Dynamic Pavement Response Measurement System using Piezoelectric Axle Sensors

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Saskatoon, Saskatchewan, Canada

by

Rebecca Jean Huff

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Dynamic Pavement Response Measurement System using Piezoelectric Axle Sensors

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ABSTRACT

Over the past several decades, the transportation of commercial goods in North America has shifted from using railways to using roadways. This came as a result of the recent development of high quality roads reaching the same destinations as the railroads'. Historically, roadway design has used an empirical approach. Essentially, this technique was adequate in dealing with small vehicles and low volumes of traffic.

Today, however, large vehicles and high traffic volumes are inflicting increasing amounts of damage on many roadways. As such, the idea of developing a mechanistic road modeling approach for design, construction and preservation was conceived. The ability to determine the Dynamic Deflection Bowl surrounding a rolling wheel is required for the prediction of structural damage.

This thesis presents the Piezoelectric Axle Sensor (PAS) as a possible tool for obtaining the Dynamic Deflection Bowl information. It is a sensor which converts mechanical deformation into a proportional electrical charge, and there are already thousands of these sensors installed in systems world wide, measuring the Dynamic Weights of vehicles. The operation of several different types and orientations of these PAS's were examined and tested. Valuable data was extracted from their outputs. This data allowed the prediction of many, but not all, of the Deflection Bowl characteristics.

For instance, the length and inflection point of the Deflection Bowl along with footprint size were all successfully predicted. The horizontal and vertical components for the two pseudo-rectangular PAS's were combined and found to exhibit the same characteristics as the cylindrical PAS. This research has shown that the outputs from several popular PAS's can be used to generate data useful in planning and maintenance of the nations roadways.

ACKNOWLEDGEMENTS

It is my pleasure to recognize, with utmost appreciation, all those who have helped in making my research a success. In particular, many thanks to both of my supervisors, Dr. Brian Daku and Dr. Curtis Berthelot. Dr. Daku is an Electrical Engineering Professor at the University of Saskatchewan, whose excellent assistance provided a good foundation for, and continual support throughout, the writing of this thesis. Dr. Berthelot is a Civil Engineer in the Transportation Research Center at the University of Saskatchewan, who not only identified the problems that formed the basis of my research, but was extremely helpful in discussing and evaluating possible strategies to solve them, and ultimately showed me that nothing was impossible.

Likewise, I gratefully acknowledge the support of Mr. Ron Koenderink, Chief Engineer at International Road Dynamics Inc., who was also extremely instrumental in problem identification and was always available to consider and assess various approaches.

This Master of Science project in Electrical Engineering was pursued in collaboration with Telecommunication Research Laboratories (TRLabs), International Road Dynamics Inc. (IRD), the Transportation Research Center at the University of Saskatchewan, and the Department of Highways and Transportation, a department within the Government of Saskatchewan - whom all have been very supportive with funding, in-kind contributions, and continual assistance.

Credit is also due to the Highway Crews and IRD Roadies that did the installation!

Moreover, thank-you is extended to my colleagues for lending an ear and offering suggestions from time to time.

I conclude by sending a special thanks to my close friends and family, especially my parents Bev and Jerry Huff who have been by my side throughout. Without their tremendous love and support, I would not be where I am today.

Thank you...

To my parents, with love
R.J.H.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

A/D	Analog to Digital Converter
BL	Brass Linguini
CV	Coefficient of Variation
DCF	Dynamic Compensation Factor
D84011	Benkelman Beam Truck Number
FWD	Falling Weight Deflectometer
GNP	Gross National Product
H/D	Hard Drive
HMAC	Hot Mix Asphalt Concrete
I/F	Interface
IRD	International Road Dynamics Inc.
LM35	Precision Centigrade Temperature Sensor
LVDT	Linear Variable Differential Transducer/Transformer
MDD	Multi-Depth Deflectometer
MSI	Measurement Specialties Inc. – Roadtrax BL PAS
MSI90	Measurement Specialties Inc. – Roadtrax BL (Tilted 90°) PAS
PAS	Piezoelectric Axle Sensor
PCL-818H	A/D Card
POC	Point of Contact
PVC	Polyvinyl Chloride
PVdf	Polyvinylidene Fluoride
St. Dev.	Standard Deviation
Thermo-B	Thermocoax - Vibracoax (8mm Bare) Piezoelectric Axle Sensor
Thermo-E	Thermocoax - Vibracoax (3mm Encapsulated) Piezoelectric axle Sensor
TL082	Operational Amplifier
TRLabs	Telecommunication Research Laboratories
WIM	Weigh-In-Motion

1 Introduction

The gross national product (GNP) of a particular country is a strong function of the efficiency of that country's transportation infrastructure. It is only during the last 40 years that there have been high quality roads that reach all of the same communities and destinations that the railroads have historically served. In contrast to railroads, trucks, with the ability to operate economically on short runs, have considerable scheduling flexibility. This allows the convenience of 'door to door' and 'just-in-time' delivery of goods [1].

In the past several decades, there has been a major shift in rural transportation from rail to road, resulting in significant increases in load related damage to the road infrastructure. In addition, due to the increase in allowable axles and gross vehicle weights on roadways, commercial trucks are now permitted to be bigger and carry larger loads than ever before, causing additional damage to roadways [2].

Saskatchewan, for example, has been noted for being at the forefront in the development of new road and trucking technology. The province works in partnership with industry and universities to develop new trucking technologies. For instance, air-spring and dynamic tuned suspension systems are essential developments of this type of technological advancement. Generally, these measures have enhanced safety and efficiency. Moreover, they have minimized, but not eliminated, damage inflicted on the road infrastructure as a result of dynamic loading effects.

As such, the Government of Saskatchewan co-operates with the trucking industry to create a positive environment that enables this industry to offer service as efficiently as

possible, providing due regard to the safety of the motoring public and the preservation of the publicly owned highway infrastructure [3].

The physical damage inflicted on the road is related to the surface deflection in the pavement due to loading. Each vehicle tire surface that touches the road creates some surface deflection. This deflection (road structure response to static/dynamic loading) in the vicinity of the tire is referred to as a "Deflection Bowl", and is illustrated in Figure 1.1.

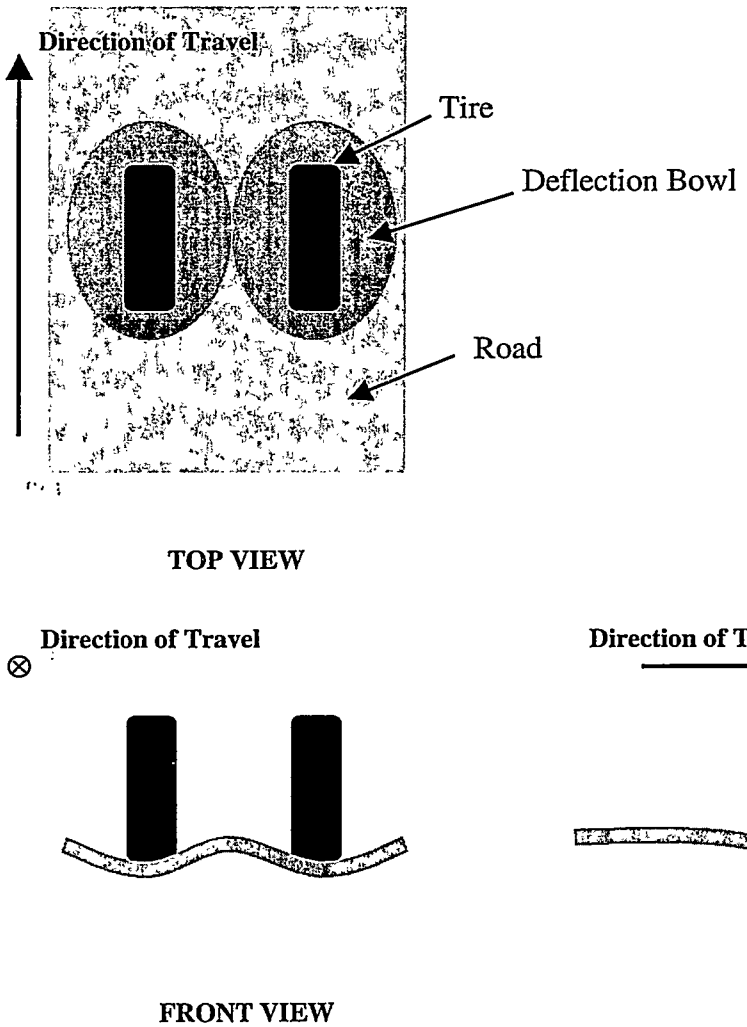

Figure 1.1 Top, Front, and Side Views of a Deflection Bowl

This figure shows that road deformation starts to occur at some distance in advance of the actual tire to pavement contact area - approximately 2 m for the average commercial truck on a Hot Mix Asphalt Concrete road structure. This distance varies with respect to material properties and thickness' of the road, size of the tire, and degree of loading. If the surface deflection does not fully recover, pavement damage has occurred. Cumulative pavement damage will eventually result in road failure.

In the past, Departments of Highways have typically measured this surface deflection on roadways using instruments and techniques such as the Benkelman Beam, the Falling Weight Deflectometer (FWD), and the Multi-Depth Deflectometer (MDD). Basically, these instruments and techniques have been developed to measure surface deflection in an attempt to characterize deterioration of roadways. The Benkelman Beam technique is capable of yielding accurate static surface deflection results, but it cannot obtain the dynamic measurement. It is also dangerous because it requires a team of persons on the roadway to obtain these measurements. The tip of the beam, shown in Figure 1.2, is initially placed perpendicular to the tire at its center point and the Recording Dial Gauge is set to zero. Manual readings are taken every 10 cm, by an operator lying on the surface of the road, as the Benkelman Beam truck pulls away from the tip of the beam.

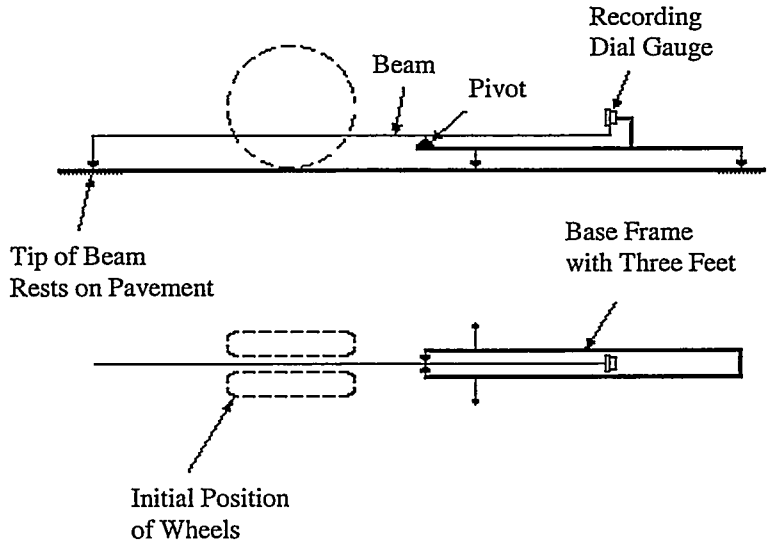

Figure 1.2 Benkelman Beam Measurement Technique

The FWD technique is, conversely, capable of simulating and measuring effects of dynamic loading. As the weight drops, the spring system (visco-elastic damper) shown in Figure 1.3, is engineered to simulate a passing wheel load while data is recorded from the geophones. Although it still cannot give a response to an actual moving vehicle - only a simulation of such - it does however, have the advantage of being portable and through back-calculation techniques it is capable of determining material properties.

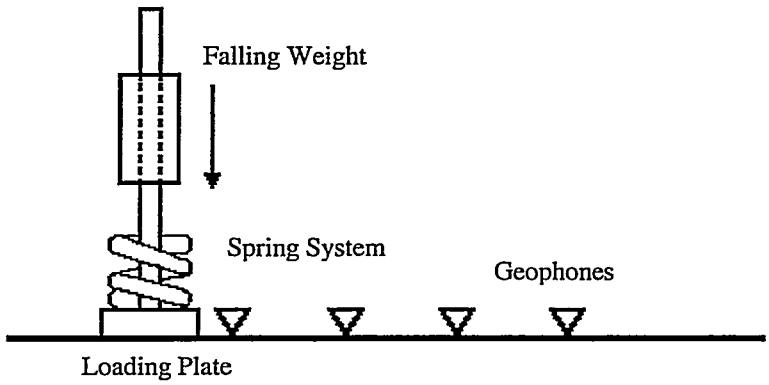

Figure 1.3 Falling Weight Deflectometer Measurement Technique

A system that is capable of dynamic measurements, such as "in-situ" elastic deflections and (or) permanent deformations in multiple pavement layers, is the MDD. The MDD consists of a series of Linear Variable Differential Transducers (LVDT). As the vehicle travels over the sensor, the pavement deflects under the wheel load. This deflection will cause the series of LVDT's, anchored to the sides of the hole, to move with respect to the 3 m stationary rod (anchored into the subgrade), as shown in Figure 1.4. These sensors work magnetically on the principle of a transformer with a variable coupling coefficient. The LVDT's movement (displacement) is recorded - as a voltage - with respect to the location of ferrous metal "slugs" in the center rod. Although there is damage to the road caused by drilling this 3.81 cm (1.5") vertical hole during installation, a more significant reason this technique is not widely accepted for determining surface deflection, is because of its excessive cost and lack of portability.

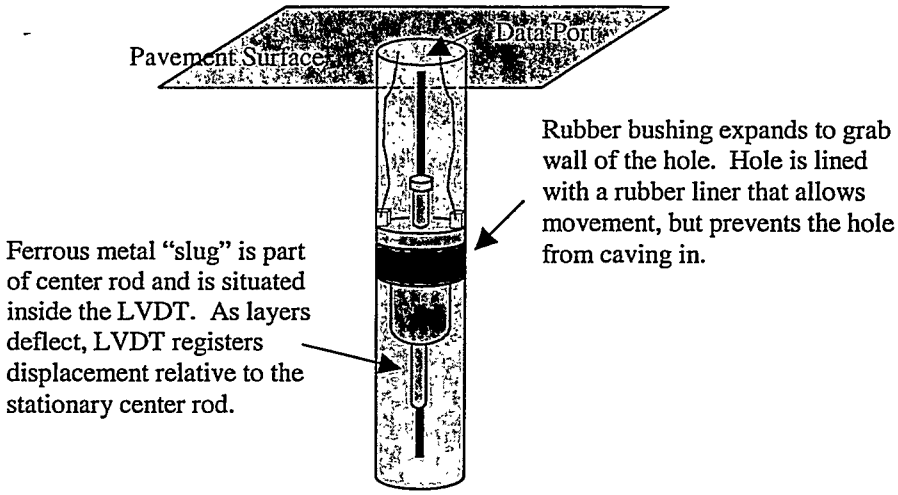

Figure 1.4 Multi-Depth Deflectometer Measurement Technique

1.1 Proposed Approach to Measure Surface Deflection

Around the world, commercial trucks are monitored for planning, design, and preservation requirements by Highway Departments using Intelligent Transportation Systems, such as Weigh-In-Motion (WIM) systems (i.e., dynamic weighing of vehicles). Many of these WIM installations (sensor configurations) use piezoelectric sensors in combination with other vehicle sensing technologies that are installed directly into the surface of the roadway, across the width of each lane. These sensors are called Piezoelectric Axle Sensors (PAS) since both tires of each axle cross the sensor at the same time, as shown in Figure 1.5.

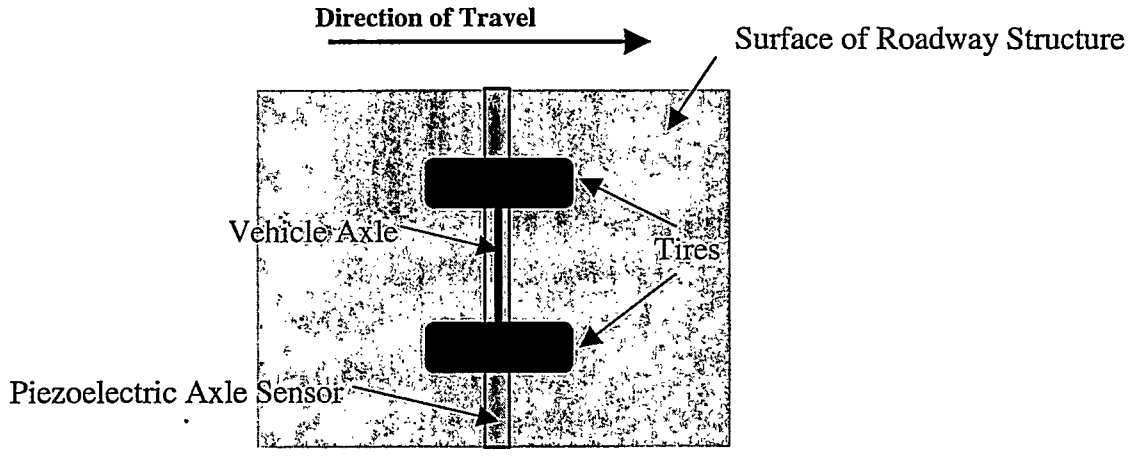

Figure 1.5 Top View of an Axle Passing Over a Piezoelectric Axle Sensor

The outputs from these sensors provide the input to a set of System Electronics comprised of a Data Acquisition System used to acquire, analyze, and through calculations, determine the Dynamic Weight of each passing vehicle. The Dynamic Weight of a vehicle is time varying because of accelerations induced to the wheel by irregularities in the road surface. The vehicle suspension also plays a part in this situation. This Dynamic Weight oscillates around the Static Weight of the vehicle. The output of the PAS is used to calculate this instantaneous weight (point on the oscillating output). This calculated instantaneous weight consists of a dynamic component and a system error component due to the sensor itself and the electronics supporting the sensor.

An example of a signal from a PAS, after partial processing (one level of integration), is shown in Figure 1.6. This particular processed version of the raw data was chosen because it is used to directly calculate the Dynamic Weight. This signal has three very different and distinct regions which are labeled A, B, and C.

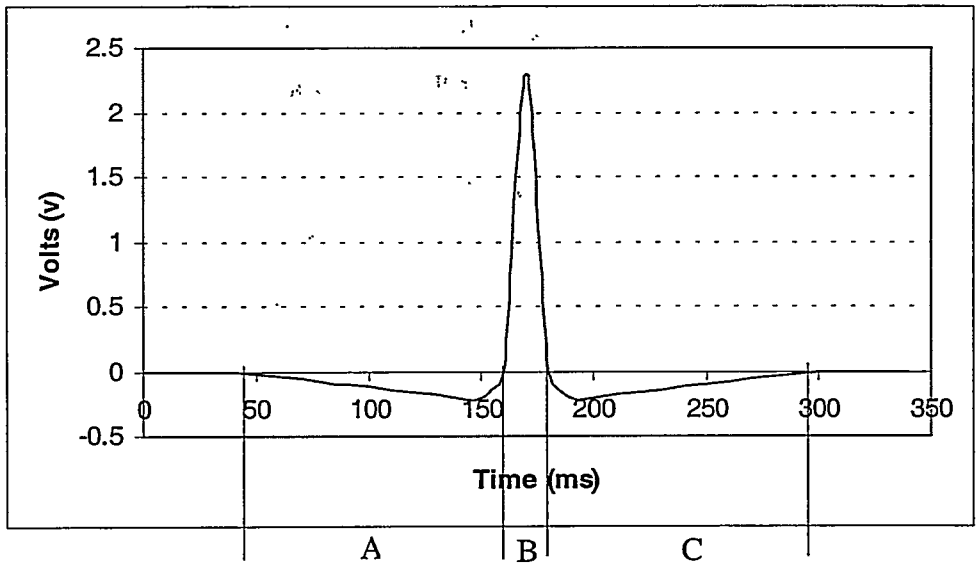

Figure 1.6 Piezoelectric Axle Sensor Response to a Dynamic Load (Output signal, from the previous Figure 1.5, as the tire approaches, passes over, and departs from the PAS)