A Portable Electronic Scale for Weighing Vehicles in Motion

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Basic electronic equipment has been used in the experimental stage of the scale development. Signals are displayed on an oscilloscope, and Polaroid photographs made for permanent records. An instrument system will record in digital form on magnetic tape information regarding date, time of day, vehicle speed, number of axles per vehicle, axle spacing, and wheel weight. This system will be operative early in 1966.

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•ELECTRONIC scales for weighing moving vehicles are not new, but until now a portable scale capable of weighing highway vehicles moving at normal road speeds has not been available. Early attempts to weigh moving highway vehicles were reported by O. K. Normann and R. C. Hopkins (1, 2) in 1952. For their work, a massive reinforced-concrete slab about 3 by 10 ft in plan dimensions and 12 in. thick was supported flush with the adjacent road surface by four conventional load cells set in a pit beneath the road, and electrical signals from the load cells were recorded on appropriate instruments. This configuration, with minor modifications, has been used experimentally and commercially both in this country (3 through 11) and in Europe (12).

Although several expensive scales of this type have been installed during the past fifteen years, at least three inherent inadequacies in the design have hampered successful operation. The scale location is fixed; therefore, its usefulness is limited to one site. Construction of a pit beneath the pavement is necessary, and even with good drainage, moisture in the pit damages the equipment. And finally, the inertia of the heavy slab and its horizontal translation have adverse effects on the response of the system to dynamic loads.

A critical analysis of the vehicle weighing problem, performed in the light of experience, makes obvious the need for eliminating these and other inadequacies in the

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scale system if usable results are to be obtained. Certain basic criteria for the kind and quality of information required must be established before a suitable system can be developed. The fundamental question of whether static vehicle weight or dynamic wheel force information is desired must first be answered; then performance criteria for a weighing system can be defined.

Static vehicle weight is generally used for law enforcement and for planning purposes and dynamic wheel force data for structural design of pavements and bridges. A relationship exists between static weight and the forces exerted on the pavement by a moving wheel for any given vehicle operating under a specific set of conditions, but as yet the relationship is not clearly defined. Neither is the relationship precisely known for the general case of mixed traffic operating on different types of roadways. It may be reasoned, however, that the static wheel load and the dynamic wheel load are nearly equal for a vehicle operating at moderate speed on a perfectly smooth, level surface. From this, it follows that, in a practical sense, wheel loads of a vehicle moving over a smooth pavement can be sensed by a suitable dynamic scale and summed to give a good estimate of the static vehicle weight.

Factors such as pavement roughness, tire roundness, vehicle suspension-system characteristics, aerodynamic lift, weight sensing time or distance, and response characteristics of the weighing device all affect the accuracy with which this estimate can be made, but static vehicle weight can probably be estimated from dynamic wheel forces with sufficient precision for planning and design purposes by sampling vehicle wheel loads with a suitably responsive dynamic scale of finite length, set flush in a smooth pavement. The precision of the estimate can undoubtedly be improved either by measuring wheel loads continuously as the wheel moves over some relatively long finite distance, or by sampling it several times. In any case, a scale with good dynamic response is required.

Other criteria for a practical weighing system include portability, insensitivity to tractive forces or position of load, ruggedness, flexibility, and reasonable cost. The system should be such that a two-man crew can transport, install, and operate the scale for extended periods of time, using a station wagon or light truck as a working vehicle. Only the component of wheel force, acting normal to the pavement surface, should affect the scale output signal. Neither tractive forces nor position of the wheel load on the sensing device should affect the signal. Ruggedness and reliability are of prime importance since the scale is expected to operate for long periods of time under severe traffic and climatic conditions. The weight transducers should deflect in a manner similar to the pavement structure into which they are set so as not to cause a bump or depression in the roadway surface under load. A minimum amount of pavement should be removed for installing the scale. This is particularly important when transducers are installed in bridge decks and in rigid pavements. The total cost of owning and operating the system must compare favorably with the cost of procuring vehicle weight information by present techniques if the system is to be considered as a replacement for such techniques. Fortunately, this is not necessarily true of a system intended for research purposes. Although minimum cost is certainly desirable, progress depends to a large extent on research and on the successful application of the results of research; therefore, sizable investments are reasonably justified when the technology of planning, design, and operation of our vast highway system is advanced. Through advanced technology we can expect to effect long-range economies.

The only known portable scale used routinely for weighing moving highway vehicles is the one operating in Sweden, as described by Stig Edholm (13). This unit, although apparently successful, fails to satisfy all the criteria previously suggested in that the load detector is over 4 in. thick and the speed of the vehicles to be weighed is restricted to 12.5 mph. Also, data from the scale are recorded on paper tape in analog form; interpretation is tedious and expensive.

The criteria outlined are formidable, and past experience seems somewhat discouraging, but a portable scale system capable of sensing the dynamic forces exerted normal to the pavement surface by the wheels of highway vehicles moving at normal road speed has been developed through the cooperative research program of the Center for Highway Research at the University of Texas, the Texas Highway Department, and the U. S. Bureau of Public Roads. The basic configuration of the load transducer was first described in a thesis at Mississippi State College in 1956 (14). Transducers have recently been tested under actual operating conditions at three different field sites and have successfully weighed vehicles moving at speeds up to 70 mph.

WHEEL LOAD TRANSDUCER

The load-sensing element of the system is a special transducer which detects the component of wheel force acting normal to the pavement surface and converts this force into a corresponding electrical signal. Two transducers are required for each lane of traffic (Fig. 1). They are placed side by side and are proportioned so that the wheels of a vehicle traveling in the normal traffic lane will pass individually over a transducer. Each unit is 50 by 20 in. in plan dimensions and slightly over 1 in. thick.

A sheet metal diaphragm, welded to a rectangular steel frame, forms the top of the transducer (Fig. 2). The diaphragm transmits any tractive forces produced by the wheels of an accelerating or braking vehicle directly to the frame, and thus cancels their effect on the sensor. Vertical deflection of the diaphragm permits any forces applied normal to the surface to act, for all practical purposes, entirely on the structural steel plates immediately underneath. The three steel plates distribute this component of the wheel forces among a set of load cells arranged to support the corners or edges of each plate. The load cells supporting the corners of the outer plates are set in recesses to reduce the overall height of the unit. The middle plate rests directly on four load cells and supports one edge of each outer plate by means of a ledge-type joint. In this arrangement, the plates are hinged at the support, and no uplift occurs beyond the support when a single plate is loaded.

Load cells of unique design convert load to a usable electrical signal. The configuration of the cell is shown in Figure 3, and dimensions are shown in Figure 4. Each cell is machined from tool steel, heat treated, and stress relieved. A spiral etched-foil strain gage cemented to the plane surface of the circular restrained-edge diaphragm detects the tangential strain caused in this surface by a load acting against the boss on

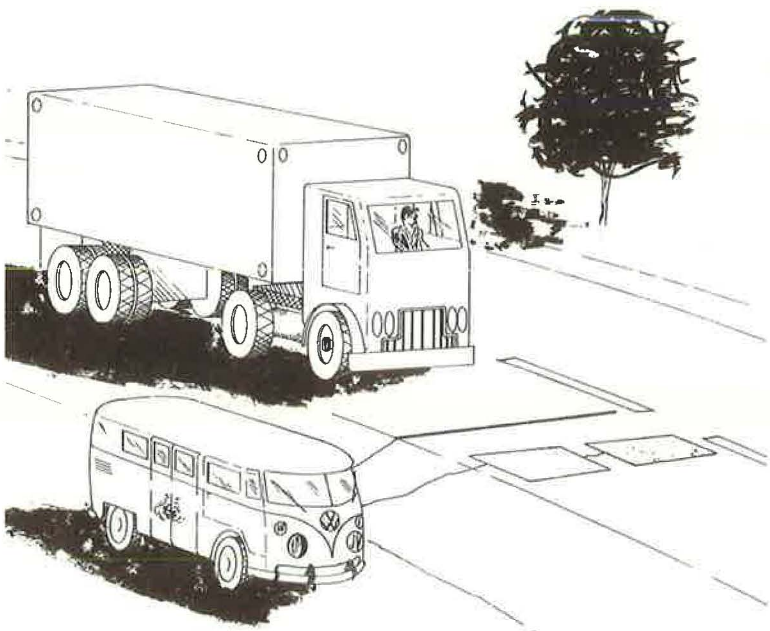


Figure 1. Typical installation of portable scale.

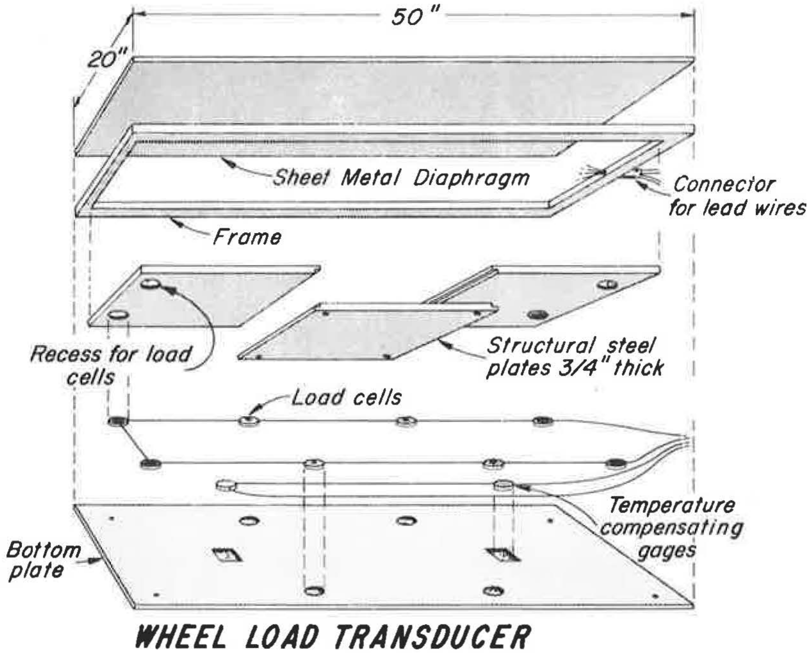


Figure 2. Exploded view of wheel load transducer showing arrangement of plates and load cells.

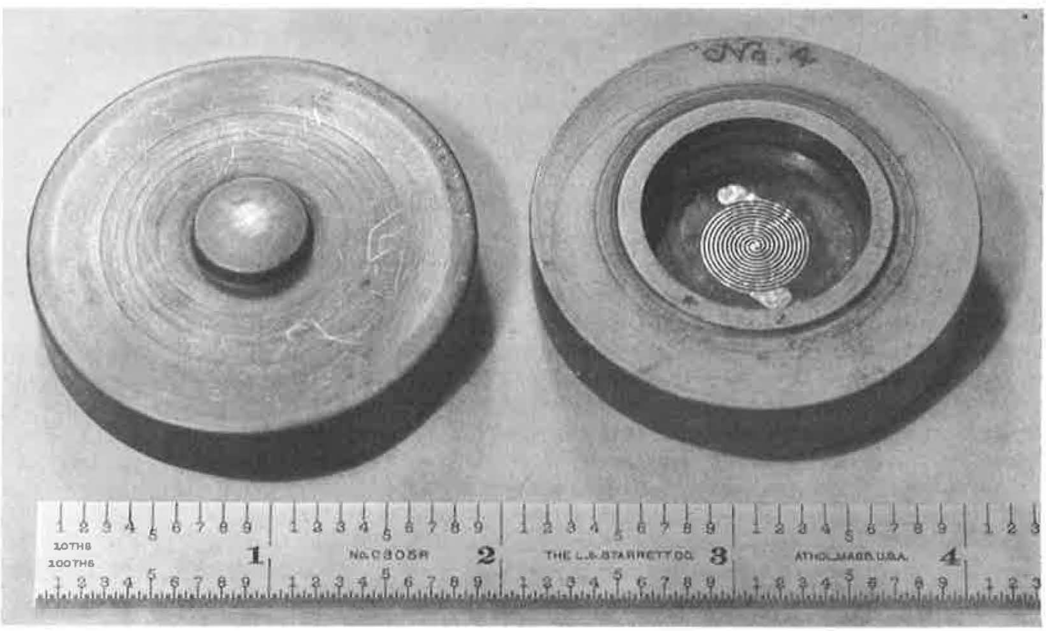


Figure 3. Load cells with spiral strain gage in place.

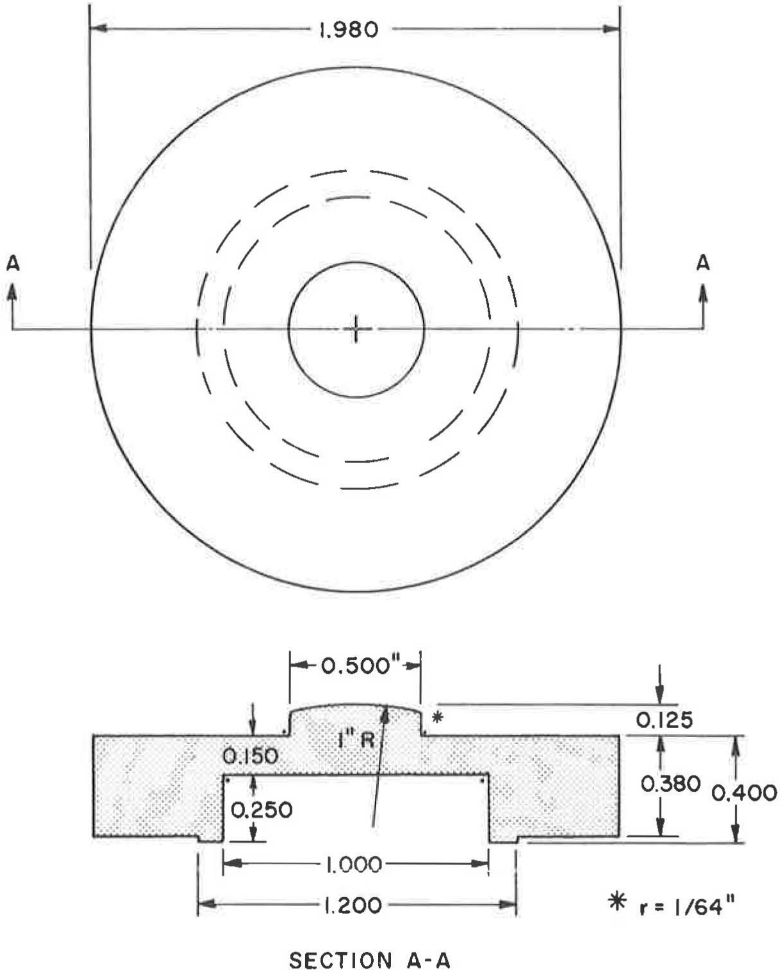


Figure 4. Top view and section showing dimensions of load cells.

the opposite side of the diaphragm. Strain thus detected is evidenced by a change in the electrical resistance of the gage, and is related linearly to the applied load.

All load cells used in the transducer are connected in series (Fig. 2). Since eight cells having identical change in electrical resistance with load are selected by individual calibration, and since the change is linear with load, the total change in resistance in the series-connected set of cells is the same for a given load whether the load is carried by one cell or distributed among several. This arrangement of load cells and plates makes the electrical output signal independent of either load contact area or placement of the load on the transducer.

The spiral strain gages used on the load cells are of the so-called temperature-compensating type, but compensation is not complete over the full range of temperatures to which the transducer will be subjected. Eight gages, identical to those on the load cells, are therefore bonded to steel discs which are exposed to the same temperature environment as the load cells, but which are not loaded in any way. These gages sense temperature-induced strains of precisely the same magnitude as those set up in the load cells. They are connected in an electrical network so as to cancel exactly the effects of temperature on the output signal from the transducer.

The bottom steel plate is ¼ in. thick and serves to transfer load from the load cells to the pavement into which the transducer is installed. It is bolted around its periphery to the rectangular steel frame, with a thin neoprene gasket to effect a waterproof seal. Recesses which accommodate the middle four load cells are provided in the plate and result in small protrusions from the bottom surface, but these are only about ½ in. high and 3 in. in diameter. Hardened steel inserts are placed to provide a bearing surface for the spherical boss on each load cell.

Strain gage circuits are notoriously sensitive to moisture. Each strain gage in the transducer is waterproofed by being coated with Di-Jell wax and a layer of room-temperature vulcanizing rubber. All lead wire junctions are similarly treated, and external access to these lead wire terminals is provided through gold-plated contacts of a miniature connector which is sealed inside a standard ¼-in. pipe nipple threaded into the rectangular steel frame. Even the small amount of moisture contained in the air which is trapped inside the transducer can adversely affect the performance of the strain gages if it condenses. Air is therefore purged from the sealed transducer by introducing dry nitrogen through small ports in the frame. These ports are subsequently sealed with special plugs. It is entirely feasible to maintain a small positive pressure in the void space of the transducer and thereby prevent moisture from entering. Lead wires between the transducer and a roadside terminal point are cased in 5/16-in. copper tubing. Nitrogen under pressure can be introduced conveniently into this conduit if moisture in the transducer becomes a problem.

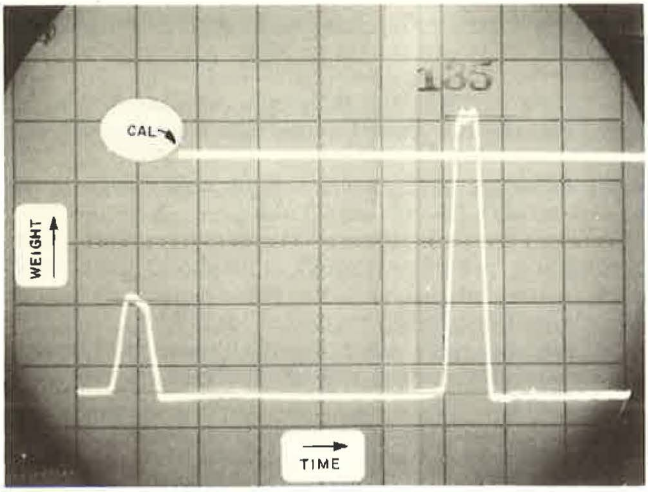
This description indicates that the design of the transducer incorporates many desirable features such as portability, insensitivity to load contact area or load position, ruggedness, and good dynamic response characteristics. It is difficult at this time to estimate the cost of manufacturing the transducers in quantity, but since no elaborate production techniques are involved, costs should be quite reasonable.

INSTRUMENTATION

Load applied to the surface of the transducer causes a small, but proportional, change in the electrical resistance of the strain gages on the load cells. Under dynamic loading conditions, the magnitude of this change can be measured most conveniently by determining precisely the amount of unbalance in a Wheatstone bridge circuit. For the experimental work, use was made of a half-bridge arrangement in which one arm of the bridge consisted of eight load cells connected in series, with the adjacent arm consisting of eight temperature-compensating gages connected in series. Precision resistors for completing and balancing the bridge were provided outside the transducer. A full bridge can be formed inside the transducer by connecting four load cells and four temperature-compensating gages alternately in a closed network. This arrangement has certain advantages and will be used in subsequent research.

Conventional SR-4 strain gage indicators were used to determine the calibration factor for each load cell under static load and to study the behavior of the transducer under static load. Certain advantages in instrument simplicity and in precision are inherent in a balanced bridge system, but it is not feasible to balance the bridge for measuring rapidly changing loads.

To display the electrical signals of a few milliseconds duration, which were produced by a wheel passing over the transducer, an oscilloscope with a high-gain dc amplifier was used. The light beam of the oscilloscope was made to sweep horizontally at a precisely controlled speed to form a time reference, and the beam was deflected vertically by the voltage across the unbalanced bridge circuit of the transducer. The horizontal sweep of the beam was initiated when the front wheels of a vehicle actuated a pneumatic tube detector placed at a given distance in advance of the transducer. Figure 5 shows the face of the oscilloscope, with a typical trace produced by the wheels of a 2-axle vehicle moving at a speed of approximately 35 mph. The front axle of this vehicle weighed 2,500 lb and a rear axle weighed 7,700 lb. A calibration trace representing 6,600 lb was superimposed on the photograph for reference purposes. The horizontal sweep speed of 50 msec/cm was selected so that the electrical signals produced by all the wheels of the vehicle would be displayed in parade fashion as shown. From this



Horizontal sweep speed, 50 ms/cm

Vertical sensitivity, 0.1-1.0 mv/cm

Calibration trace	=	6,600 lb
Front wheel wt	=	2,500 lb
Rear wheel wt	=	7,700 lb
Axle spacing	=	14.1 ft
Vehicle speed	=	35 mph

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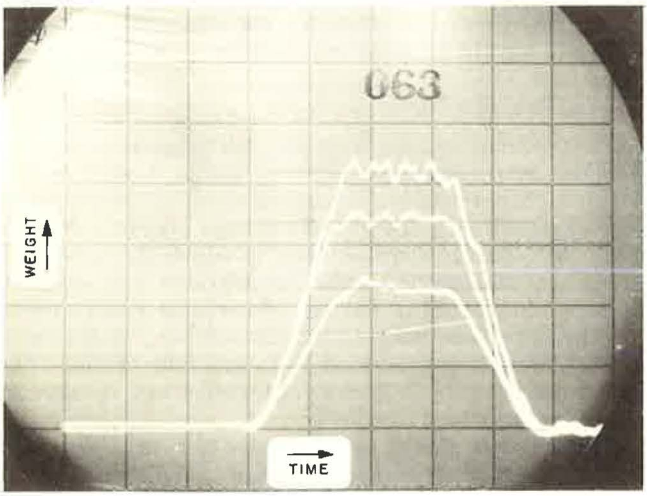
Figure 5. Typical trace on oscilloscope for 2-axle vehicle.



Horizontal sweep speed, 10 ms/cm

Vertical sensitivity, 0.50-1.0 mv/cm

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Figure 6. Oscilloscope trace showing superimposed pattern for 3-axle vehicle.

display, vehicle speed, axle spacing, and wheel loads can be determined. Speed is determined by dividing the known distance between the pneumatic detector and the wheel load transducer by the time required for the front wheel of the vehicle to travel this distance. The time can be measured directly from the oscilloscope trace. Axle spacing is calculated by multiplying speed by the time between successive wheel actuations on the transducer. Wheel load is, of course, represented by the height of the trace on the oscilloscope display.

By increasing the horizontal sweep speed, wheel load traces can be superimposed in the manner shown for a 3-axle vehicle in Figure 6. This form of display yields more information about the high frequency variation in load, but axle spacing cannot be determined. Inertial effects of the transducer are negligible, and there is a rapid, but small, variation in the magnitude of the wheel load during the time it is on the transducer. The speed of the vehicle was constant.

The oscilloscope provided a convenient means for displaying the transducer signals, and Polaroid photographs of the traces produced a permanent record of the data. For some of the development work, an oscilloscope with a memory feature which permitted retention of the display for several minutes was used. The pattern could be evaluated visually and then recorded on film if desirable.

Some 500 photographs of oscilloscope traces were studied to determine the frequency response characteristics required in a recording instrument for the scale. Specifications have been written for a special digital recording system, and the instrument is now under contract. Digital information concerning date, time of day, number of axles per vehicle, vehicle speed, axle spacing, and wheel load will be recorded on magnetic tape in a form ready for computer processing. One pair of portable wheel load transducers and three vehicle detectors provide all necessary electrical signals for the recorder.

EXPERIMENTAL EVALUATION

A single wheel load transducer was used in a series of laboratory and field experiments designed to evaluate its response to static and dynamic loads. In the laboratory, the transducer was supported on the lower platen of a hydraulic testing machine in a box of sand, and load was applied at different positions on the surface through wooden blocks with approximately the same contact area as typical vehicle tires. The output signal was affected by neither the contact area nor the position of the load. A relationship between applied load and electrical response under static loading conditions was developed from these tests.

The transducer was then installed successively at three different field sites. Each installation involved removing about 1½-in. flexible pavement, setting the transducer in a thin layer of fresh cement-sand grout, and pressing it flush with the pavement surface. Conventional hand tools were used for removing the pavement material, and the installation took between 2 and 3 hr at each site. Power equipment would, of course, facilitate this work and reduce the time required for initial installation.

The site selected for the first series of field studies was on a 4-lane farm-to-market road near Austin and was conveniently located adjacent to a Texas Highway Department maintenance warehouse. The pavement on this road was a double-surface treatment with good riding qualities. Precise elevations of the pavement surface were determined at 1-ft grid intersections with a Wild level for 200 ft in advance of the detector; the elevations varied no more than about 0.02 ft between adjacent points. The pavement was considered reasonably smooth. Although truck traffic was rather heavy, the significant experimentation was confined to studying the static and dynamic loads produced by a series of test vehicles. These vehicles were loaded to represent typical operating conditions, weighted on a loadometer, and driven at various speeds across the transducer. Some tests involved stopping the vehicle on the transducer, and speeds ranged up to 70 mph.

During the eight months following the first field installation, test vehicles, which ranged from passenger cars and two-axle trucks to multi-axle vehicles and front-end loaders, made several hundred trips across the transducer. A systematic study was made of the effects of vehicle speed, load placement on the transducer, tire-inflation pressure, vehicle acceleration, braking, and other factors. The transducer responded satisfactorily under all conditions. The magnitude of the output signal was not affected by speed, load placement on the transducer, or tire inflation pressure. Acceleration and braking caused a transfer of load among the wheels of the test vehicles, which was expected and indicated by the studies. The transducer withstood the traffic and the winter environment without adverse effects.

The second series of tests conducted during the summer of 1964, subjected the scale to heavy traffic on Interstate 35 near Temple, Texas. The transducer was placed in the outer lane and was positioned to weigh the wheels on the right side of all vehicles (Fig. 7). The site was about a mile downstream from the loadometer station, which is operated periodically by the planning survey division of the Texas Highway Department. The normal operating schedule called for occupancy of the loadometer station for 4 hr

Figure 7. Portable scale installation on Interstate 35 at Temple-Belton, Texas.

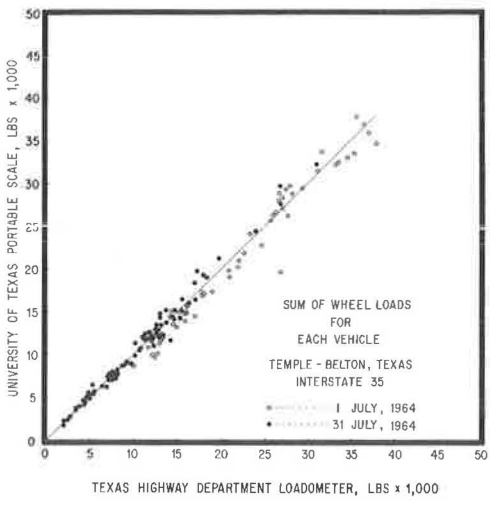

Figure 8. Loadometer weights vs portable weights.

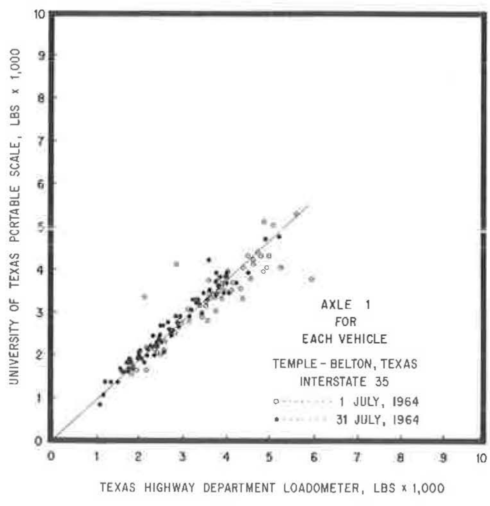

Figure 9. Loadometer weights vs portable weights.

on the first and last day of July. The portable scale was operated during these periods to obtain comparable data on the static weight and the dynamic weight of a large variety of commercial vehicles. Walkie-talkie radios were used to coordinate weighing operations at the two sites, and wheel weights for over 200 vehicles were recorded. The vehicles which were weighed while moving were traveling at speeds ranging from about 35 to 60 mph. Polaroid photographs made permanent records of the oscilloscope traces.

Wheel load data were scaled from these photographs and transferred to punched cards for machine processing. Wheel load data procured by loadometer weighing were also punched on cards. A computer was used to plot these data in the form shown in Figures 8 through 13. The regression lines through the points are the straight lines of best fit

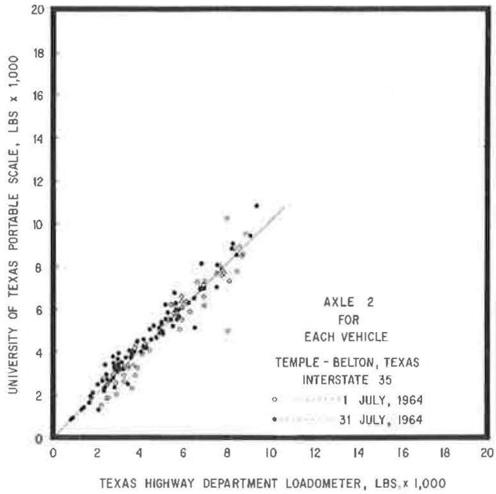

Figure 10. Loadometer weights vs portable weights.

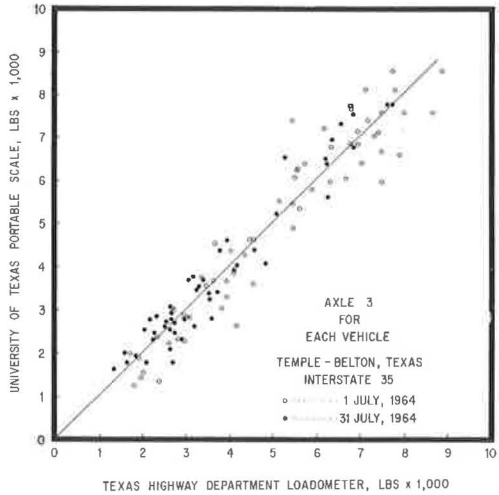

Figure 11. Loadometer weights vs portable weights.

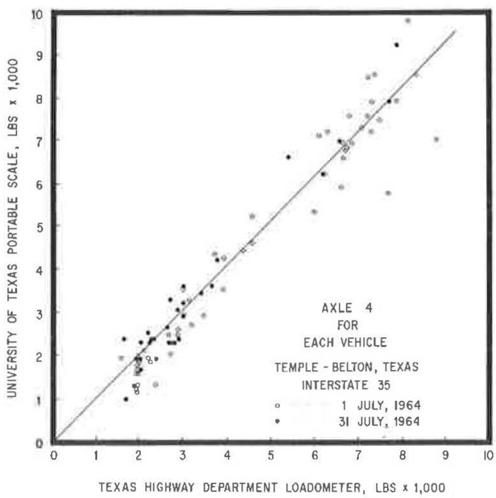

Figure 12. Loadometer weights vs portable weights.

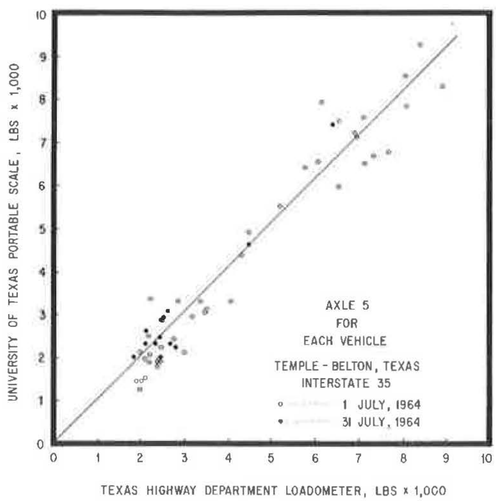

Figure 13. Loadometer weights vs portable weights.

as determined by a least squares technique. If there were perfect agreement between the loadometer weights and the portable scale weight, all data points would lie along a straight line inclined at 45 deg. Figure 8 shows that the line of best fit is inclined at approximately 45 deg, but that the data points are somewhat scattered about this line. In some cases the portable scale weights for the sum of the wheel loads on each vehicle are higher than the loadometer weights; in other cases they are lower. In virtually all cases the portable scale weights are within 10 percent of the loadometer weights and the scatter is approximately equally distributed on the high side and on the low side.

Figure 9 shows the relationship between the loadometer weights and the portable scale weights for the right front wheel of each vehicle. The portable scale weights are, on the average, lighter than the loadometer weights, and the variation of the dynamic weight from the static weight is as much as 40 percent in a few cases. Most of the data points agree within about 15 percent, however.

Since many of the vehicles were accelerating when they passed over the portable scale, it is logical that a part of the normal front axle load might have been transferred to other axles. For certain axles (Figs. 10 through 13) the wheel weights determined by the portable scale are higher than those measured statically, whereas for other axles they are lower. The scatter in the data is somewhat larger when considering individual wheel loads than when considering the sum of the wheel loads for each vehicle. The scatter is, however, approximately equally distributed on the high and low side for every case.

The third site at which the portable scale was installed was also adjacent to a loadometer station operated by the Highway Department near Luling. Truck traffic during the 4-hr weighing period was very light, and this installation served more to demonstrate the portability of the scale than to provide data. As a matter of fact, only 13 commercial vehicles were weighed during the 4-hr period. This installation took only 2 hr to complete.

At each site, premix asphalt laid on a sheet of paper was used to fill the grout-lined depression remaining after the wheel load transducer had been removed. The paper prevented the asphalt mix from adhering to the grout, and it was a simple matter to remove the temporary patch material at a later time. The transducer could be replaced at a previously occupied site in about 20 min. No difficulty with keeping the transducer or the patch material seated in its recess has been experienced.

SUMMARY

The portable electronic scale consists of a pair of wheel load transducers and associated electronic recording instruments. The transducers, each of which is 50 by 20 in. in plan dimensions and only slightly over 1 in. thick, are simple in design, rugged, and portable. Inertial effects in the transducer are negligible, and the electrical output signals depend only on the magnitude of the load applied normal to the surface. Since only 1½ in. of pavement must be removed, the transducers can be installed in any smooth roadway surface including rigid pavements and bridge decks. Initial installation requires approximately 3 hr, but subsequent installation at a previously occupied site requires only about 30 min.

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Analysis of data on nearly 300 different vehicles, each of which was weighed both statically by a conventional loadometer and while moving at normal road speed by the portable electronic scale, indicates that static vehicle weight can be estimated from the weights obtained by the portable electronic scale with sufficient precision for planning and design purposes. The precision of the estimate can undoubtedly be improved by using more than one pair of transducers for sensing the moving wheel loads.

There are many potential uses for the portable electronic scale in highway planning, design, and operation. Routine statistical data procurement without stopping or delaying traffic has been described. Vehicles can be classified automatically into groups according to the number of axles per vehicle and wheel weight. Land use by various classes of vehicles can be studied. Traffic control devices can be operated. Unnecessary delay to vehicles which are within the legal weight limits can be eliminated by using the electronic scale as a sorting device at static weight enforcement stations. Research leading to a better understanding of the behavior of highway structures and pavements subjected to repeated dynamic loads can be initiated. Engineers with imagination will find many applications for the portable dynamic weighing device.

A patent application on the portable electronic scale described herein was filed in April 1965 with the U. S. Patent Office.

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