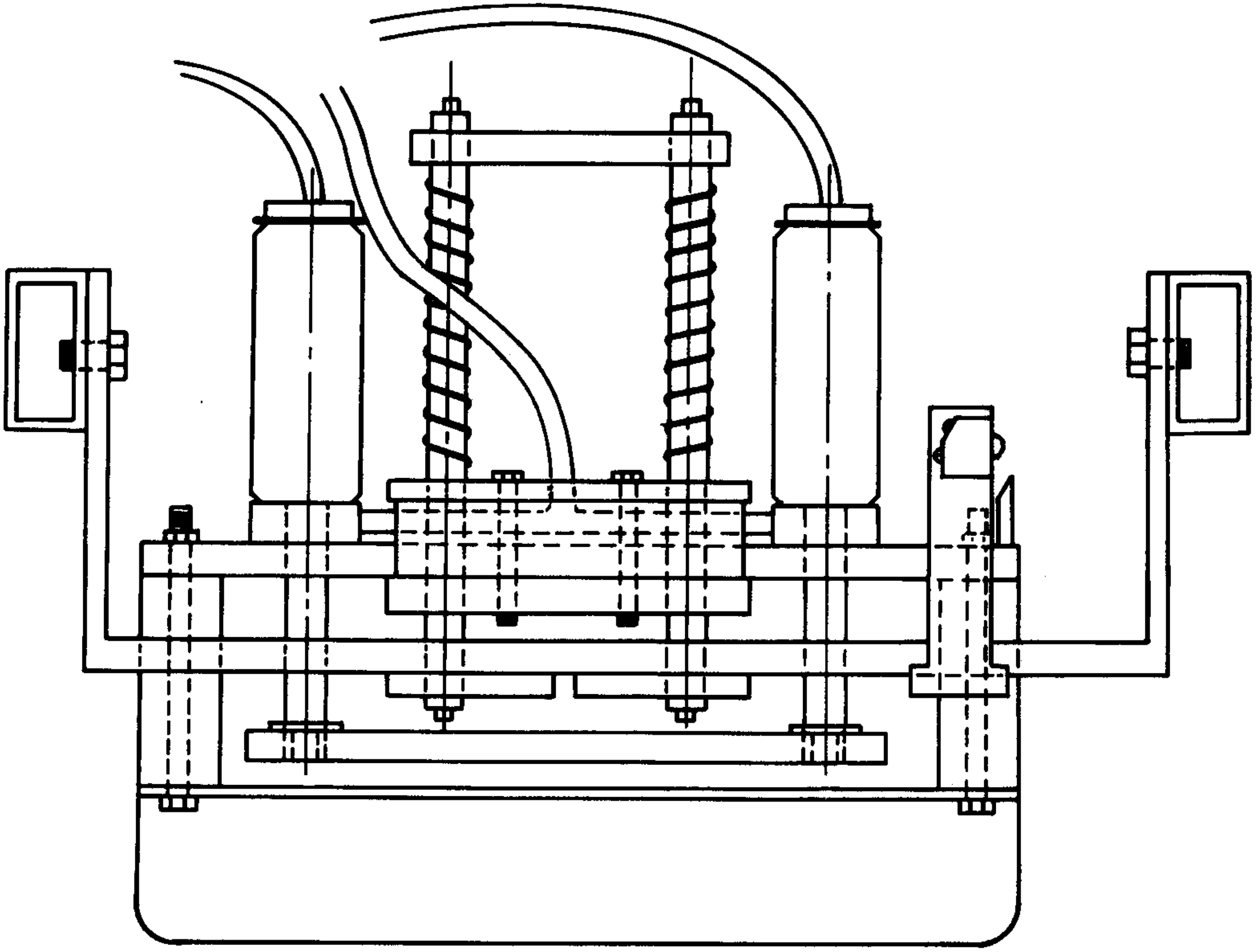


FIGURE III-4

Diagram of Pneumatic Hammer

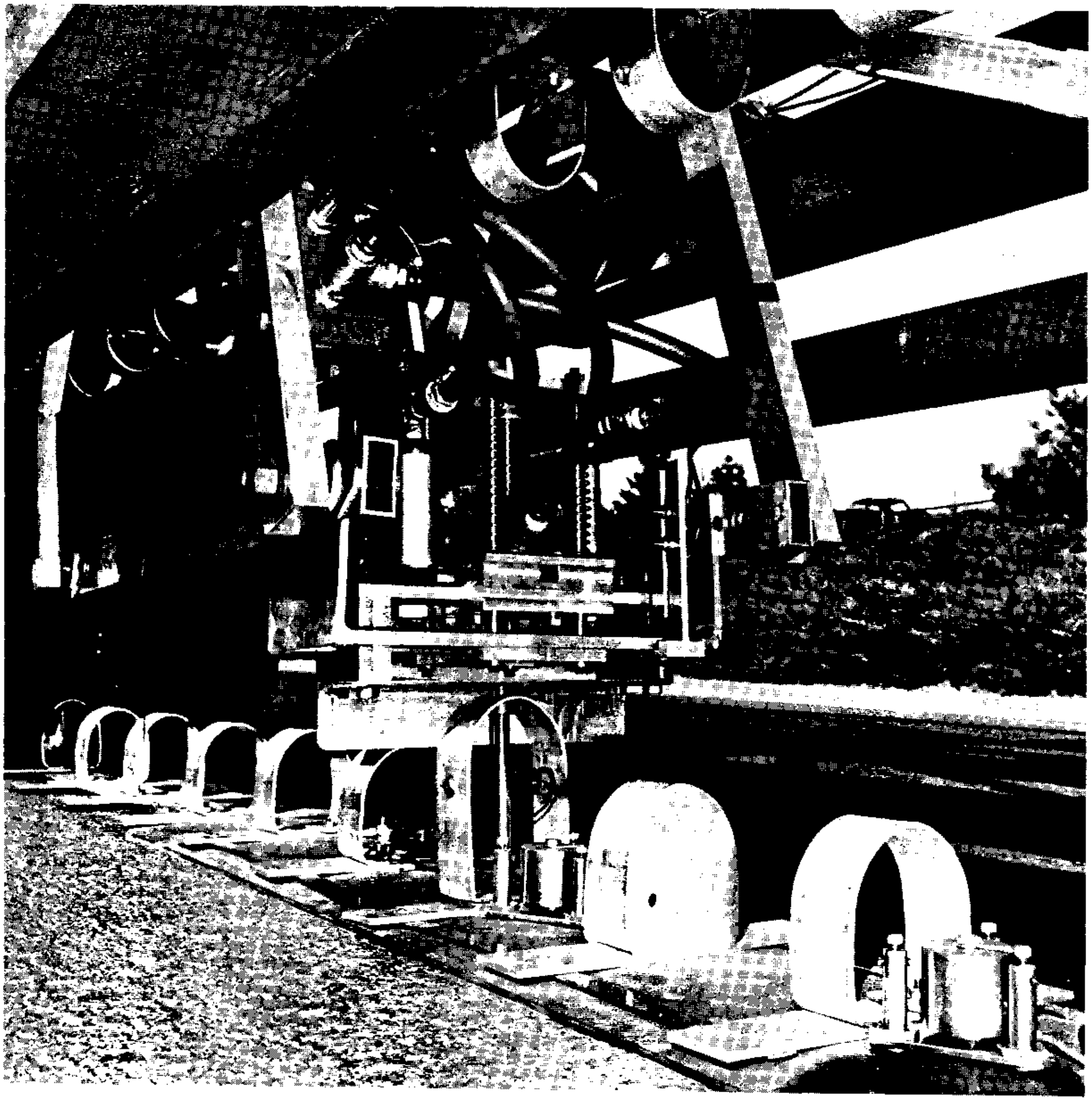


FIGURE III-5

Close-Up Photograph of Pneumatic Hammer

The movable frame is mounted by means of four sets of linear ball bearings on four hardened steel shafts so that it can be displaced vertically with respect to the four bar hammer support linkage. Springs wound on each of the four shafts provide downward pressure on the movable frame. The four hardened steel shafts are secured to a cross arm which is bolted to each of the coupler arms of the twin four bar support linkage. The cross arm is mounted on the coupler arms a few inches from the bearing connecting the coupler arms to the rocker arms. This distance is fairly critical in relation to the lengths of the arms of the four bar linkage and is set to give the desired path of motion to the hammer as shown in the diagram of Fig. III-1.

The photograph of Fig. III-5 shows the hammer immediately after it has engaged the tall cleat and the springs on the four shafts are only slightly compressed. As the vehicle advances a few more inches, the cross arm support and the four shafts are moved downward due to the action of the coupler arms, and the springs are compressed more. As this motion proceeds, a microswitch is depressed. The microswitch closes the electrical circuit to the four way air valve and the hammer strikes. The movable frame exerts sufficient force on the tall cleat during this process that the cleat is not appreciably moved horizontally by the hammer blow. Horizontal movement during the process could drag the transducers over the pavement surface, causing an intolerable amount of electrical noise in their outputs.

Road Tests

The vehicle with hammer linkage installed was road tested to check its operation. The transducers and the air tank were not as yet installed. The tests were primarily intended to determine if the hammer linkage would operate successfully, and if the tall cleat could do its job of re-timing the hammer linkage each cycle and synchronizing the motion of the hammer to its own motion relative to the vehicle.

At speeds of two or three miles per hour the hammer and tall cleat successfully engaged with each cycle and a constant forward velocity could be maintained. As the speed was increased, the bending force on the tall cleat caused by the drag of the hammer would tip it an increasing amount, but it continued to operate successfully. The maximum speed obtained was about eight miles per hour at which speed the tall cleat was noticeably tilted and in addition vibrations in the machine discouraged any attempts to increase the velocity further.

The principal origin of the vibrations appears to be from the dual motorcycle wheel belt supports riding over the washboard surface presented to it by the bars of the cleats which contact the pavement. Fig. II-3 provides an excellent view of the source of the problem. The horizontal bars of the cleats are two inches wide and, with their rubber pads, are three-eighths inch high and spaced eight inches on centers, thereby providing regularly spaced ripples in the roadbed traversed by the wheels and causing the vibration observed.

No attempt was made to alleviate the problem at this time because it was considered to be more appropriate to accept temporarily the limited speed of the vehicle and concentrate effort instead on other aspects of the project. A suggested method for substantially reducing the vibration is to install two or three horizontal bars on the belt in between each of the present cleats, making the space between the bars too short for the wheels to drop into and therby giving the wheels a smoother ride.

CHAPTER IV

TELEMETERING

The transducers which generate the signal containing the pavement condition information are mounted directly on the belt, and a system was required to retrieve the signals. Direct wiring is not possible because the belt is in motion and wires would be continually wound up and twisted. The most appropriate solution to the problem appeared to be to transmit the signals over short distance telemetering links from the belt to receivers placed on the main frame of the vehicle or in the towing vehicle.

Signal Flow Location

The decision was considered as to exactly where in the data flow diagram the telemetering link would best fit. It is of major concern that the telemetering link must not permit errors in the information to be generated by such phenomena as transmitted signal strength. A frequency modulated link is therefore a good selection.

The first location considered is shown in the Signal Flow Diagram of Fig. IV-1 as point A. This location presented the advantage of requiring only one transmitter and receiver. The signal to be transmitted from this point is essentially a D.C. level. In order to transmit a D.C. level or very low frequencies, more accurate results would be obtainable by using the signal to first modulate an audio frequency range voltage controlled oscillator and the voltage controlled oscillator would in turn modulate the

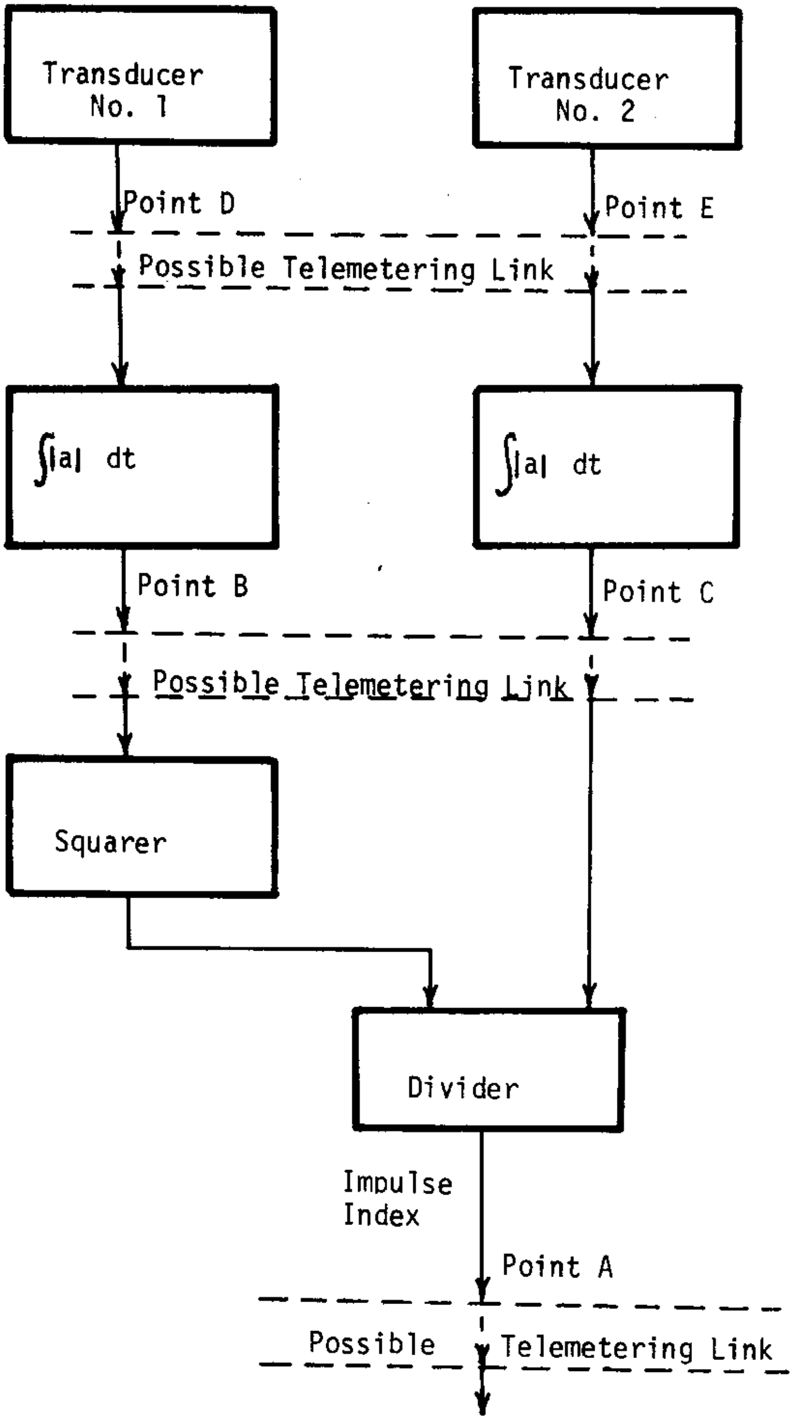


FIGURE IV-I
Signal Flow Diagram

transmitter. The receiver would have to be followed by an audio frequency discriminator to recover the signal. The quantity transmitted from point A would be the Impulse Index. The Impulse Index Computer and its batteries would have to be mounted on the belt. The aluminum cleats can be closed off to create protected spaces for installing such hardware as required.

Concurrently with the development of the test model vehicle, the hand carried suitcase sized version of the Impulse Index Computer (3) was being designed and fabricated. Experience with this instrument demonstrated the value of receiving for recording not only the computed Impulse Index but also the time integral of the magnitudes of the outputs of the transducers, thereby permitting plotting of the deflection profile as well. For this reason it appeared more desirable to install the telemetering link at points B and C on the Signal Flow Diagram as shown on Fig. IV-1. Telemetering at these points would require two transmitters and receivers having characteristics similar to the previous requirements. The two links would have to transmit and receive the signals without altering their relative magnitudes, or errors would be generated.

Further investigation of the problem caused the consideration of inserting the telemetering link directly after the transducers at points D and E on the Signal Flow Diagram. The signal at this point has no D.C. component of importance and all of the frequency components of interest lie in the audio spectrum. The voltage controlled oscillators would no longer be required, nor would the audio frequency discriminators in the receiving equipment. The requirements that the two links transmit the signals with faithful relative magnitude reproduction still exists, but no more stringently than with the other methods. An added advantage of inserting the telemetering at points D and E is that it minimizes the amount of electronic equipment that must be installed on the belt with its rather severe environment and accelerations. Preliminary bench tests were performed to determine if there existed any unrecognized problem of telemetering the signals directly produced by the transducers.

After examining all the alternatives, it was clear that the most desirable locations in the Signal Flow Diagram for the telemetering links are immediately following the transducers as shown on the Signal Flow Diagram at points D and E, and these points were consequently selected.

Telemetering Transmitters

Federal Communications Commission regulations governing transmitters permit low power devices to be operated under specified conditions in several frequency bands. The technical requirements of the telemetering link required for this project were determined to be not severe. The transmitting range required is only a few feet, the frequency spectrum of the information to be transmitted is within the audio band, and the stability requirements can be met with ordinary frequency modulation equipment.

The fastest and most economical solution to the telemetering link requirement appeared to be to use already developed equipment wherever possible. Several transmitters were investigated and two Electro-Voice Model DM-55 wireless microphones were finally selected for use. The frequency spectrum of the emitted signal from this model was monitored on a Hewlett Packard 8550 series Spectrum Analyzer and proved to be exceptionally clear and stable.

The Electro Voice DM-55 operates into any ordinary FM receiver and is tuneable. Two small battery operated FM receivers are used to receive the signal and the signal is available at the earphone jacks of the receivers.

Enclosures were built for the two metal cleats on the belt nearest to the location of the transducers to house the transmitters. There is ample room in each cleat for one transmitter and its battery with foam padding to protect it from mechanical shock.

The transducers were coupled to the transmitters and the transmitters were tuned to two separate frequencies. One radio was tuned to receive the signal from transducer number one, and the other radio was tuned to receive the signal from transducer number two. An oscilloscope was used to view the signal at the earphone jacks of the receivers, and it was determined that the signals could be easily received up to twelve feet from the transmitters. With care, additional range could be obtained. Using a Tektronix Model 454 memory oscilloscope the waveform of the signals from the receiver were compared with the waveforms of the signal directly from the transducer and the fidelity of reproduction was observed to be quite satisfactory with no important differences noticeable between the two signals.

The final tests were made with the compressed air supplied to the pneumatic hammer and with the two channel memory oscilloscope monitoring the receiver outputs. The forward motion of the vehicle advanced the hammer into its firing position on top of the tall cleat and the mircoswitch caused it to strike at the correct time in its cycle. The resulting oscilloscope traces were clear and strong with the expected waveforms and had no noticeable extraneous noise. Repeated testing with the pneumatic hammer supplying the impulse demonstrated reliable operation of the telemetering link.

CHAPTER V

TEST RESULTS AND RECOMMENDATIONS

Belt and Cleats

During the course of the project, tests were conducted from time to time to evaluate performance. The hammer linkage and cleated belt were road tested at velocities up to about eight miles per hour without the transducers attached to the belt. The tall cleat of the belt engaged the hammer as designed and caused it to synchronize its motion with the ground. As the speed was increased from about two or three miles per hour, the force exerted on the tall cleat by the drag of the hammer linkage caused it to tilt visibly, however the synchronizing action continued to function. As the speed was increased the tilting increased. Operation continued to speeds of about eight miles per hour, when vibrations became sufficiently severe that additional velocity was not attempted.

The principal source of the vibration is attributed to the washboard surface presented to the motorcycle wheels supporting the belt by the horizontal tread bars of the metal cleats. The rough surface presented to the wheels can be clearly seen in Fig. II-3. Time did not permit attempts to rectify this problem, however a suggested remedy is to attach two or three additional horizontal tread bars in between each of the existing widely spaced bars thereby effectively smoothing the path for the wheels. It is desirable, however, to keep the belt as light in weight as possible. The cleated belt presented no other problems and cannot come off its supports, which was the main problem with the flat belt previously used.

While the tall cleat does perform its function, it should be made mechanically more rigid because it tilts due to the drag of the hammer as vehicle speed is increased.

Telemetering Link

The telemetering link was tested for its ability to transmit the signals from the transducers located on the belt to receivers located a sufficient distance from the belt to permit flexibility in their mounting location elsewhere on the vehicle main frame. The signal as reproduced by the receiver was also checked and found to be an adequately faithful reproduction of the original transducer signal.

Pneumatic Hammer

The pneumatic hammer was tested for the adequacy of its strike to create a satisfactory impulse. The air supply used was a high pressure cylinder with an adjustable regulator. Tests were conducted with the regulator set between 60 and 80 pound per square inch. This produced a fast strike of the hammer and the resulting signals from the transducers were strong and normal in appearance. The hammer blow did not produce any observable lateral motion of the hammering pin or the belt.

Transducers

The transducers used were of the same type as have been used very successfully on the hand carried suitcase sized Impulse Index Computer. These transducers produce a large signal under the conditions of normal use, and have been sufficiently rugged that no problems were experienced with them while installed in the suitcase.

It was recognized that the transducers installed on the belt would be subjected to much more physical abuse than in the hand carried device, and they were mounted on specially constructed air cushion shock absorbers in an effort to reduce the shock sufficiently. Despite this precaution, one of the transducers did break during the tests.

The amount of signal produced by a piezoelectric crystal is proportional to the stress induced in the crystal. These transducers were designed for large signal outputs and consequently develop high stresses in use.

It appears that the pneumatic hammer can be made to supply an impulse of greater energy than is obtained using the drop hammer installed on the suitcase version. Consequently, the transducers probably do not need to be quite as sensitive and could be made to be more rugged by using a smaller mass. In addition, the stress region where the breakage occurred can be relieved somewhat.

Alternatively, the piezoelectric crystal can be fabricated as a hollow cylinder and the mass and supporting stem arranged concentrically to provide a more rugged but less sensitive transducer.

In addition it is recommended that the entire transducer be mounted in a sturdy enclosure to protect it from accidental blows.

Additional Tests

The conclusion of the time allotted for this project brought a termination to additional tests on the system as currently installed on the test model vehicle. It is clear that substantial improvement in the design concepts have been made over the first system installed using the flat belt. At this time there does not appear to be any major impediment to the present scheme being refined into a working design although additional evaluation tests should be made, especially on the suggested modifications.

While observing this machine in action, another system for performing the task of the vehicle has been conceived and is described in the following section of this chapter. It appears to have several advantages over the cleated belt system, and no disadvantages have as yet been exposed.

Transducers on Hammer Linkage System

Considerable design effort went into the twin four bar linkages which support the hammer with the cleated belt system. The effort was aimed at making the path of the hammer coincide with the path of the transducers during the part of the cycle when measurements are being made. It does this job so effectively that it seems reasonable to mount the transducers along with the hammer on the linkage and do away with the belt. The hammer foot would have to be somewhat re-designed to come down to the pavement, but pavement friction would then do the job of synchronizing which the tall cleat now does.

The advantages of this system are that the belt is eliminated, the telemetering would not be required, and the synchronizing problem would be simplified. Any disadvantages are not obvious at this time.

BIBLIOGRAPHY

1. Brands, Frank and Cook, John C., "Pavement Deflection Measurement-Dynamic-A Feasibility Study," Highway Research Section Publication H-32, Washington State University, June 1970

2. Brands, Frank and Cook, John C., "Pavement Deflection Measurement-Dynamic, Phase II, Highway Research Section Publication H-35, Washington State University, June 1971

3. Brands, Frank W. and Cook, John C., "The WSU Impulse Index Computer, Phase III, Section 1 (Suitcase)," Highway Research Section Publication H-37, Washington State University, August 1972.

4. Phelps, Joseph M. and Theordore R. Cantor, "Detection of Concrete Deterioration Under Asphalt Overlays by Microseismic Refraction," Highway Research Record No. 146, Publication 1421, Highway Research Board, Washington, D. C., 1966

5. Szendrei, Michael E. and Charles R. Freeme, "Road Response to Vibration Tests," Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, Vol. 15, No. 6, Nov., 1970, pp. 7709-2124.

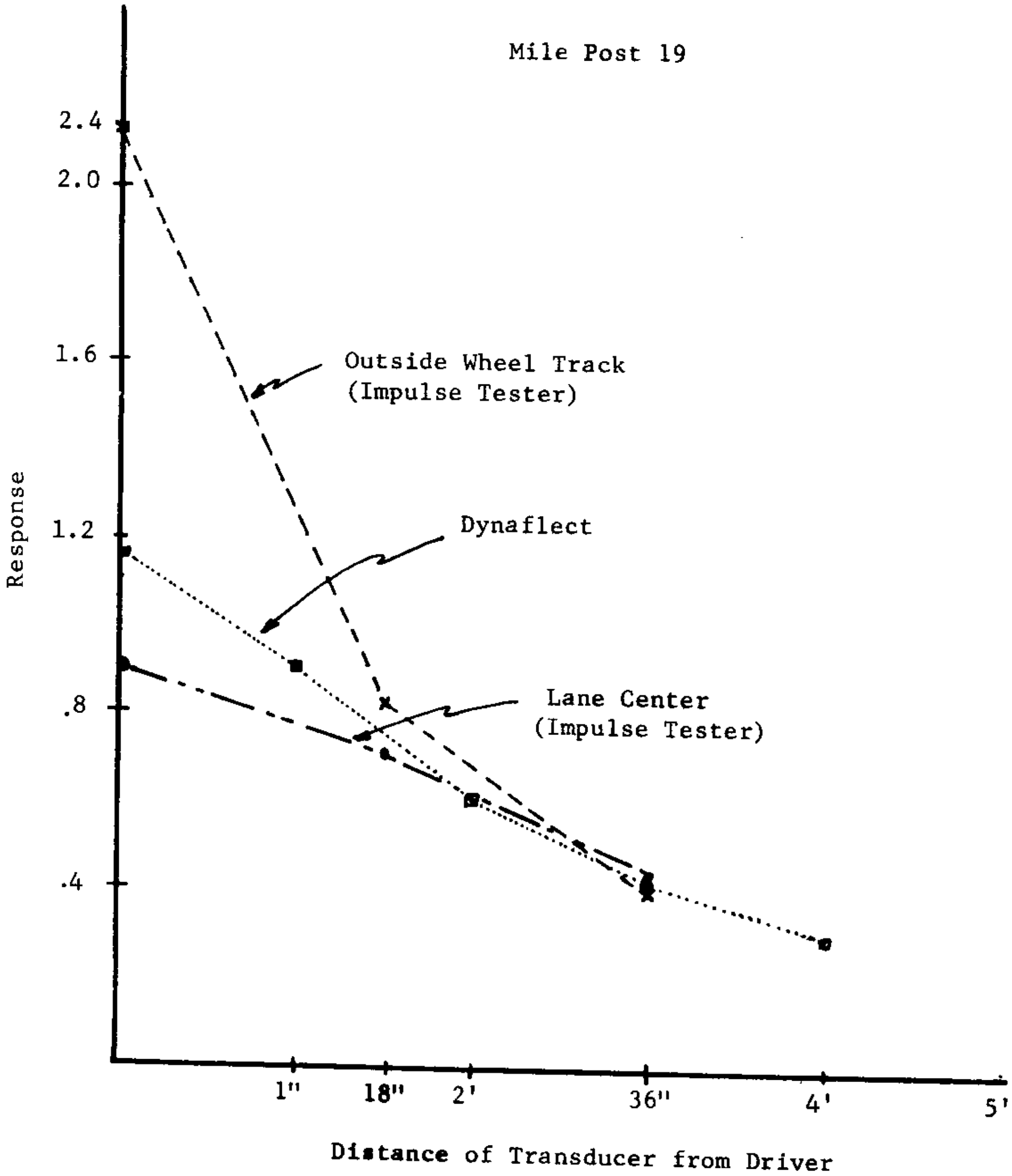
6. Bracewell, R. The Fourier Transform and its Applications, McGraw-Hill, New York, NY 1965.

7. Craig, E. J., Laplace and Fourier Transforms for Electrical Engineers, Holt, Rhinehart, New York, NY 1964.

8. Cheng, David K., Analysis of Linear Systems, Addison-Wesley, Reading, Massachusetts, May 1961.

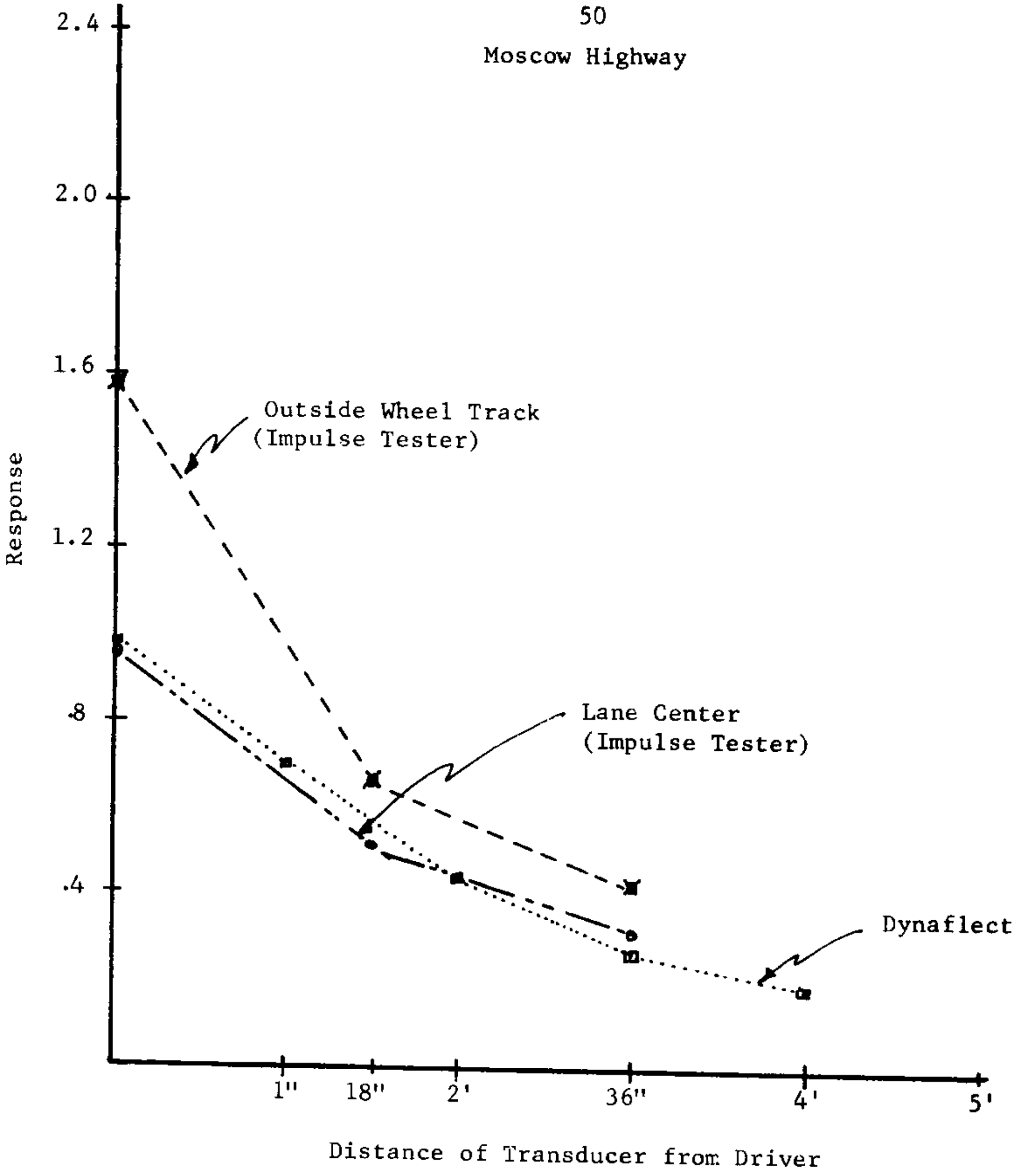
APPENDIX A

Some illustrative results of impulse testing are included in this appendix. Figures A-1, A-2 and A-3 show the profile of response from a set of three transducers using the impulse technique, and the results are plotted along with Dynaflect data taken at nearly the same points. Due to the configuration of the Dynaflect, the actual Dynaflect readings were taken somewhat toward the lane center from the outside wheel track of the pavement. The impulse test results, being much less cumbersome to obtain, were taken at the outside wheel track and also at the lane center. Notice that in each case, the Dynaflect profile falls between the impulse test profiles. This is exactly where it should be taking into account the expected deterioration of the pavement in the wheel track. Of particular significance on these curves is the obviously steeper profile of the impulse data taken in the wheel track compared to the data taken in the lane center for Mile Post 19 on the Lewiston highway and again on the Moscow highway. On the new road, this difference is significantly less because the pavement had not received much use.



Comparison of data from the transducer of the impulse tester compared to the data from the transducers of the Dynaflect.

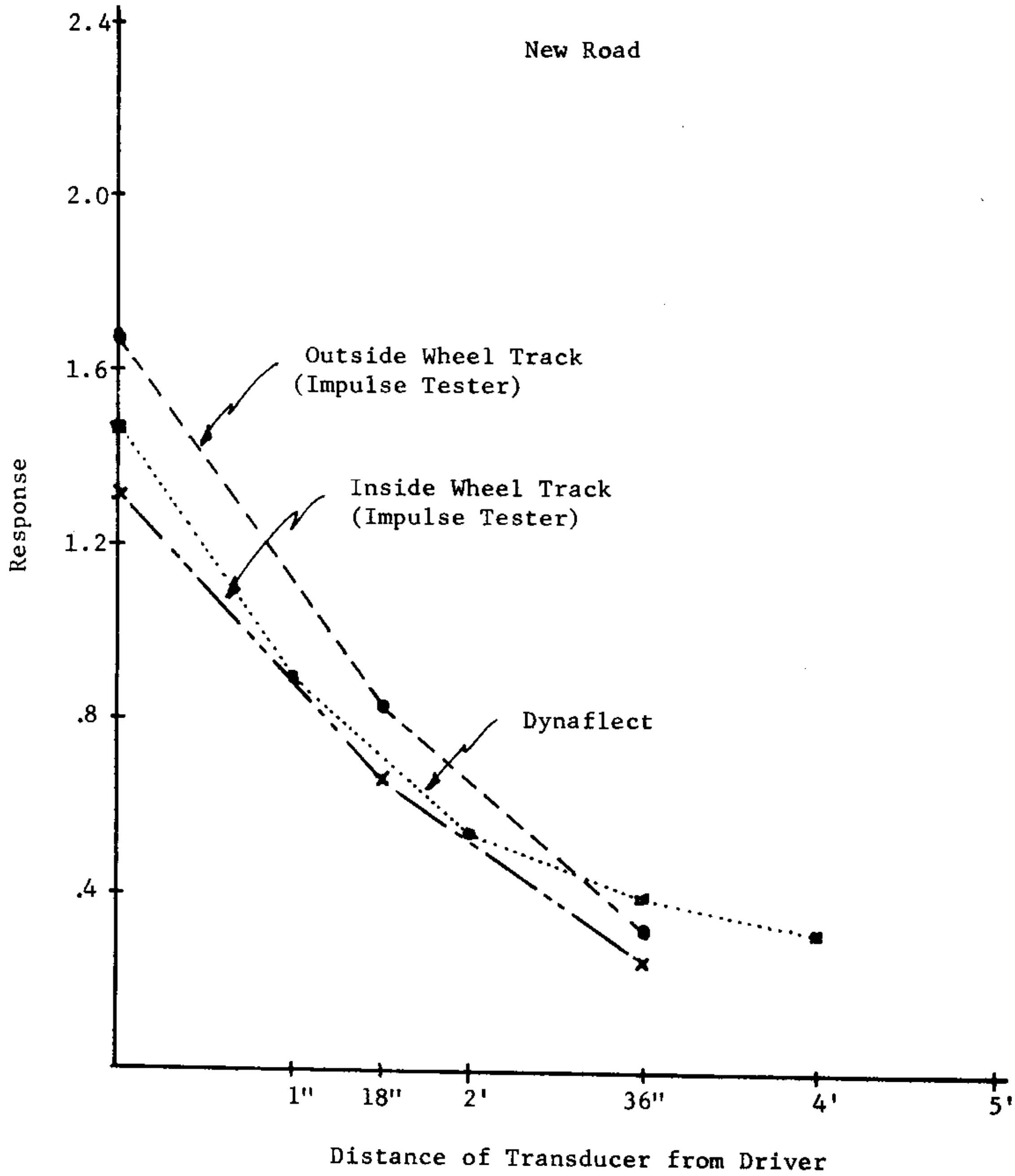
FIGURE A-1



Moscow Highway

Comparison of data from the transducer of the impulse tester compared to the data from the transducers of the Dynaflect.

FIGURE A-2



Comparison of Data from the transducer of the impulse tester compared to the data from the transducers of the Dynaflect.

FIGURE A-3

A summation of some of the data reported in Reference 3 of the bibliography is presented in Figure A-4. The Impulse Index in the wheel tracks and in the lane center for three widely diverse quality and conditions of pavements are compared. These measurements were made with hand carried suitcase sized Impulse Index Computer.

I-90 is a relatively new pavement designed for modern loads and has the lowest values of the Impulse Index.

US 195 is not new and has been resurfaced in some areas but not at the location measured here. The Impulse Index is two to three times as high as for I-90.

The county road has been recently subjected to very heavy loading, especially in one lane. The very high readings of Impulse Index obtained for this road indicate a high degree of distress. This road has broken up in many places.

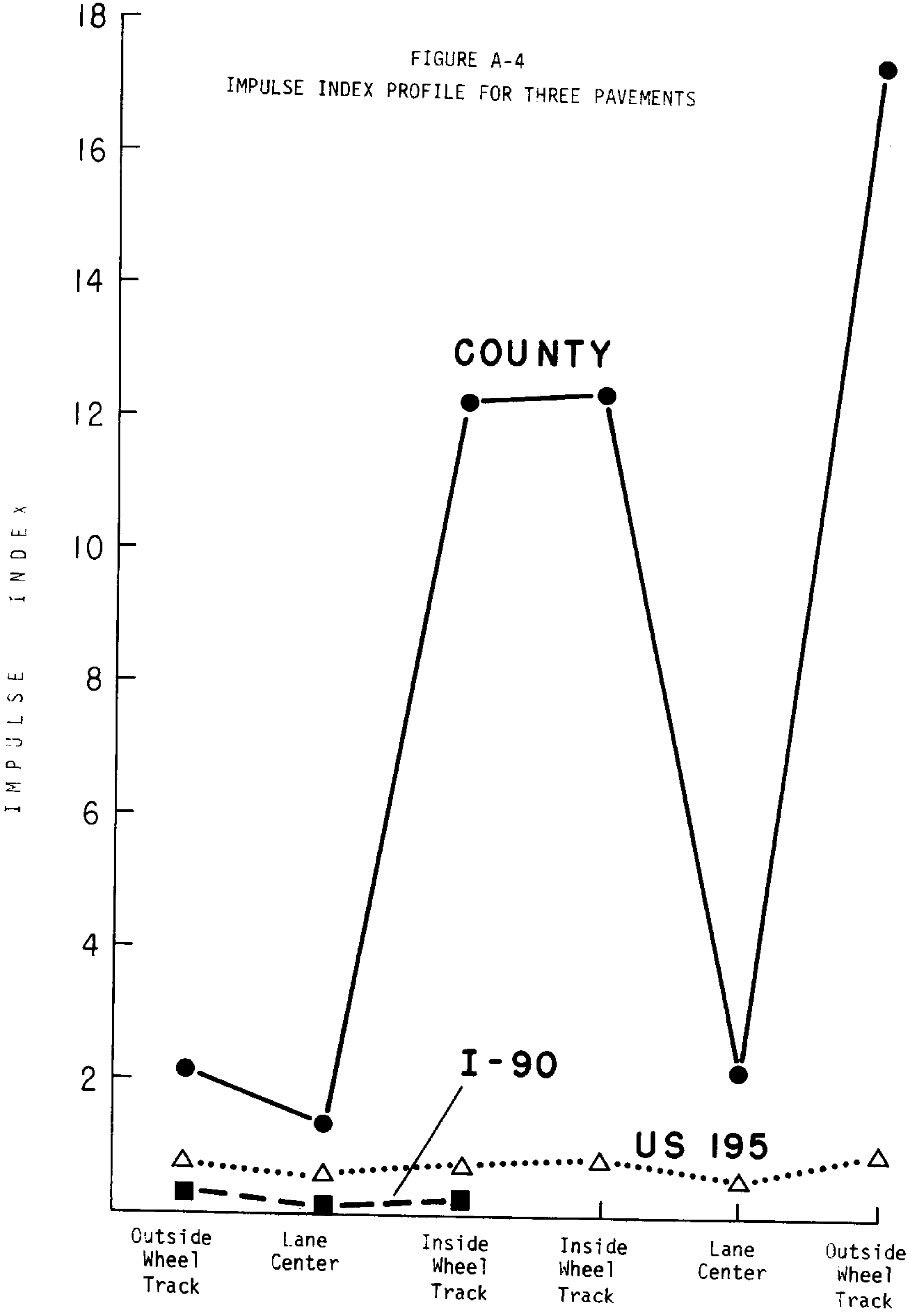


FIGURE A-4
IMPULSE INDEX PROFILE FOR THREE PAVEMENTS