Rolling deflectographs and equipment's for load capacity monitoring of roads, an overview

Leif Sjögren
Swedish National Road and Transport Research Institute
SE-581 95 Linköping, Sweden
E-mail: leif.sjogren@vti.se

Peter Andrén
Swedish National Road and Transport Research Institute
SE-581 95 Linköping, Sweden

ABSTRACT

This paper discusses the need for performance monitoring of structural condition of roads, and presents some existing and previous equipment's that are capable of monitoring the condition in motion.

Many different kinds of deflection assessment equipment exist, or have existed. These can broadly be placed in three categories: stationary, semi-stationary, and moving. The first category includes equipment like the General Electric travel gauge, Linear Variable Differential Transformers and Multi-Depth Deflectographs, light emitting diode systems, accelerometers and geophones, etc. The second category includes, e.g., devices like the Benkelman Beam, the different types of falling weight deflectometers, plate bearing tests. The third category consists of the moving mechanical or laser based deflectographs described in the paper.

Background

Roads are still one of the most important parts of the, both regional and global infrastructure. The annual budget for road maintenance worldwide is enormous, making it easy to draw the conclusion that huge savings can be made if road construction and maintenance would be more cost effective. Not only would it mean good opportunities for the industrialised part of the world to economise on the road expenses, but it would also provide better possibilities for the underdeveloped regions, as transportation usually is one of the major barriers for industrial and agricultural development and growth.

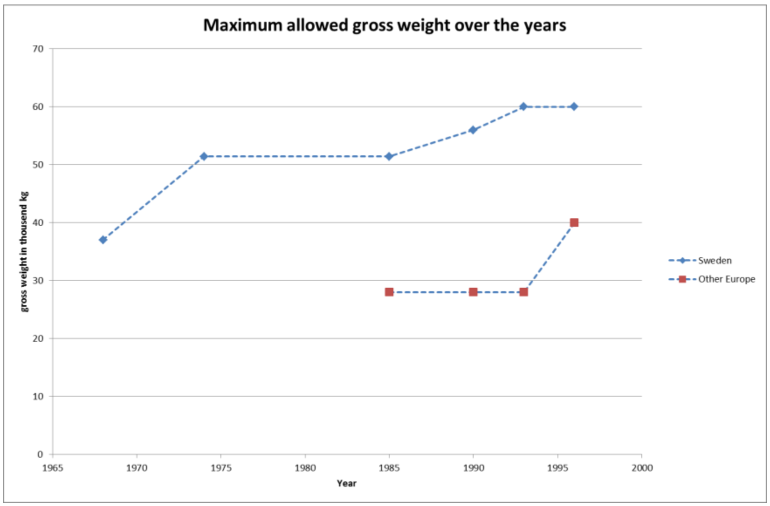
Today a lot is known about how to build roads, but not so much is known on how to keep roads in a good condition, and very little is known about how to determine the structural condition of a road in some not too complicated and slow manner. Therefore much more effort must be put into the research on how to keep the existing road net in a permanently good condition. Any technique capable of doing this will be an immense assistance in any road and pavement management system.

Objectives

This paper discusses the need for performance monitoring of structural condition of roads, and presents some existing and previous equipment's that are capable of monitoring the condition in motion.

The challenge

In Sweden the maximum allowed gross weight has increased over the years from 10 metric tons in the year 1920 to 60 metric tons today. Discussions are going on to increase this even more. In most other European countries the maximum allowed weight is around 40 metric tons.



For the road construction the number of single axles and load from single axles is the critical issues. For structures such as bridges it is the gross weight that is important. In general, the main road network was constructed many years ago and later this has been improved and complemented with new roads. Often the history of the construction is unknown or at least undocumented. Neither is the information always available in databases. New wearing courses are built with new long lasting-material. In Sweden, the use of studded tires has decreased and the new types of studs are friendlier to road surface wear. All this leads to that the wearing course last longer. The bearing capacity increases when a new wearing course is installed. If this is done less frequently it also affects the existing road structure. The configuration of trucks is another factor to consider, not only the number of axles but also the tire pressure. Using a higher pressure reduces the fuel consumption but increases the wear on the road construction. Finally, the widening of roads to fit the two plus one road concept increase the risk of low bearing capacity in the outer edges of the roads.

In a modern road asset management system good knowledge of the condition of the road network is crucial. The condition has to be monitored regularly. This is in most cases the fact for the road surface condition but not for the road´s structural condition. Many attempts have been made to assess the structural condition from surface charactertics but have not been that successful. So to conclude; the need for knowledge of a road´s structural condition increases with the need for consistent and quality assured road network coverage of information. This is fulfilled for many characteristics but not for bearing capacity or structural condition! Many systems have been developed to accomplish this. In the following we have made a review of such systems.

Equipment inventory

The structural condition or pavement strength can be explained as the structures ability to resist the traffic load that is applied to it. Actually no equipment measures this directly. Instead, in most cases, the deflection of the surface is measured when it is exposed to a known load is used as an indicator of structural condition.

The purpose with any sort of deflectograph is, of course, to measure the deflection of a pavement under a given force and use this deflection either to calculate some strength or stiffness parameter (e.g. the elasticity modulus) or to use the deflection as a direct measure of the strength and stiffness. The definition of pavement deflection used in the present report. is: ‘‘A transient downward movement of the pavement when subjected to vehicle wheel loads. A deflected pavement rebounds shortly after the load is removed.’’ Pavement deflections under normal traffic loads are in the range from less than a tenth of a millimetre for Portland concrete pavements to one or a few millimetres for a weak asphalt concrete road.

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Semi-stationary

Falling weight deflectometer (FWD)

The falling weight deflectometer is the standard in this class of equipment. A weight is dropped down on the surface a beam with sensors measure the reaction/deflection in a number of discrete points in a radius from the attack point. Parameters like the weight, sensortypes, and footprint-size as well as point distribution must be fixed.

The Benkelman beam

Benkelman's Beam is a mechanic device for measuring the deflection of the road structure under a defined static live load of 2-axle heavy vehicles. Measurement is taken manually at previously fixed points and at intervals of 10-20 along the right rut of the traffic lane. In the fifties the Benkelman Beam, with about 300 deflection measurements per day for a skilled three-man crew, was thought to be a quick method.

Moving devices

California Traveling Deflectograph

The operating principle is that of an automated Benkelman Beam. A truck plus trailer held a traversing frame that carried up to four Benkelman Beam type probe arms. The frame holding the probes was put to rest on the pavement while the steady-moving vehicle passed, and the frame was then moved automatically to the next point on the pavement. (It’s probably safe to assume that two of the probes were always placed to measure the deflection between the dual tyres.) Data was originally registered on chart paper, and later recorded electronically on tape. The operating speed was about 0.8--1.2 km/h, with one set of samples assessed every 3.8 metres. A three-man crew made 1500--2000 deflection measurements per day. The axle load could be varied, by means of a movable weight, from about 5 to 7 tonnes. The California Traveling Deflectograph was used until 1969 for routine work and until 1980 in research. Only one device was manufactured, indicating that the project was not a total success. When the California Traveling Deflectograph was taken out of service the trailer part was retained to be used with Benkelman Beam test. This is now referred to as the California Deflectometer.

Lacroix systems

A, with the California Traveling Deflectograph, contemporary deflectograph project was the French Lacroix system. The Lacroix-style rolling deflectograph measures the deflection between a pair of double rear tyres, but the measuring probe arms and registration mechanism

are a bit different from the Benkelman Beam. The operating procedure is basically the same for all Lacroix deflectographs.
Lacroix's Deflectograph is a device for continuous automatic measuring of the elastic deflection of the road pavement under a specified axle load. The expected loading is in the range of 5-13 t/axle. Measuring is carried out simultaneously for the wheel tracks of the inspected traffic lane. Recordings of the deflections are taken at intervals of approximately 6 m. Data obtained are used for the analysis and assessment of the load-bearing capacity of the road pavement and for defining the thickness of the strengthening pavement layers required for the road repair. The device can measure the length of the travelled road sections, thus relating all data to their real location on the road with no additional marking. Results of measurements are recorded on a disc and then processed with the respective software.

The first Lacroix-style deflectograph was constructed in 1956 by M. J. Lacroix, at that time chief engineer at Ponts et Chaussées à Périgueux in Dordogne in the southwest of France. This first prototype had an operating speed at about 1.8 km/h, and could only measure the deflection in the right wheel path. The 0.8 metres L-shaped beam with one probe arm measured one point every 3.6 metres. The deflection measures were registered on paper.
The second prototype of the Lacroix was developed in 1961. With a 1.2 metres T-shaped dual probe arm this version assessed the deflections in both wheel paths, and also used an electro-optical photographic recording device beside the chart paper recorder.

The third version was developed in 1964 (and was also called version 1964). The operational speed was increased to 2.0--2.7 km/h depending on the condition of the road surface. The length between two test points was 3.2 metres. The recording of data was still done with both a graph paper and an optical device. The third version (no longer called a prototype) was widely used in France (and other countries) and in 1965 1300 km of road was measured in France alone.

British Pavement Deflection Data Logging Equipment (PDDLE)
The technical data of the PDDLE is pretty much the same as for the Lacroix ---an operating speed of 2.5 km/h and recording of the maximum deflection every 3.8 metres. The PDDLE 2000 series had an accuracy of 0.001 mm due to improved sensor technique. The British (probably inspired by the French) also built a 6.5 metres wheel-base machine for stiffer pavements
In the mid-seventies a private company, WDM Ltd, started to manufacture the PDDLE on a commercial scale, and had contracts to do the larger part of the routine surveys in the UK.

Danish Deflectographs
The first generation Danish Deflectograph was developed from 1972 and put in operation two years later. The construction seems to have been inspired more by the California Traveling Deflectograph than the Lacroix. A fifteen metres long trailer carries an eight metres long truss framework with the Benkelman Beam type probes. The measuring procedure is the same as for the Lacroix or California Traveling Deflectograph, where the probes are placed on the road surface to measure the deflection from the constantly moving lorry. The probes are then automatically moved to a new position for a new measurement cycle. One set of deflections was assessed every eleven metres, and the speed was 1.5 km/h. This deflectograph was called the ‘‘grasshopper’’, due to their similar movements while jumping along the ground/pavement.

The second generation Danish Deflectograph was completed and put in regular operation in 1988. With the need for only one deflectograph in Denmark the first was donated to the Danish

Road Museum. Although the second generation was a complete rebuild from the first generation, the working principle, with minor modifications, is the same. The new deflectograph could operate in curves and the speed was raised to 7 km/h. Both of the Danish deflectographs were one-of-a-kind and used only in Denmark.

Australian Systems

The Department of Main Roads, New South Wales, Australia purchased a Lacroix Deflectograph in 1975 and one more in 1978. The Deflectolab is different to other deflectographs in that the Benkelman Beam type probe arm are mounted behind the rear axle. The measuring cycle then starts with with probes being positioned between the dual tyres and the unloading is recorded. The operating speed is 4 km/h, and samples are assessed variably every 4 to 20 metres.

Curviamètre

The first deflectograph not based on the Benkelman Beam concept was the French Curviamètre. It was developed not by the LCPC but by the Centre Expérimental de Recherches et d'Etudes du Bâtiment et des Travaux Public (CEBTP). The first prototype, based on a Unic-Fiat 220 R with a 13 tonnes axle load, rolled in 1973. In 1977 the first unit suitable for production use was completed.

Figure 1 Curviametré

The basic of the Curviamètre's operating principle is similar to that of a caterpillar tank. Geophones or accelerometers are mounted on a continuous closed-loop chain that travels on the pavement surface between the dual rear wheels. The acceleration or velocity of the surface during a passage of the rear wheel is recorded, starting two metres before the wheel passes and stops one metre after. The Curviamètre can assess both the deflection and the radius of curvature of the pavement deflection bowl at a speed of 18 km/h. The 1977 version had only one sensor on the chain which gave it a sampling distance of 12.45 metres, which was the length of the chain.

A new model, the MT 15, was produced in the early nineties. The operating speed was now one metre per second faster than before (6 m/s or 21.6 km/h), but the main improvement was that the now fifteen metres long closed-loop chain was equipped with three geophones generating a result every five metres. A variable rear load made it possible to vary the rear axle load from 8 to 13 tonnes.

Other systems

The Rolling Dynamic Deflectometer (RDD) was developed at The University of Texas at Austin. The RDD was constructed by modifying a Vibroseis truck. Particularly useful in oil prospecting, the Vibroseis trucks apply large dynamic forces to the ground in order to generate seismic waves. The hydraulic vibrator mounted on the RDD transmits sinusoidal forces in the 5--100 Hz range to the road surface, and rolling sensors to assess the deflections. The operating speed is about 2.5 km/h.

The FrenchCollograph can also be seen as a sort of rolling deflectograph. Derived from a small rolling and vibrating compactor it transmits a 50 Hz load with a peak of about 3 kN. The Collograph is primarily developed for detection of cracks, separated pavement layers, etc.

Laser-Based Systems

The mechanical deflectographs discussed in the previous section made it possible to make routine network level deflection measurements. With a top speed of about 20 km/h for the Curviamètre, they were, however, all far from normal traffic speed. With an ever increasing traffic volume during the nineteen-sixties, seventies and eighties their low speed started to be a problem. A method that could assess the deflection at normal traffic speeds would not only make it possible to test more, but the tests could be done in a much safer way ---for both the deflectograph operators and other road users.

Purdue Deflectograph

The first practical solution to this was the Purdue Deflectograph. (This deflectograph never had an ‘‘official’’ name. The Purdue Deflectograph system did not only aim at measuring the deflection, but also the surface texture and longitudinal profile. The concept was based on the TRRL high-speed profilometer. In short, at least four non-contact laser range finders are mounted in a line along the vehicle. A geometric relationship is then used to calculate the deflection.

Ohio DoT and Surface Dynamics Inc.

In 1985 the Ohio Department of Transportation ordered a feasibility study from the company Surface Dynamics Inc. regarding high-speed measurement of highway pavement deflections under moving loads. With no explicit references to the work by Harr and Elton the TRRL walking beam reference system was chosen. Six non-contact Selcom 2204-64 Optocator lasers was proposed to get some redundancy from the minimum four. In order to minimise the laser misalignment which caused problems for the Purdue Deflectograph a thermo-insulated and liquid cooled reference beam with a velocimeter correction unit was proposed. The deflection measuring devices should be mounted, with three vibration insulation mounting pads, on a suspended platform under the trailer. The feasibility study was positive, but no information has been found whether the Ohio Department of Transportation developed the project or not. In any event, in the mid-nineties two American rolling deflectograph projects started. They had similar names (Rolling Wheel Deflectometer and Rolling Weight Deflectometer) and were both based on the work by Elton and Harr.

Rolling Weight Deflectometer
The Rolling Weight Deflectometer2 (RWeD) of Quest Integrated, Inc. and Applied Research Associates was mainly aimed at airfield evaluation. It had the same setup as the Purdue Deflectograph, i.e. four equally distanced non-contact Selcom lasers. Designed for airfield evaluation, the load is transfered to ground through an F-15 wheel assembly.

Rolling Wheel Deflectometer
The RWD system is mounted within a custom-designed 53-ft semi-trailer. The measured deflection is the response from one-half of an 18-kip single-axle load traveling at normal traffic speeds. At the time this testing was conducted, an aluminum reference bar, suspended beneath the trailer, contained four laser sensors to measure the distance to the pavement surface. Three lasers are used to measure the distance to the unloaded pavement surface (i.e., forward of and outside the deflection basin), and a fourth laser, located between the dual tires and just behind the rear axle (Figure 1), measures the distance to the deflected pavement surface. The deflection is calculated by comparing the laser scans profile as the RWD moves forward.

Road Deflection Tester
The Road Deflection Tester (RDT) was built with the intention of providing a safe, fast, accurate and reliable way to assess the bearing capacity of roads, airport runways, and other pavement surfaces. Primarily, its use was intended for the Pavement Management System network level.

A prototype RDT was built in the early nineties. The 1964 Volvo Titan truck proved to be a suitable carrier. The rear axle weight and the sensor locations could quite easily be altered, and many different sensor configurations were tested. However, the relatively short distance between the two wheel axles of the truck was assumed to limit the function of the system. A longer wheelbase would make the deflection reading more accurate, it was thought. Other problems were the low maximum speed of 70 km/h and the difficulty to keep an even speed while going uphill. Also, the facilities, comfort and working environment for driver and operator in the vehicle were very limited, making more than day-trips practically impossible. It served well as a research vehicle, but it was clearly unsuitable as a production unit.
The new RDT was built on a modified Scania R143 ML truck. The major modification is that the engine is placed in the back of the truck in order to maximise the rear axle force on the road.

High Speed Deflectograph, nowadays TSD
The latest addition to the rolling deflectograph scene is the Danish High Speed Deflectograph (HSD).

Figure 2 The TSD deflectograph

Rather than the ‘‘standard’’ laser triangulation distance-meters, the HSD is using laser Doppler velocity-meters. These laser Doppler sensors assess the road surface deflection speed by measuring the shift in the outgoing and incoming laser light, i.e. the Doppler effect. (The basic idea, to measure the deflection velocity instead of the deflection, is the same as for the French Curviamètre with the difference that the Curviamètre measured the deflection velocity in a large number of points and then could integrate this to a deflection. By measuring the deflection speed, theoretically only one laser sensor is needed. As an absolute value is obtained no reference sensor is needed. This also does away with the problem of measuring in curves, which cause alignment problems for more or less all other deflectographs.

How quickly the road surface deflects instantaneously at one point near a moving load is, however, not quite as interesting as how much it deflects. On the other hand, a relationship between deflection velocity and actual deflection should not be very hard to find, even though it’s likely that this relationship will vary with the road construction and, especially, the viscoelastic properties of the asphalt.

The Doppler sensor actually measures the relative speed of the sensor and the road surface, so it’s of utmost importance to filter out the movement of the sensor. On the HSD this is achieved with a combination an inertial three axle accelerometer and a three axle gyroscope. Data from the inertial units are used both in post-processing and as input to a servo system controlling the position of the sensor in real time.

Reference

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