critical headways for crossing four-lane roads than for two. Possibly, the influence of adjacent signals, more likely to be found on four-lane roads than on two, is involved.

PART 3 BY BÅNG

Mr. Bång's work on signalized intersections is a valuable contribution to the state of the art, particularly with respect to its consideration of turning movements related to pedestrians. This is one area where the public expects and seems to assume that we have much more information than we actually do.

I was surprised to note that the principal Swedish intersection capacity criteria, prior to the subject work, were based on the original American 1950 HCM rather than the 1965 edition, which is the principal reference in use today. Apparently this is because Sweden was in the forefront in the 1950's and developed its own procedures soon after ours were published.

It would be useful to learn which evaluations were made in Sweden after the 1965 manual was issued that caused them to decide to start over rather than try to adapt its procedures. Such information would be particularly timely as we begin the initial steps of preparation of a new edition of the American manual.

The Swedish procedure appears to emphasize a different range of operational levels than does our manual. While they indicate that their work omits design levels and centers on saturation flow or capacity, which is our level of service E, they suggest that 0.8 times saturation flow be used in practice as a feasible maximum. In effect, then, they closely relate to our level of service D, which of necessity has become our design level for many urban applications even though level C is considered more desirable.

The Swedish procedures then appear to extend from our level D into level F, with a description of consequences throughout including level F, as compared to our levels of service A through E, with only general reference to broad breakdown of level F. This is rather characteristic of foreign signalized intersection capacity investigations and procedures as compared to current U.S. procedures; they typically concentrate on saturation flow to a greater extent than do U.S. procedures.

I agree that any new American method must include consideration of stops, queueing, and delay, which are the elements of intersection performance most visible to users. Our load factor (that is, percentage of fully utilized green intervals) is inadequate where most needed.

It is not clear why the Swedish measures developed on a by-lane basis are "not always meaningful" when expanded to a complete approach or whole intersection; this concerns me.

The conclusion that both width and number of lanes are significant is interesting. This point is controversial, not only within the United States but internationally, where viewpoints range from the 1965 HCM's overall approach width criterion to Australia's basic number-of-lanes procedure.

Regarding the pedestrian effect, I find the tabulation form of presentation quite good and a step toward what I would like to have, to answer citizens' questions. I wonder, though, whether such national criteria could ever be established for the United States as a whole, given the widely differing degrees of respect shown each other by drivers and pedestrians from one city to another. It would seem that city factors would have to be developed, much as both we and our Swedish counterparts dislike them.

It is interesting to note that several of the same factors that have escaped easy solution in this country also defy solution in Sweden, including bicycles, actuation of signals, and weather.

The problem solutions described conform with Mr. Peterson's introductory comments; they relate to situations where the traffic volumes and geometrics are known, and the nature of the resulting operation is desired. It is not indicated whether or not the method can be used effectively for other situations, where either volumes or geometrics are the unknown. (The sample problems that exist in the manual undoubtedly assist greatly in providing an understanding of the procedures.)

At first glance, the typical problem solution time, 3-6 h, looks long. However, given that this involves a detailed solution including queue lengths and so on, something much beyond our current procedures, and that a basic signal timing solution is possible in an hour, it is probably reasonable.

Finally, it is unfortunate that this work, like nearly all other work in this field in recent years, must be tagged as "needing validation." I hope users will soon do sufficient testing and evaluation so that validity can be more firmly established.

Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.

Weighing Vehicles in Motion

A. T. Bergan, G. A. Sparks, and G. Dyck, College of Engineering, University of Saskatchewan, Saskatoon

A scale for weighing vehicles in motion was developed at the University of Saskatchewan. This scale has been successfully operated unmanned at two locations in Saskatchewan for the past 2 years. An expanded evaluation program is currently under way in which the scale will be installed and evaluated in Ontario, Quebec, and New Brunswick by a project committee of the Roads and Transportation Association of Canada.

The relationship between vehicle and axle loads and the structural requirements of bridges and roadways has been and continues to be an area of particular interest to those concerned with the provision and maintenance of bridge and roadway facilities. The need for comprehen-

Figure 1. Design of the scale.

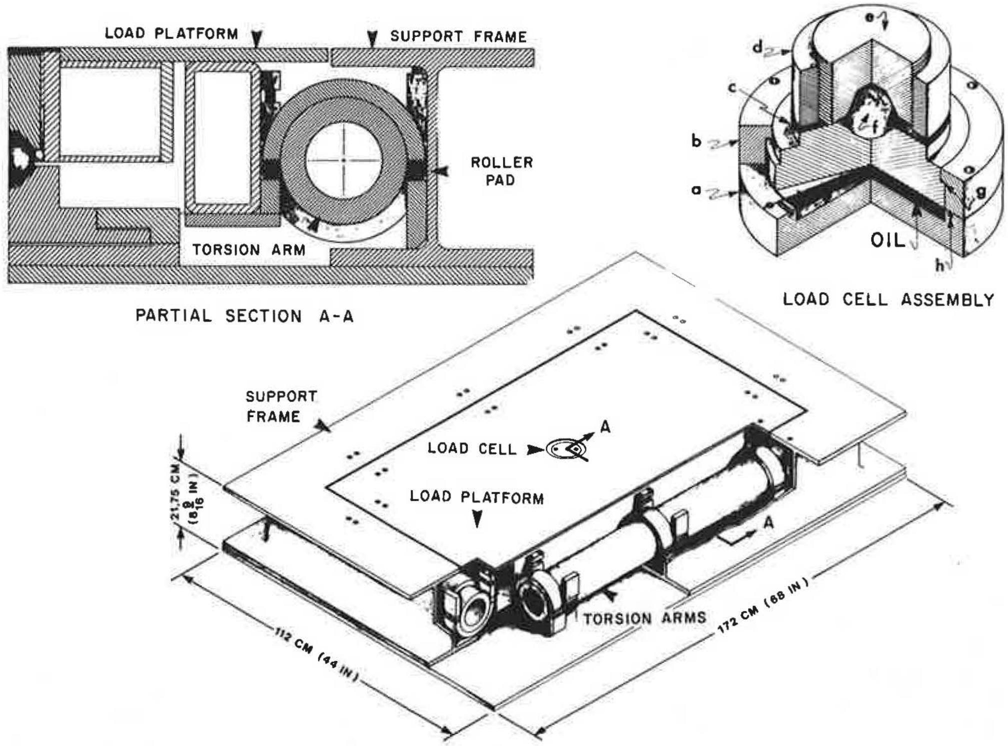
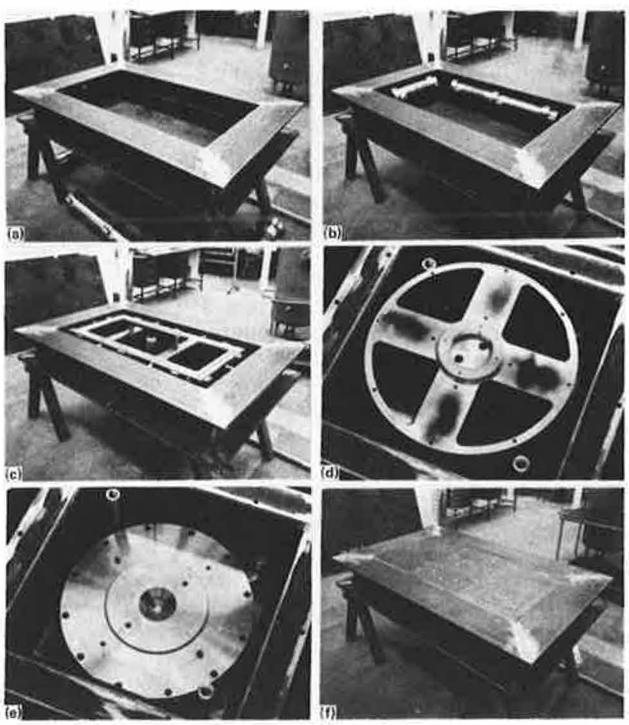


Figure 2. Steps in assembling the scale.



sive information on the nature and characteristics of roadway traffic as related to the design and maintenance of bridge and roadway structures is well documented (1, 2, 3).

In an attempt to fulfill this information requirement, a number of organizations have in recent years worked on the development of scales for weighing vehicles in motion. Such a scale has been developed at the University of Saskatchewan (4, 5, 6).

The efforts at the University of Saskatchewan were initiated primarily because existing scales for weighing vehicles in motion were incapable of operating in a continuous unmanned manner in the harsh Canadian environment.

The scale for weighing vehicles in motion that was developed at the University of Saskatchewan utilizes the hydraulic pressure principle. Loads applied to any point on the load platform are transmitted evenly around the perimeter of the platform by four torsion arms. (Figures 1 and 2 illustrate the scale assembly.)

The load platform can move only vertically as a rigid unit. This vertical motion is extremely small [i.e., of the order of 0.015 cm (0.006 in) at 4500 kg (10 000 lb)] and is nearly frictionless due to the roller pad contacts between the load platform, the torsion bars, and the support frame. The entire load is then supported by a single, centrally located load cell, which is an oil-filled piston cylinder arrangement with a strain gauge transducer.

DEVELOPMENT PROGRAM

Until the fall of 1976, the major effort was devoted to the development and evaluation of the scale unit itself. The first prototype of the scale was constructed during the summer of 1974 and was installed in an abandoned section of highway. The results of the series of tests using several vehicle weights and speeds were very encouraging. The observed differences between the actual static weight and the observed dynamic weight typically compared within 10 percent.

A second scale incorporating several small design changes but utilizing the same principles was constructed during the winter of 1974-1975 and was installed in an in-service section of roadway in the spring of 1975. Results of tests on this scale were even more encouraging; however, two problems were encountered.

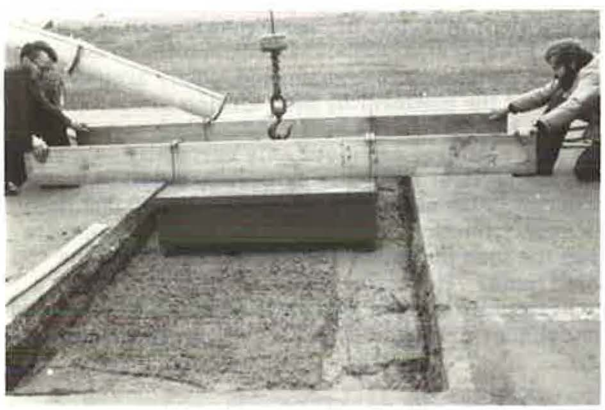
The first was the failure of a seal that allowed moisture to enter the interior of the scale and cause a corrosion problem. The second was associated with the testing program. The scale was located on a section of highway far removed from any highway weigh scale, which made calibrating and testing of the scale inconvenient.

The third-generation prototype was constructed and installed during the summer of 1975 in a section of highway 5 km (3 miles) from a government weigh scale near Clavet, Saskatchewan. This location greatly facilitated the testing procedure, and the design modifications included in this generation of the scale successfully overcame the moisture problem previously encountered.

When the third-generation scale was installed, special attention was given to the pavement surface leading to the scale. Since any irregularities in the road surface would be expected to cause transient perturbations of the vehicle suspension, an infinitely smooth section of roadway would be desirable. In attempting to approach this ideal condition, the highway was resurfaced for a distance of 60 m (200 ft) in front of and 15 m (50 ft) beyond the scale.

Figure 3. Installing the scale.

Excavation concrete pad



Installing dummy frame

Dummy frame installed in roadway

Scale installation methods have been modified with each generation of the scale. The installation methods used with the third-generation scale are illustrated in Figure 3. They involved making the appropriate excavation in the roadway, pouring the required concrete base, and installing the dummy frame. The scale units themselves were then placed in the dummy frames, which give the scale units a degree of portability.

The data acquisition equipment was housed in a temperature-controlled trailer adjacent to the scale site. Axle-load information was recorded on a 24-h/d basis. In addition to the weigh scale, two magnetic loop detectors were placed in the roadway adjacent to the scale. These loop detectors turn on and shut off the magnetic recorder that is used to record the signal from the weigh-scale load cells and can also determine vehicle speeds. Approximately once a month the magnetic tape containing the recorded weigh-scale load cell information was picked up. This tape containing the analog output was digitized and analyzed using computer facilities located at the University of Saskatchewan. The information obtained included total traffic counts (cars included), detailed speed information, individual axle weights and axle spacing, vehicle types or classifications, and time of day associated with each of the above.

In the fall of 1975, a scale was installed on a major pulp haul road in Northern Saskatchewan near Montreal Lake on Highway 2 (Figure 4). Five-axle trucks involved in the pulp haul are permitted to carry 25 000 kg (55 000 lb) per tandem on this roadway. The data-acquisition equipment used at the site was identical to that used at the Clavet site.

Data have been collected on an unmanned basis at the Clavet and Montreal Lake sites since the fall of 1975. The scales have not required any maintenance or adjustments over the nearly 2-year period.

Digitizing and processing the analog tape obtained from the field data acquisition system has proved to be a time-consuming and costly procedure when utilizing the relatively archaic methods initially developed. Recent efforts have been devoted to developing more efficient methods of handling the data-processing requirements.

Figure 4. Montreal Lake installation.

These new methods were expected to be operational in the fall of 1977. The details of these new data acquisition methods are discussed in a following section.

A number of trial run series have been undertaken over the last 2 years to evaluate the performance of the scale unit. Figure 5 illustrates the results of three of these test series for the Montreal Lake installation.

It is apparent from Figure 5 that, while the average axle load measured by the scale is relatively insensitive to speed, the variations about the average are observed to increase with speed (as might be expected because of vehicle dynamics). Further, it is apparent from the figure that the observed variations for the October and December tests are significantly greater than those for the May tests. This can be attributed to roadway roughness.

The scale was installed during the early fall of 1975. Prior to testing in October, there was considerable settlement in the vicinity of the scale that resulted in a rough approach. The approach was improved with minor patching but again, before testing in December, differential frost movement caused deterioration that resulted in a rough approach for the December tests. Prior to the testing in May, minor surface improvements within 3 m (10 ft) of the scale were made to improve the smoothness of the approach wheel paths. This improvement in riding quality resulted in the considerably improved results for the May test.

The preliminary testing and evaluation work undertaken during the first 2 years of the development program have resulted in the following conclusions: (a) the scale developed at the University of Saskatchewan is capable of weighing vehicles in motion with sufficient accuracy to meet the information requirements of pavement and bridge engineers, and (b) the scale is rugged and reliable enough to be operated on a continuous unmanned basis in the harsh Canadian environment.

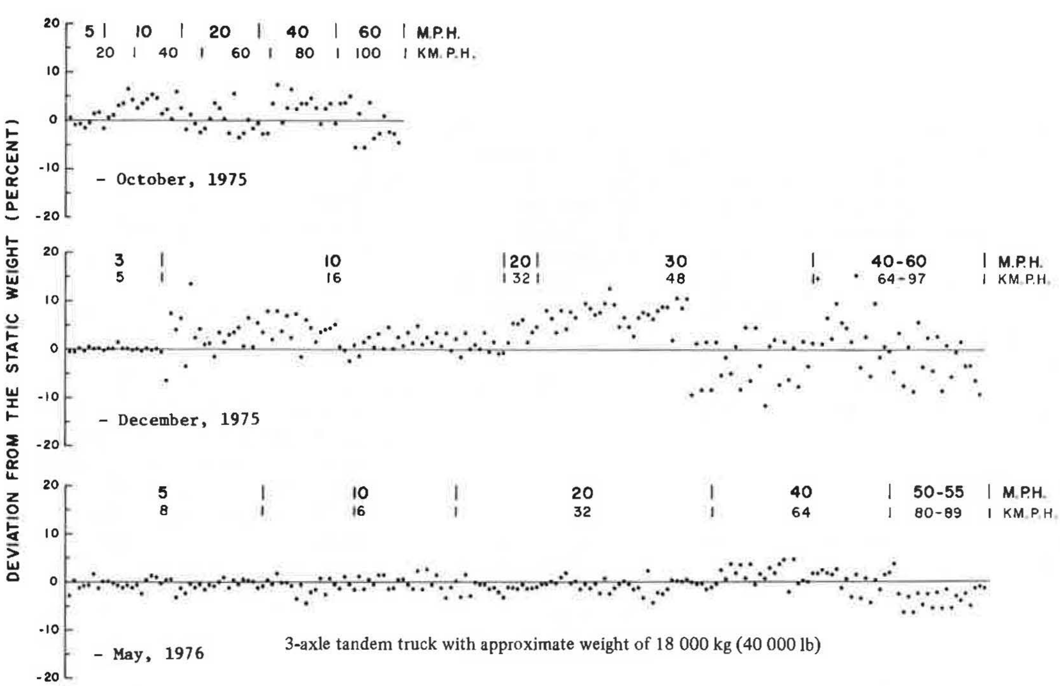
CURRENT PROGRAM

As a result of the widespread Canadian interest in developing a capability to weigh vehicles in motion, the Roads and Transportation Association of Canada formed a project committee to monitor vehicle and axle weights in 1976. The primary task of the project committee is to make recommendations for equipment and procedures for monitoring programs by which to determine the vehicle axle and gross load data required in the assessment of impacts of pavement and bridge structures.

As part of the activities of this project committee, three types of weigh-in-motion scales are being tested and evaluated at various locations in Canada during 1977 and 1978. The Viatec axle weight analyzer is to be evaluated at various locations in Alberta and Ontario by Alberta Transportation and the Ontario Ministry of Transportation and Communications respectively. The Texas weigh-in-motion system is to be evaluated in New Brunswick by the New Brunswick Department of Transportation. The University of Saskatchewan scale was installed in the fall of 1977 in Saskatchewan, Ontario, Quebec, and New Brunswick and the evaluation undertaken by the Saskatchewan Department of Highways and Transportation, the Ontario Ministry of Transportation and Communications, the Quebec Ministère des Transports, and the New Brunswick Department of Transportation respectively.

The University of Saskatchewan scale units to be installed will be as previously illustrated. The data acquisition system, which has been under development since the fall of 1976, will be a substantially improved system. The two alternative data acquisition systems under development will be installed as illustrated in Figures 6 and 7. The primary difference between the 11/03 and the 11/04 systems is that the summary reports of traffic will be produced in the field by the 11/03 system, whereas such reports will be produced by remote software analysis programs for the 11/04 system. No permanent individual vehicle data records will be maintained with the 11/03 system, but the 11/04 system will produce a permanent record of the vehicle data. This permanent data record could be available for analysis of historical traffic volumes and processing or both, as may be required. Similar flexibility regarding the analysis of historical data will not exist with the 11/03 system.

Figure 5. Montreal Lake installation test results.



3-axle tandem truck with approximate weight of 18 000 kg (40 000 lb)

Figure 6. The 11/03 data acquisition system.

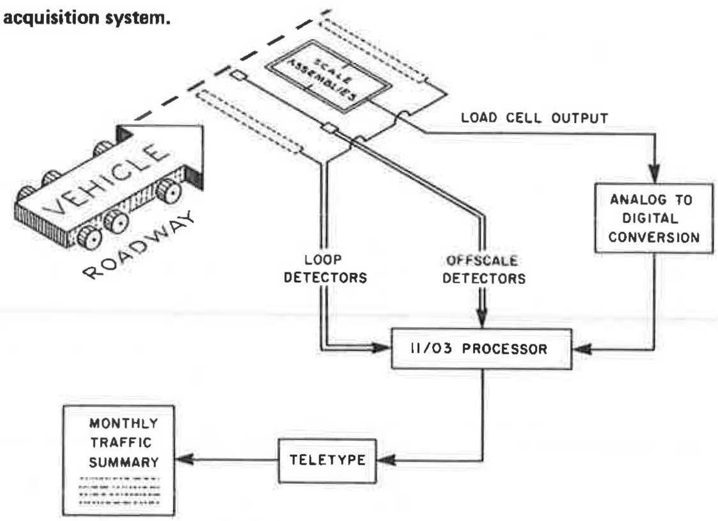
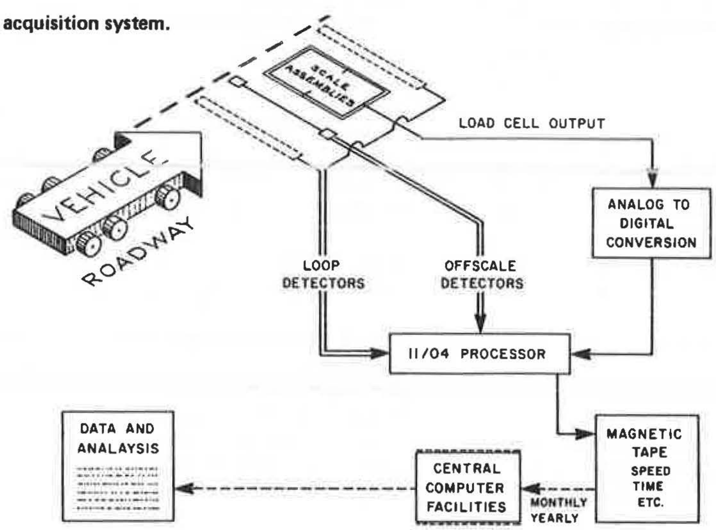


Figure 7. The 11/04 data acquisition system.



Upon completion of the evaluation of the various scales by the provincial organizations, a report giving a comparative assessment of the weigh-in-motion devices tested in the program will be prepared. The Roads and Transportation Association of Canada project committee will make recommendations regarding the suitability of the devices tested for various purposes. The report will include data on capital and operating costs and technical information on the quality of the data and the reliability of the equipment. Details concerning equipment, installation, recommended procedures for data collection, handling, and transformation will be provided.

ACKNOWLEDGMENT

The authors would like to acknowledge the support received from the National Research Council of Canada, the Saskatchewan Department of Highways and Transportation, Transport Canada, the provinces of Ontario, Quebec, Alberta, and New Brunswick, the University of Saskatchewan, and the Roads and Transportation Association of Canada.

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Discussion

J. H. Havens, Kentucky Department of Transportation

Some agencies that have invested heavily in the development of devices to weigh highway vehicles on-the-run can fully appreciate the futility of almost achieving success. The team of authors have, here, asserted their success matter-of-factly. The paper does not reveal the pitfalls they have avoided or escaped. Indeed, two years of operating experience in an unmanned mode, with only monthly harvesting of data, is an impressive accomplishment.

Kentucky has two of the Texas scales (7); one site has produced 53 manned days of data out of 763; the other has produced 3 out of 333. Neither is operative at the present time. Downtime of the platforms, however, has been only about 20 percent.

Before succumbing to the Texas system, we abandoned a very sophisticated platform and data system developed for the Department of Highways by the University of Kentucky during 1961 and 1971 (8, 9). Of several designs investigated, a "broken-back" platform—that is, two simple spans with abutting ends supported commonly on load cells—was judiciously selected. It was modeled after one developed at the Otto-Graf Institute, Stuttgart, Germany, in 1958 (10).

This type of platform produces a triangular output signal from the load cells as a load (axle) traverses the platform. The apex of peak of the triangular signal from the load cells is calibrated in weight units. The unique feature of this type of design is that the base leg of the triangle represents the span length; the addition of an internal timing signal permits speed of traverse to be calculated. Then, by presetting a practical time gap between vehicles, it is possible to determine the number of axles per vehicle (classification) and to sum the several axle loads, which yields a gross load for each vehicle. Thus, the digitized output capabilities of the system are: load impulses of individual axles, vehicle speed, gross load, and vehicle classification by number of axles. Various statistical analyses may be programmed to determine specific characteristics of the traffic stream.

The axle loads sensed by this system are not necessarily equivalent to static weights. Vehicles in motion tend to undulate or bounce as they travel; there is a random probability or likelihood that a vehicle (or axle) will be on an "upswing" or "downswing" when it crosses the platform. The most unlikely events would be to catch an axle at either extreme or at its null (equivalent static) state; however, there is a greater probability that an axle will be closer to a null condition than to an extreme as it crosses the platform. The standard error of estimate is judged to be of the order of ±5 percent of the static weight (11). Statistically speaking, the errors tend to cancel, and so the use of the system for survey purposes is not impaired.

Whereas the scale system is capable of measuring the force exerted by a set of wheels moving at high speeds, the force impressed on the platform is simply not the static weight force of the axle. The ratio of the peak downward forces to the static weight force defines impact factor. This explanation merely emphasizes the fact that the weighing platform senses only the instantaneous, dynamic force of each transient axle.

Despite overwhelming hardware failures that beset the development of an automatic, in-stream, vehicle-weighing system—which we then became convinced we must abandon—significant measures of success were achieved. In other words, we created an automation that almost worked. The decision to abandon the prototype installation arose from pilot operations and proof testing. The basic defect was in the weighing platform in the pavement. Unfortunately, it was a design defect. Tie rods anchoring the platform in the pit induce a purposeful preload on the load-sensing elements. These tie rods change the preload as the temperature fluctuates. Thus, the balance or null point drifts. The noticeable effect was a triggering of the counting and weighing circuits when there was no live load on the platform. Since this load was not transient—but sustained—the circuitry "locked in" on the excess preload. The preload and tie rods were intended to keep the platform in firm bearing on the load-sensing units and to eliminate resonances and friction. Conceivably, it would have been possible to control the temperature in the pit, but other factors were equally dissuasive.

Whereas the cargo box or principal mass of a heavy vehicle may be on the downswing or about to "bottom out" as it passes over a weighing platform, the most abrupt change (reversal) in direction at this point induces the greatest force on the platform. The acceleration imparted tends to cause the mass to rise higher on the springs and to soar or dwell longer on the upswing. If the axle were to bounce off the pavement, the upward acceleration would necessarily have been greater than 1 g. On the other hand, the maximum downward acceleration may never exceed 1 g. Thus the "impact factor" at the end of the downward excursion is the greater. In other words, the centroid of the points exceeding the static weight will lie farther above the static-weight line than the centroid of the points showing less than the static weights. The number of points should be about equally divided—that is, half should be above and half should be below the line. These are prerequisites in the performance criteria of a weighing-in-motion device—regardless of the speed of vehicles. Perhaps the authors should comment further in regard to Figure 5 in their report and perhaps define for us what they mean by "average axle load."

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Stephan Fregger, Bureau of Planning, Florida Department of Transportation

The paper presented by Bergan, Sparks, and Dyck is quite well prepared and clearly written. It adds an important new chapter to the knowledge of dynamic weighing. There is every reason to believe that the University of Saskatchewan scale system can accurately weigh, record, and analyze heavy vehicles with the torsion arm load transfer. Apparently it can also perform satisfactorily under very cold conditions for an extended period of time (2 years).

Two types of questions come to mind. The first relates to details that would aid in the potentially wide application of the research to operational use. For example, one wonders how many scales are installed at the weigh site. The use of the word "scale" in the singular and references to axle weights (not wheel weights) would tend to imply a single unit. Yet dimensional measurements of the scale indicate a size only big enough to accommodate a single wheel path (or indicate very narrow Canadian trucks).

Reference is made to a "degree of portability" of the scale. Does this mean only that the scale can be shop-constructed and then delivered to the weigh site, or does it imply portability in the sense of convenience for periodic relocation from site to site?

It would be helpful to know the expected order of magnitude of cost of a typical installation, the approximate cost of a scale unit, site preparation, field processor, and so forth.

In addition to the several applications questions, there is a second type of question of even greater relevance. This is directed at the implied premise of the paper, that it is desirable to obtain an in-motion weighing scale capable of operating in a continuous unmanned manner in the harsh Canadian environment.

The authors are correct in noting the need for comprehensive roadway traffic data to provide information for highway maintenance and design. Those data have traditionally been obtained from the three-tiered counts-classification-truck weight program. Traffic counts are obtained from a large sample of sites representing the range of road systems and geographic locales; vehicle classifications are obtained from a sample of the count stations to determine the percentage of trucks in the traffic stream; weigh stations are established at a sample of the classification stations in order to determine trends in truck weights, configurations, and dimensions. The weight trends are factored up through classifications and counts to predict the load replications essential to design and maintenance.

The concept of weight trend is crucial. What is needed are weight data from a representative sample of trucks in their principal uses, across a broad geographic coverage, and over a long term. The trend or time series analysis of truck weights is employed because change in fleet and deployment of trucks is generally quite slow. As a matter of fact, because the annual change is generally so slight, many states are now considering conducting weight surveys only on alternate years.

The question, then, is whether the Saskatchewan scale, with its 100 percent sample of trucks weighed at a continuously operating site for almost 2 years, is an appropriate step forward in dynamic weighing. Unfortunately, the answer is not yet clear, since it will depend upon the responses to the earlier questions of size, portability, and cost. I suspect, however, that the answer is negative.

I also suspect that the rugged design required to permit the unattended, continuous usage may have sacrificed practical portability and precluded inexpensive fabrication and installation. If such is the case, then the Saskatchewan scale may be a regression from the successful Texas weigh-in-motion system.

That system, as adapted by the Florida Department of Transportation, has been satisfactorily operated in Florida for several years. Using a single pair of transducers and operated by a three-man crew (in order to obtain 24-h coverage) and a single climatized mobile trailer that houses the field computer, Florida covered 15 weigh-in-motion survey sites in 1977 and weighed more than 425 000 vehicles, including approximately 60 000 trucks. The sites were geographically distributed throughout the state. The data collected appear to be statistically stable and satisfactory for our needs. In 1978 we plan to expand to 20 sites to improve our weigh-in-motion coverage.

Authors' Closure

Some additional comments may clarify some of the issues raised by Mr. Havens and Mr. Freeger.

A typical installation using the University of Saskatchewan scale includes two weighing platforms, one in each wheel path. The output signals from each of the these weighing platforms are then summed to yield an axle weight.

Concerning portability of the scale units, procedures have been developed that facilitate the movement of a scale from one location to another. These involve the preparation of a particular site with the installation of frames and dummy units. These dummy units can be lifted out of the frames and weighing platforms installed. This procedure takes approximately 3 h to complete. The portability feature of the University of Saskatchewan scale would permit the use of a pair of weighing platforms at a number of different sites.

The University of Saskatchewan scale is only in the development stage, and thus it is impossible to comment on the costs apart from saying that the computer equipment required for the acquisition of data makes up a substantial portion of the total cost of an installation. Further, the cost of the computer equipment is highly variable and depends on the degree of sophistication desired. Details regarding costs will be available by the fall of 1978 and will be one of the topics covered in the final report for the evaluation project.

We agree with Mr. Fregger regarding the question on the desirability of obtaining continuous data from a single location. In looking at the application of the University of Saskatchewan scale for the collection of vehicle and axle weight data, there would appear to be considerable merit in investigating the appropriateness of a small number of permanent installations within a province or state with a larger number of sites with frames and dummies, which would allow periodic sampling throughout the highway network.

Finally, regarding Mr. Havens' comment on the large number of pitfalls, he can be assured that, in the course of developing the scale, we have not escaped all of the pitfalls. We may have been able to avoid some of the more serious ones because of having the advantage of others' experiences.

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