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# Mechanistic-Empirical Load Equivalencies Using Weigh in Motion

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## ABSTRACT

In Saskatchewan, recent transportation rationalization, economic development, and value added initiatives in the resource sectors are resulting in significant increases in commercial trucking. To help facilitate improved efficiency in commercial trucking, Saskatchewan Department of Highways and Transportation (SDHT) is partnering with commercial carriers to allow increased allowable weights and larger more efficient truck configurations. Unfortunately, these new commercial truck loadings do not fall within the inference of traditional load equivalency models, especially with regards to secondary roads (thin pavements and gravels). Because of this, it is difficult to predict with certainty the impact increased weights and dimensions will have on the Saskatchewan road network. This study presents a framework from which performance based mechanistic-empirical load equivalencies may be calculated for diverse road structures and axle loadings. In order to calculate performance based mechanistic-empirical load equivalencies, this study proposes using weigh in motion to measure traffic load profiles in the field, and using these traffic load profiles to specify laboratory frequency sweep tractions to characterize the inelastic behavior of road materials necessary for mechanistic road modeling.

## 1.0 INTRODUCTION

Empiricism is defined as: *"relying on experience or observation without due regard for system and theory"*(Webster's, 1991). In the context of road-modeling, purely-empirical road models are based solely on judgment inferred from past road performance observations, usually during accelerated road tests. Different traffic loadings have traditionally been equilibrated to an 80KN equivalent single axle load (ESAL) based on empirical road performance observations at the AASHO Road Test (AASHTO, 1993).

Purely-empirical road models employ a classical statistical regression analysis framework to derive road performance relations. As shown in Figure 1, a purely-empirical road performance modeling framework assumes performance predictor variables and calibrates the predictor coefficients based on regression analysis of repeat road performance observations. Linear or log-linear regression techniques are commonly used because higher order nonlinear regression is more complex and requires additional model calibration data, which can be expensive to obtain. Once formulated and calibrated, the predictive capability of the model is evaluated for accuracy and statistical significance, the statistically insignificant variables are removed and the model is recalibrated.

Phenomenological (simulative) materials tests are sometimes used to augment purely empirical road models with material behavior predictors encoded into the road performance regression formulation. Common phenomenological road material tests include Marshall stability and flow, Hveem stability, unconfined compressive strength, resilient modulus, repeated load creep, and flexural beam fatigue. The AASHTO flexible pavement design equation (2) is an example of a phenomenological-empirical road performance model:

$$[\text{Eq. 1}] \quad \log(W_{80}) = Z_R S_o + 9.36\log(SN+1) - 0.20 + \frac{\log\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40+\frac{1094}{(SN+1)^{5.19}}} + 2.32\log M_R - 8.07$$

Where:

- $W_{80}$ = predicted number of 80 KN equivalent single axle loads
- $Z_R$ = standard normal deviate = $\frac{\log W_{80} - \log W_{t80}}{S_o}$
- $W_{t80}$ = number of 80 KN axle loads applied up to time t
- $S_o$ = combined standard deviation of the traffic and performance prediction
- SN = road structural number: $(a_1D_1 + a_2D_2m_2 + a_3D_3m_3)$
- $a_i$ = load carrying capacity layer regression coefficients of layer i: (asphalt concrete = .44; crushed stone base = .14; sandy gravel base = .11)
- $D_i$ = thickness of layer i (m)
- $m_i$ = drainage coefficient of layer i
- $\Delta$PSI = difference between the initial PSI and the terminal PSI specified in design

$M_R$ = resilient modulus of subgrade soil (Pa)

PSI = present serviceability index= $5.03 - 1.9\log(1+SV) - 1.38(RD)^2 - 0.01\sqrt{(C+P)}$

SV = slope variance over one linear foot

RD = rut depth based on a 4 foot straightedge centered over the rut (inches)

C = linear feet of cracking per 1000 square feet of road surface

P = square feet of patching per 1000 square feet of road surface

As can be seen in the AASHTO flexible pavement design equation, the calibrated accuracy of empirical road performance models are solely dependent on regression coefficients encoded into the model based on observations of performance with little or no regard for the physical–mechanical behavior of the road structure. Given the diversity of the Saskatchewan road infrastructure and recent increases in commercial truck weights and dimensions, the inherent non-linear performance behavior of roads can instill false confidence in traditional empirical based load equivalencies.

## 2.0 MECHANISTIC–EMPIRICAL ROAD MODELING

This study proposes a performance based mechanistic-empirical road modeling framework for quantifying load equivalencies based on material constitutive relations, primary road responses, and road performance predictions across a broad spectrum of roads, loads and environmental conditions. As shown in Figure 2, a mechanistic based road modeling framework (Berthelot, 1998) consists of apriori information including: traffic loading, environmental conditions, road structure, and road materials. Apriori information establishes the state conditions used to characterize the constitutive behavior of the road materials comprising each road structure layer. These constitutive relations are then used to quantify primary road response profiles of the road structure, which are used by damage mechanics road performance prediction models to predict the performance related distress behavior of the road structure as an operating system. To illustrate, spatial and temporal strain profiles $\varepsilon(\vec{x}, t)$ coupled with spatial and temporal temperature profiles $T(\vec{x}, t)$ can be used to directly predict permanent deformation. Similarly, spatial and temporal stress profiles $\sigma(\vec{x}, t)$ coupled spatial and temporal temperature profiles $T(\vec{x}, t)$ can be used to predict crack initiation and propagation.

Life cycle road performance predictions can then be used by life cycle cost/benefit models to evaluate the relative life cycle costs and benefits to both road agencies and road users. Advantages of a mechanistic-empirical road-modeling framework include:

a) The fundamental principles of thermomechanics are universal across all materials and engineered systems.
b) Thermomechanics facilitates a multidisciplinary approach to predicting road performance.
c) The thermomechanical axioms of nature are always observed and do not vary in time, thereby providing a stable road-modeling platform that facilitates ongoing

improvements to the model and provides the ability to accommodate future changing conditions.

d) Thermomechanical material constitutive characterization provides a fundamental mapping from material behavior to road performance.
e) A mechanistic based road-modeling framework can be applied as a uniform theory across all road structures, road materials, traffic loadings, and environmental conditions.
f) Thermomechanics provides a comprehensive analytical process that can be used across all road engineering activities.
g) A mechanistic based road modeling framework facilitates a discretized and probabilistic approach to evaluating road performance and load equivalencies.

## 3.0 WEIGH IN MOTION FOR MECHANISTIC–EMPIRICAL LOAD EQUIVALENCIES

As can be seen in Figure 2, a primary input to a mechanistic based performance prediction model is knowledge of the loading that will be applied to the system. This is especially true for road structures because they can exhibit a relatively high degree of inelastic deformation and fracture behavior under traffic loading compared to other engineering structures. As a result, in order to accurately quantify the inelastic behavior of road structures, vehicle weight, configuration, dynamics, tire type, tire pressure, environmental conditions and the specific road materials comprising the road structure influence the impact traffic load profiles have on the road structure.

When a vehicle is in motion, the magnitude and coordinate direction of the load-induced stress state at a given point in the road structure changes as the vehicle passes over that point. As a result, in order to accurately predict traffic load related damage inflicted onto a road structure, spatial and temporal traffic load profiles are required as illustrated in Figure 3. If the dynamic load profile can be accurately measured in the field for different truck loadings and road structures, then the applied tractions for laboratory constitutive relation characterization can be accurately specified. To illustrate, rapid triaxial frequency sweep testing as shown in Figure 4, can be used to characterize the fundamental stress dependent bulk behavior of road materials:

[Eq. 2] $$E^* = \frac{T_{11}(t)}{\varepsilon_{11}(t)} = \frac{T_{11}e^{i\omega t}}{\varepsilon_{11}e^{i(\omega t-\phi)}}$$

Where:

$T$ = applied triaxial traction
$\varepsilon$ = measured triaxial strain
$\omega$ = angular load frequency
$\phi$ = linear viscoelastic phase angle

t = load period

In order to take advantage of inelastic road structure analysis techniques, spatial and temporal load profiles must be accurately quantified as they are applied in the field. Weigh in motion (WIM) is uniquely capable of quantifying spatial and temporal axle loads to support performance based mechanistic-empirical load equivalency calculations. By employing WIM, the actual load state profiles in the field can be used to specify rapid triaxial traction states used to characterize road material constitutive relations based on the actual traffic loading spectrum in the field.

An advantage to using WIM, is it is well established as a road management tool in two traditional capacities: traffic planning data collection, and commercial vehicle enforcement. As a traffic planning data collection tool, WIM has been used to provide traffic information needed to support future road infrastructure planning decisions. WIM data collection systems are often used to provide traffic stream volumes, vehicle speeds, axle weights, and vehicle configuration. As a weight enforcement tool, WIM is used to sort trucks prior to entering a weigh station either on the mainline traveling at highway speed or off-ramps at reduced speed. Where truck volumes are low, static scales provide sufficient capacity to weigh most trucks passing through the facility. However, many weigh stations experience such high truck traffic that they do not have the capacity to weigh all trucks statically. In these cases, trucks that the WIM identifies as near the allowable weight limits, are directed to the static scales, while all other trucks are allowed to bypass. Given the road industry's move towards mechanistic-empirical road modeling techniques with such initiatives as the Strategic Highway Research Program and the proposed AASHTO 2002 design guide, WIM is also well suited to provide a field data collection tool that directly quantifies load state profiles in the field to support of performance based mechanistic-empirical road design and analysis methods. To illustrate, the Strategic Highway Research Program (SHRP) Long Term Pavement Performance (LTPP) employ WIM systems to quantify traffic loading on LTPP pavement test sections throughout North America.

As illustrated in Figures 5 through 7, several types of WIM systems are currently available and have been widely implemented throughout North America including: single load cell scales; bending plate scales; and piezoelectric, quartz and fiber optic sensors (portable and permanent). The accuracy and costs of the different WIM systems range from a few thousand dollars per lane to several tens of thousand dollars per lane. WIM system accuracies relative to vehicle static vehicle weights also range from less than one percent to over twenty percent. As a result, the type of WIM system appropriate for the specific application will depend on the specific needs of the road agency and the sophistication of the road modeling capability.

## 3.0 SUMMARY AND CONCLUSIONS

Transportation rationalization, economic development, and value added initiatives in the resource sectors are significantly increasing commercial trucking. Different traffic loadings have traditionally been equilibrated to 80 KN equivalent single axle loads (ESALs) based on empirical road performance observations at the AASHO Road Test. Because purely-empirical road models are based solely on judgment inferred from past road performance observations, it is difficult to predict with certainty the impact increased commercial trucking will have on the performance of the road network. Given the road industry's move towards mechanistic-empirical road modeling techniques with such initiatives as the Strategic Highway Research Program and the proposed AASHTO 2002 design guide, and given recent advances in mechanistic materials characterization and road modeling capabilities, WIM is well suited to provide a field data collection tool that directly quantifies field load state profiles to support performance based mechanistic-empirical road design and analysis methods.

This study proposed a framework from which performance based mechanistic-empirical load equivalencies may be calculated for diverse road structures and axle loadings. A mechanistic based framework is required for conditions not within the inference of traditional load equivalency models such as that derived during the AASHO Road Test. However, in order to validate performance based mechanistic-empirical load equivalencies, the ability to measure traffic load state profiles spatially and temporally under alternative truck loadings in the field is required to specify material constitutive relation characterization necessary for mechanistic road modeling. Weigh in motion is uniquely suited as a field data collection platform to provide spatial and temporal traffic load state profiles for supporting performance based mechanistic-empirical load equivalency calculations.

## REFERENCES


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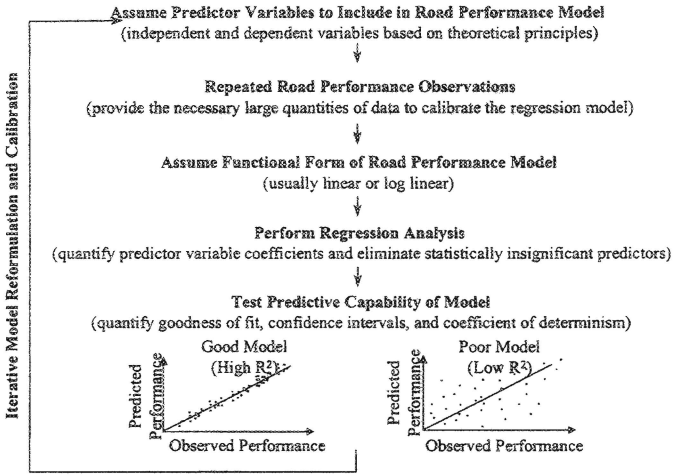


FIGURE 1 Purely-Empirical Road-Modeling Framework

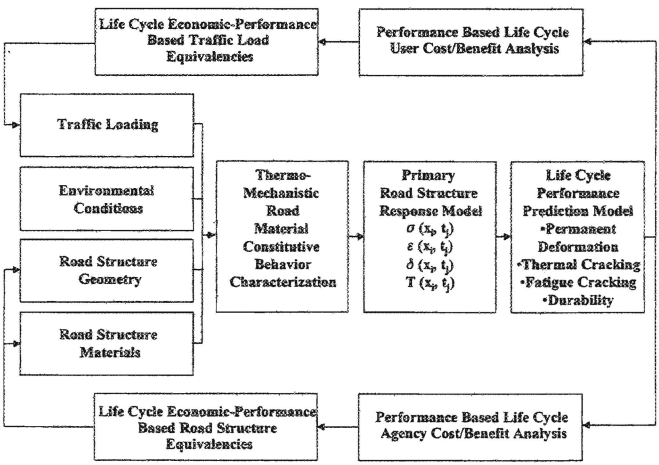


FIGURE 2 Mechanistic-Empirical Road-Modeling Framework

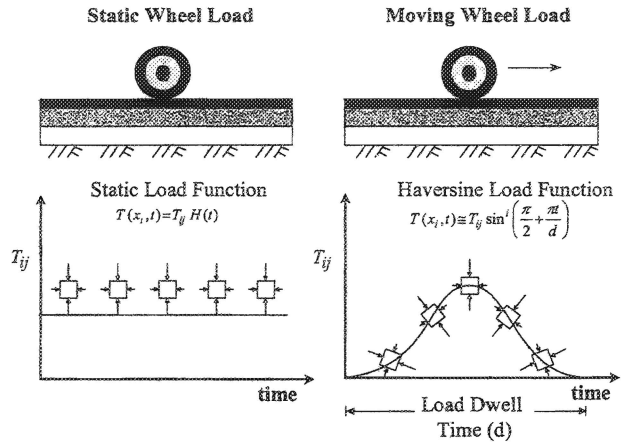


FIGURE 3 Static and Dynamic Wheel Load Tractions

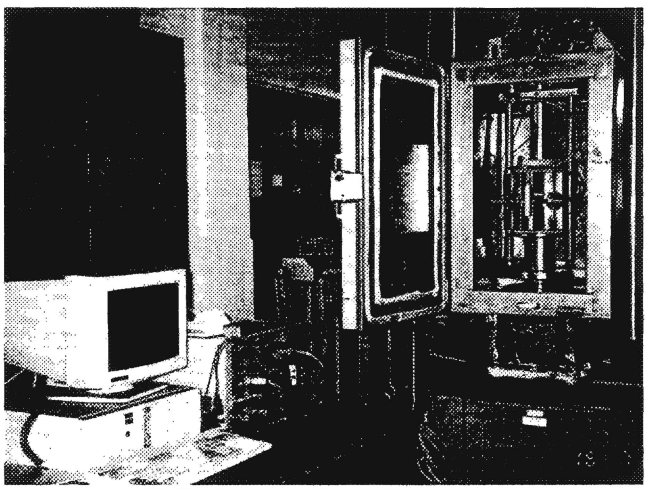

FIGURE 4 Rapid Triaxial Test Apparatus

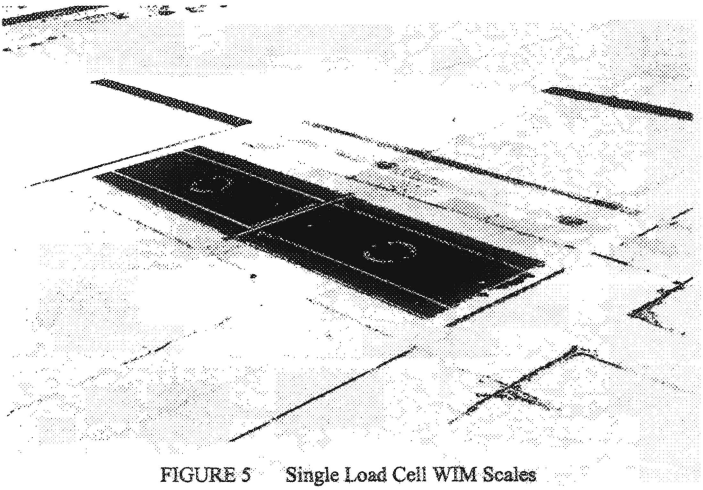

FIGURE 5 Single Load Cell WIM Scales

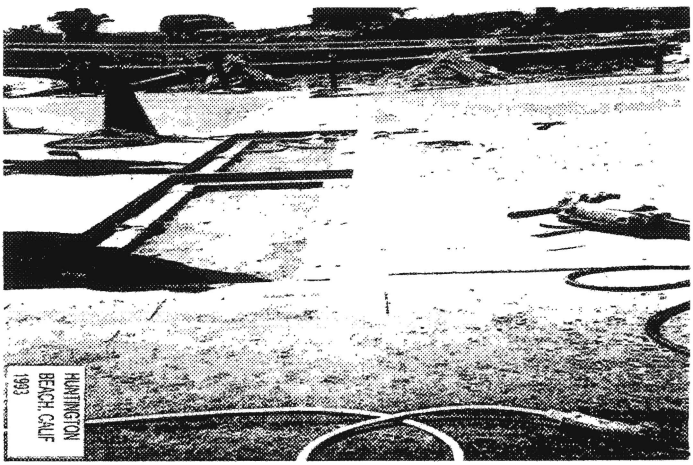


FIGURE 6 Bending Plate WIM Scales

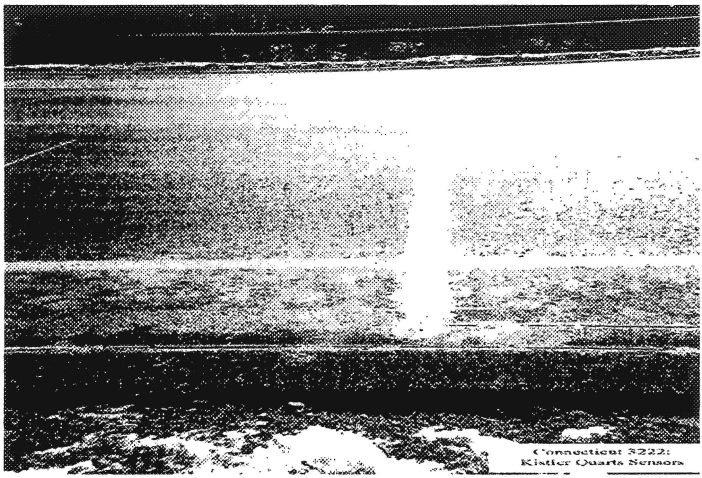


FIGURE 7 Quartz WIM Sensor