Pavement Comparative Analysis

Final Draft Desk Scan

Comprehensive Truck Size and Weight Limits Study

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FINAL DRAFT DESK SCAN

1.1 Introduction

The Pavement Comparative Analysis Desk Scan Report was prepared to support the technical analysis work to be undertaken in the Comprehensive Truck Size and Weight (CTSW) Limits Study with regard to heavy truck/pavement interactions. In this Scan, studies that investigate pavement costs caused by heavy vehicles that do not use the axle load equivalency factors derived from the AASHO Road Test are most relevant and useful to the work that will be done in this Study. These studies include state, national, and international cost allocation and truck size and weight studies, as well as any other studies that include estimates of vehicle-induced pavement costs on either an absolute or relative basis. The studies also include pavement analysis or design studies that will help in the application of *AASHTOWare Pavement ME Design®* or in the compilation of data required for that model. The principal objective of the search was to gain a thorough understanding of the current state of research and practice concerning pavement cost analysis related to heavy vehicle use. The literature search included a variety of information sources: (1) engineering and scientific periodicals and journals; (2) conference proceedings; (3) federal, state, international, and university reports that show up in library search engines, such as Compendex, based on key words; and (4) studies identified during the May 29, 2013 public hearing for the CTSW Study or by USDOT officials.

Cost allocation studies develop detailed estimates of costs related to vehicle weights and other characteristics in somewhat more detail than a typical Truck Size and Weight (TSW) study, so this desk scan included both highway cost allocation (HCA) and TSW studies at the federal and state levels and in other countries. FHWA's HCA and TSW studies stopped using unmodified AASHO-Road-Test-based Equivalent Single Axle Loads (ESALs) in 1979, after the Congressional Budget Office (CBO) strongly criticized their continued use, based on the outdated assumptions used to derive the formula for ESALs, which was based on a small set of pavement cross sections in a single environmental zone. Only a limited range of axle types were included in the study, and the calculation of ESALs for tridem axles is based on extrapolating a dummy variable. Most, but not all, states followed the federal lead and discontinued use of ESALs for HCA studies, but typically continued to use them when they commissioned TSW studies.

Overall, no studies with new methodologies were found, but several will help in the pavement cost analysis for this CTSW Study, and several more lend support or perspective to the proposed approach. Below, are listed all studies reviewed as part of this process including comments about the utility of each study for this project. The first group of reports includes readily-available reports that were identified through web search or prior knowledge, while the second section includes studies suggested at the May 29, 2013, CTSW Study's Public Hearing webinar that in some cases were less easily located.

1.2 Summary of Publicly-Available Reports Reviewed

Acimovic, Benjamin, Leela Rejaseker, and Reza Akhavan. *Forensic Investigation of Pavement Failure on Vasquez Boulevard.* Colorado DOT Research Branch, Report No. CDOT-2007-7.

May 2007.
http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CC8QFjAA&url=http%3A%2F%2Fwww.coloradodot.info%2Fprograms%2Fresearch%2Fpdfs%2F2007%2Fvasquez.pdf%2Fat_download%2Ffile&ei=EVHlUa3ELob84APO6YCIBA&usg=AFQjCNGAHQ0JgEiOrUiU4nscsx7X8rXdpQ&sig2=jKCllzvuu3SZuRhv9bHIVA&bvm=bv.48705608,d.dmg

Vasquez Boulevard in Commerce City, Colorado, as part of U.S. 6, provides a main trucking route in the I-25 corridor for overweight and over-height trucks. After reconstruction in 2001, parts of the pavement showed severe rutting in less than one year. Pavement failure was found to be related to repeated heavy loads, exposure of a layer constructed in the 1940s that did not contain an anti-stripping agent, inexperience with the stone-matrix asphalt technique used in the rehabilitation, and variable mix gradation and Asphaltic Cement Concrete (ACC) content. ***Although the study confirms that heavier trucks do, indeed, contribute to accelerated pavement wear, especially with faulty pavement designs, the findings are too general to contribute to the analysis methods we rely upon in the current CTSW Study.***

Allen, Gary, Audrey Moruza, and Brian Diefenderfer, Oversize and Overweight Vehicle Studies. Virginia DOT Presentation to the Transportation Accountability Commission, August 4, 2010. http://dls.state.va.us/GROUPS/transaccount/meetings/080410/oversize.pdf

*Researchers used the array of all axle weights from Virginia WIM data, as well as historical expenditure data, to determine an average cost per Equivalent Single Axle Load (ESAL) mile of travel. If overweight vehicles are charged only for the extra costs (beyond the legal axle load limit), they would be assessed 3.56 cents per ESAL mile, but that rate needs to be reviewed and updated over time as truck characteristics change****. The overall approach is directly applicable to the CTSW Study, in that it is one of the few studies that attempted to calibrate relative pavement damage to actual expenditures and imputed costs, but the ESAL assumption requires an updated form of the analysis to reflect better current knowledge. Replacing the ESALs with updated, distress-specific load equivalence factors could overcome this limitation and make the report findings useful for truck size and weight studies.***

Bai, Yong, Steven D. Schrock, and Thomas E. Mulinazzi, Estimating Highway Pavement Damage Costs Attributed to Truck Traffic. Mid-America Transportation Center, Report # MATC-KU: 262. 2010.
http://matc.unl.edu/assets/documents/matcfinal/Bai_EstimatingHighwayPavementDamageCostsAttributedtoTruckTraffic.pdf

Sponsored by the USDOT University Transportation Centers Program, this University of Kansas study collected highway data on 41.13 miles of U.S. Highway 50/400 in Kansas, and applied FHWA's Highway Economic Requirements System (HERS) and the American Association of State Highway and Transportation Officials (AASHTO) methods to derive an average maintenance expenditure per ESAL mile. This became the basis for estimating the additional costs that would be associated with an increase in meatpacking truck traffic. ***As with the study by Allen et al, the ESAL assumption makes the findings of only general interest to the current CTSW Study, since we now know that ESALs do not adequately measure the relative effects of tridems, particularly.***

Bannerjee, Ambarish, Jorge A. Prozzi, and Prasad Buddhavarapu, A Framework for Determination of Load Equivalences Using DARWin-ME, Paper Number 13-1770, TRB 2013 Annual Meeting, on CD-ROM of 2013 Meeting Proceedings. January 2013.

The study used DARWin-ME to compute Equivalent Damage Factors (EDF) consisting of two partial factors: Axle Load Factor (ALF) and Group Equivalency Factor (GEF), based on pavement responses that result in the same distress level, following a procedure used earlier by an FHWA research project. The overall load equivalency for a truck is equal to the sum of the EDFs for each constituent axle group. Three AC distresses were analyzed: rutting, fatigue cracking, and roughness. After analyzing EDFs for a wide range of AC pavement designs, the authors concluded that there is little evidence that EDFs are affected by structural capacity for the latter two distress types. For rutting, however, EDFs had in inverse relationship with thickness for single axles, while EDFs of multi-axle groupings peaked for structural numbers between 3.5 and 4.0 ***. The findings verify findings of the LEF derivations for the updated National Pavement Cost Model (NAPCOM) and Pavement Damage Assessment Tool (PaveDAT) models, and variation of thickness adds a nuance that will be useful in this base pavement section design.***

Barnes, Gary, and Peter Langworthy. "Per Mile Costs of Operating Automobiles and Trucks." *Transportation Research Record: Journal of the Transportation Research Board*, No. 1864. TRB. National Research Council. Washington, D.C., 71-77. 2004. Available online in pre-published form at http://www.hhh.umn.edu/centers/slp/pdf/reports_papers/per_mile_costs.pdf

Citing other studies, the report concludes that International Roughness Index (IRI) values below 80 (Present Serviceability Indices (PSIs) greater than 3.5) add nothing to vehicle operating costs, but IRIs of 170 (PSI 2.0) result in 2.5 cents per mile in additional operating cost. The additional cost derives from reduced vehicle life and in increased repair and maintenance costs. ***User costs are not being modeled in the current CTSW Study, so the findings are of only general interest. If we were to consider user costs, however, the study could be used to provide a quick proxy for estimating these costs, now that the latest version of FHWA's Highway Performance Monitoring System (HPMS) sample section data includes much more IRI data than in previous years***

Cenek, P., R. Henderson, I. McIver, and J. Patrick, Modelling of Extreme Traffic Loading Effects. Opus Central Laboratories for New Zealand Transport Agency, Research Report 499. October 2012. http://www.nzta.govt.nz/resources/research/reports/499/docs/499.pdf

The study investigated the premature failure of low-volume, low-strength roads that were sometimes associated with significant increases in heavy truck traffic on New Zealand highways, as might occur with road detours or with new mining or forestry operations. A key finding of the study was that extreme traffic loading does not immediately show increased distress or added maintenance costs. Thus, traffic deterioration models are more useful than examining historical pavement management data in assessing vehicle-related pavement costs. ***Although the findings are not directly applicable to this CTSW Study, the amount of scatter in the data as well as the length of time needed to observe accelerated wear serve as cautionary tales in analyzing the effects of heavy trucks on pavements via solely empirical data.***

Chatti, Karim, Hassan Salama, and Chadi El Mohtar. "Effect of Heavy Trucks with Large Axle Groups on Asphalt Pavement Damage." Presented at 8th International Symposium on Heavy Vehicle Weights and Dimensions, Johannesburg, South Africa, March 2004. http://road-transport-technology.org/Proceedings/8%20-%20ISHVWD/EFFECT%20OF%20HEAVY%20TRUCKS%20WITH%20LARGE%20AXLE%20GROUPS%20ON%20ASPHALT%20PAVEMENT%20DAMAGE%20-%20Chatti.pdf

Laboratory studies of a particular asphalt mix subject to pulse loadings representing various axle groupings (1 to 8 axles per group, 3.5-foot spacing) indicates that the normalized distress per ton goes down as the number of axles in a group goes up. Linear regression of Long Term Pavement Performance (LTPP) distress and Weigh-in-Motion (WIM) data confirms this observation. ***The results of this study could be useful in extending study findings to quadrem and larger axle groupings. It is likely that considering actual axle groups, rather than arbitrarily dividing large groups of axles into tridems and tandems, would increase the accuracy of pavement damage analysis, and we will attempt to partially incorporate this approach.***

Chatti, Karim. "Effect of Michigan Multi-Axle Trucks on Pavement Distress." Michigan DOT and Michigan State University, Final Report, Executive Summary, Project RC-1504. February 2009. http://www.michigan.gov/documents/mdot/MDOT_Research_Report_RC-1504__ExecSum_272183_7.pdf

*Laboratory studies were used to determine axle factors (AF) for each tridem (and larger) grouping at each weight. AFs were defined as the ratio of damage of a tridem, for example, to a single axle weighing one-third as much. The AFs were multiplied by the ESALs for each axle grouping on a truck and subbed to derive a truck factor (TF). When combined with empirical data on selected Michigan highways with flexible pavements, the study concluded that tridems (and n-groups) had less relative effect on cracking but more relative effect on rutting than single or tandem axles of an equivalent weight per axle****. The results of this study could be useful in extending study findings to quadrem and larger axle groupings. The team will attempt to partially incorporate this approach.***

Dodoo, Nii Amoo, and Neil Thorpe. "Road User Charging for Heavy Goods Vehicles." Presented at 7th International Symposium on Heavy Vehicle Weights and Dimensions, Delft, The Netherlands, June 2002. http://road-transport-technology.org/Proceedings/7%20-%20ISHVWD//Road%20User%20Charging%20For%20Heavy%20Goods%20Vehicles%20-%20%20Dodoo.pdf

Although many countries in Europe and North America have explored charging vehicles based on operating axle weights and the associated pavement damage, charging for actual damage at the point of use through use of WIM or other scales becomes problematic because of the high cost of installing weight station and the poor correlation between static and dynamic axle load. The authors instead propose an on-board system consisting of dynamic axle-load measurement combined with vehicle location measuring devices (now widely known as Global Positioning Systems or GPS). ***Interesting approach, but well beyond the scope of this analysis in this***

CTSW Study, since we have not been asked to consider alternative user-fee charging mechanisms.

Fernando, Emmanuel G. "Investigation of the Effects of Routine Overweight Truck Traffic on SH4/48." Texas Transportation Institute, Project 0-4184, Summary Report. April 2006. http://ftp.dot.state.tx.us/pub/txdot-info/rti/psr/0-4184-s.pdf

After Texas authorized 125,000-lb trucks to routinely use a state highway in Brownsville, the Texas Transportation Institute collected data to assess the impact of overweight trucks on that route. They first used ground-penetrating radar to estimate layer thicknesses and to subdivide the route into uniform subsections, where they used falling weight deflectometer tests to monitor load response over time. They also took cores at selected locations to both verify the penetrating radar thickness estimates and to characterize asphalt concrete properties. The research found good correlations between AC moduli back calculated from static and dynamic analysis and that the additional ESALs from overweight truck traffic will likely result in accelerated pavement deterioration. ***The study could be used to check consistency of their findings with the revised AASHTOWare Pavement ME Design® model, but we do not have enough calendar time and did not propose enough effort to second-guess the models incorporated in AASHTOWare Pavement ME Design®.***

Fortowsky, J. Keith, and Jennifer Humphreys, "Estimating Traffic Changes and Pavement Impacts from Freight Truck Diversion Following Changes in Interstate Truck Limits," Transportation Research Record: Journal of the Transportation Research Board, No. 1966, TRB. National Research Council. Washington, D.C. 2006, p. 71.

This TRB paper assumes all pavement damage is directly related to ESALs. We will not be using the assumptions necessary to rely upon ESALs, as cited above, so the study does not help us in our current CTSW Study.

Gibby, A. R., Ryuichi Kitamura, and Huichun Zhao. "Evaluation of Truck Impacts on Pavement Maintenance Costs," Transportation Research Record: Journal of the Transportation Research Board, No. 1262, pp. 48 - 56. TRB. National Research Council. Washington, D.C., 1990. http://publications.its.ucdavis.edu/publication_detail.php?id=1008

The study randomly selected 1,100 one-mile sections of state highways, collected data on traffic, weather, geometric conditions, and pavement maintenance costs on those sections, and used that data to develop a model of pavement maintenance costs. Incremental maintenance costs were expressed in terms of average annual maintenance cost per vehicle. ***An interesting analysis that is not directly applicable to the current CTSW Study. We do not have an adequate budget to develop the database necessary to emulate the approach nationally, and will not have developed an updated approach to characterize "traffic" as a substitute for ESALs.***

Hajek, Jerry J, Susan L. Tighe, and Bruce G. Huthinson. "Allocation of Pavement Damage Due to Trucks Using a Marginal Cost Method." Transportation Research Record: Journal of the Transportation Research Board, No. 1613, Paper # 98-1283. TRB. National Research Council. Washington, D.C., 2008.

http://localroads.wisc.edu/sites/default/files/Allocation%20of%20%20Pavement%20Damage%20Due%20to%20Trucks%20Using%20a%20Marginal%20Cost%20Method.pdf

Ontario Ministry of Transportation determined the marginal cost of providing pavement structure for one additional passage of an ESAL on various roads, and found that a typical additional truck mile resulted in marginal costs that varied significantly across the highway system, ranging from a low of C$0.004 per km ($0.006 / mile) on a southern Ontario freeway to C$0.46 per km ($0.72 / mile) on a local road. Ontario used standard Road-Test-derived ESALs for single and tridem axles, and used elastic layer theory to extend the Road Test results to derive ESALs for other axle groupings. Unlike FHWA's cost allocation procedures, however, which used average ESAL costs, Ontario's method uses marginal ESAL costs for the particular heavy vehicles of interest. Thus, the overweight vehicles receive the full benefit of the existence of other heavy vehicles, which is much more significant on major highways than on lightly-traveled local roads-- hence the much higher difference in costs than usually appears in U.S. analysis. ***We do not suggest reviving the incremental design approach (abandoned for pavement cost analysis in this country in the 1970's), and cannot use the ESAL assumption, so the findings are of only general interest to the current CTSW Study. The wide scatter in the results, however, by type of roadway provides a cautionary tale to using only a small number of pavement sections without considering the context of a national sample of pavement sections.***

Hernandez, Sarah, Andre Tok, and Stephen G. Ritchie, "Integration of Weigh-in-Motion and Inductive Signature Technology for Advanced Truck Monitoring." Institute of Transportation Studies, University of California, Irvine, Report # UCI-ITS-WP-13-3, August 2013. http://www.its.uci.edu/its/publications/papers/ITS/UCI-ITS-WP-13-3.pdf

The study points out the high rates of error when inductive loop technology alone is used to classify trucks and demonstrates how the error rates can be reduced by including axle weight data from WIM. Further, the study explores using inductive loop devices with high sampling rate detector cards to identify characteristic body type signature. This allows users to identify truck body types and dramatically reduce classification vehicle classification errors. ***While the technology is not currently used by states in reporting WIM data to FHWA, this study provides analysis of error rates for several vehicle classes that can be compared to error rates identified in the data sets that will used in CTSW Project and use this information to refine the WIM data classification algorithm that will be sued in this Study.***

Ioannides, Anastasios M., and Lev Khazanovich, "Load Equivalency Concepts: A Mechanistic Reappraisal." Transportation Research Record: Journal of the Transportation Research Board, No. 1388, pp. 42-51. TRB. National Research Council. Washington, D.C., 1993.

The paper reviews the evolution of load equivalency concepts, both prior to and after the 1958 - 1960 AASHO Road Test. The Road Test's mechanistic-empirical ESAL concept varies considerably from the purely mechanistic equivalent single-wheel load (ESWL) and equivalent single-axle radius (ESAR) approaches. The latter mechanistic approach, however, appears to offer advantages over either of the other two approaches. When the paper was written, load equivalency factors (LEFs) were vital for designing pavement for mixed traffic, since they *allowed the relative effects of each vehicle to be incorporated into design. To the extent that mechanistic-empirical models become prevalent for design, however, a study can avoid the use of LEFs, although LEFs are still needed for cost allocation and in order to assess the relative effects of various vehicles on pavement life.* ***If the backup approach or safety net approach identified in the Project Plan is employed, a comparison between sets of derived LEF values can be conducted.***

Luskin, David, and C. Michael Walton. Effects of Truck Size and Weights on Highway Infrastructure and Operations: A Synthesis Report. Center for Transportation Research: The University of Texas at Austin. Report No. FHWA/TX-0-2122-1. March 2001 http://www.utexas.edu/research/ctr/pdf_reports/2122_1.pdf

In reviewing a number of truck size and weight studies, including FHWA's 2000 Comprehensive truck Size & Weight Study, the authors found that shifting away from the dominant five-axle truck (3S-2) and increasing gross vehicle weights would not necessarily increase pavement costs, and might make them lower, but it would likely increase bridge costs. Safety effects were inconclusive. ***The ESAL assumption, as well as the wide range of diversion assumptions, makes the findings of only general interest to the current CTSW Study, although it does illustrate that heavier vehicle weights do not automatically result in higher pavement costs.***

Mallick, R., S. O'Brien, D. Humphrey, and L. Swett, Analysis of Pavement Response Data and Use of Nondestructive Testing for Improving Pavement Design, First Year Report 04-1A, Maine Department of Transportation, August 2006.

This report presents a description of instrumentation at the first fully instrumented flexible test pavement test section in Maine. Strain gauges were installed at the bottom of the Hot Mix Asphalt (HMA)layer as well as in the subbase and subgrade, while pressure cells were installed in the subbase and the subgrade. Other instruments consist of thermocouples, moisture and thermal resistivity probes. Models relating temperature at two depths of the HMA layer with ambient temperature and solar radiation were developed. Stress/strain data were collected using a loaded truck running at different speeds at different temperatures. The response pulses at different layers were modeled with the Haversine equation and its slight variations. The effect of speed on the time of loading at the different layers was examined, to develop equations for predicting time of loading for laboratory testing, for example, for different traffic speeds for similar structures in Maine. The effect of time of loading on HMA strains, especially at higher temperatures, was well manifested in the measured data. Comparisons of predicted versus measured responses showed that the tensile strains in the HMA layer match with the predicted ones at lower temperature and lower time of loading. For subbase, the stresses were under predicted, whereas predicted strains matched quite well with the measured strains. In the case of subgrade, both the stresses and the strains were consistently higher than the predicted values - the difference increased with an increase in time of loading and temperature. ***The results from this ongoing study provide much needed information on response of typical reconstructed pavement in Maine, which can be used for laboratory testing and theoretical modeling, as well as in structural design using mechanistic procedures. This section could be used as one of the sites for analysis for the Northeast zone since the Maine DOT has been collecting real-time data on that site since 2006. Specifically, they have the following information available on this***

section (on Rt. 15) that could be used with complete data for one of the pavement analysis sites: test section cross-sectional layer features (layer thickness and material types); material properties for the subgrade, base, and HMA courses; temperature data for the mid-depth of the asphalt base and at the bottom of the asphalt base; pavement mechanical response data on the speed versus time of loading in the different pavement layers.

Nicholas, John, Roger Mingo, Mark Berndt, and Eulois Cleckley, Pavement Damage Analysis Tool (PaveDAT) for Overweight Truck Permit Calculation, Talking Freight Seminar Series, June 12, 2012. https://www.fhwa.dot.gov/planning/freight_planning/talking_freight/june202012.cfm

PaveDAT builds upon the National Pavement Cost Model (NAPCOM) and the improvements made to it in recent work by FHWA. New damage models were based on running MEPDG thousands of times, systematically varying traffic to determine the relative effect that each type and weight of axle has on pavement deterioration in a full range of pavement types in a full range of climatic conditions. PaveDAT is a simplified version of the complicated, nationally representative NAPCOM model, but uses the same relative damage factors. These new load equivalence factors (LEFs) are similar in concept to the traditional ESAL concept, but vary widely across the important distresses for each type of pavement. PaveDAT was applied successfully in the District of Columbia in a recent assessment of the costs associated with overweight vehicles. ***Good broad view of the underpinnings of NAPCOM and PaveDAT for those wishing an introduction to those models.***

Oh, Jeongho, E.G. Fernando, and R.L. Lytton. "Evaluation of Damage Potential for Pavements Due to Overweight Truck Traffic, Journal of Transportation Engineering," 133(5), 308-317. DOI:10.1061/(ASCE)0733-947X(2007)133:5(308). 2007 http://www.academia.edu/937877/Evaluation_of_Damage_Potential_for_Pavements_due_to_Overweight_Truck_Traffic

Researchers installed multidepth deflectometers (MDDs) along a section of highway in Brownville, where overweight trucks were routinely allowed starting in 1998, in order to establish a correlation between field measurements of pavement response to overweight trucks and the observed critical strains of rutting and fatigue cracking. The analysis was done in the overall framework of cross-anisotropic modeling of pavement response. The researchers found excellent correlation between damage and primary response, meaning that primary response is a good proxy for expected pavement damage. ***The study could be used to check consistency of their findings with the AASHTOWare Pavement ME Design® model, but we do not have enough calendar time and did not propose enough effort to second-guess the models incorporated in AASHTOWare Pavement ME Design®.***

Papagiannakis, Athanassios, Nasir Gharaibeh, Jose Weissmann, and Andrew Wimsatt. Pavement Score Synthesis. Texas Transportation Institute, Report No. FHWA/TX-09/0-6386-1. January 2009. http://d2dtl5nnlpfr0r.cloudfront.net/tti.tamu.edu/documents/0-6386-1.pdf

The synthesis summarizes the use of pavement scores by states, including rating methods and how the scores are used for recommending pavement maintenance and rehabilitation actions. Some states considered only the dominant distress in rehab strategies, while others considered *all the distresses present. Most states considered both range and severity of distress. Differences in rating systems make comparison of overall pavement conditions among states invalid.* ***Good overview of rating systems could help refine NAPCOM, but not of direct relevance to this CTSW Study.***

Regehr, Jonathon David, Exposure Modelling of Productivity-Permitted General Freight Trucking on Uncongested Highways. Doctoral Dissertation for University of Manitoba Civil Engineering Department. October 2009. http://hdl.handle.net/1993/3167

The paper describes a methodology for improving estimates of Longer Combination Vehicle (LCV) exposure data for the Canadian Prairie Region. The dataset for the study integrated output from a classification algorithm, field observations, and industry intelligence. ***The classification algorithm is of particular interest to this CTSW Study, since it broke the LCV classes into a larger number of vehicle types than FHWA commonly uses, thereby allowing a higher degree of certainty in some of the most important LCV classes. The algorithm identified in this Study can be used to refine the WIM analysis and to help evaluate how many of vehicle classes to use in the analysis.***

Regehr, J. D, J. Montufar, and D. Middleton. Applying a Vehicle Classification Algorithm to Model Long Multiple Trailer Truck Exposure. Published in IET Intelligent Transport Systems, February 2009. Abstract available at: http://digital-library.theiet.org/content/journals/10.1049/iet-its.2008.0066

The paper describes an algorithm also described in the Regehr dissertation. A stated above, ***the algorithm can be used to refine the WIM analysis used in this Study and to help evaluate how many of vehicle classes to use in this analysis.***

Roberts, Freddy L., Aziz Saber, Abhijeet Ranadhir, and Xiang Zhou. Effects of Hauling Timber, Lignite Coal and Coke Fuel on Louisiana Highways and Bridges, LTRC Report No. 398. USDOT. March 2005. http://www.ltrc.lsu.edu/pdf/2005/fr_398.pdf.

Using the 1986 AASHTO Design Guide and standard ESALs shows that heavier tandem axles (up to 48 kilo pounds or kips) require additional overlay thickness and reduce pavement life. The current $10 annual overweight fee for an 86 kip 3S2 timber truck in Louisiana should be raised to many times higher per year if the axles are evenly loaded, and much higher, still, if the 48 kip axle is permitted. Allowing 100 kip trucks should not be permitted because pavement overlay costs double compared with an 86 kip truck. ***The ESAL assumption makes the findings of only general interest to the CTSW Study, since we will not be assuming that ESALs adequately measure relative effects of axle loads, for the reasons cited above.***

Rouen, Chhooeuy, and Mom Mony. "Damage Effects of Road Pavements Due to Overloading in Cambodia", - Academia.edu, Undated. http://www.academia.edu/1375429/Damage_Effects_of_Road_Pavements_due_to_Overloading_in_Cambodia

Synthesis of previous studies in many other countries shows that truck overloading is a serious problem that can greatly increase pavement costs. ***Not directly usable for this CTSW Study since there is insufficient information about the axle loads, the pavements, or the materials.***

Saber, Aziz, Mark Morvant, and Zhongjie Zhang. "Effects of Heavy Truck Operations on Repair Costs of Low Volume Highways". Presented at TRB 200 Annual Meeting, on CD-ROM of 2009 Meeting Proceedings. January 2009. http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CC0QFjAA&url=http%3A%2F%2Fsites.kittelson.com%2FIUHUserFee%2FDownloads%2FDownload%2F21822&ei=EMnmUcycNPSq4AO_vIGgAQ&usg=AFQjCNFBV8fRPgXBkJRE1zI8ICCQfFHovQ&sig2=IZmW61v6vQcBodLm8xthgA&bvm=bv.49405654,d.dmg

Using standard ESALs, the study analyzed two vehicle types and three gross weights and concluded that 100 kip sugarcane trucks should be paying an annual fee of many times higher than their current annual fee if they are use the standard five-axle 3S-2 truck configuration, but would not need an increase in that fee if they use a 3S3 configuration. ***The ESAL assumption makes the findings of only general interest to this CTSW Study, for the reasons cited above.***

Sadeghi, J. M., and M. Fathali. Deterioration Analysis of Flexible Pavements under Overweight Vehicles. Journal Of Transportation Engineering, 133(11), 625-633. DOI:10.1061/(ASCE)0733-947X(2007)133:11(625). 2007. http://www.nlcpr.com/Deterioration%20Analysis%20of%20Flexible%20Pavements.pdf

The authors used layer theory, following the Burmeister approach, to derive operational life reduction factors for two-axle and three-axle single unit trucks and for five-axle 3S-2 truck configuartionss. ***Not really credible for the purposes of this Study given alternative available models. AASHTOWare Pavement ME Design® model will be used in this Study and there is not sufficient calendar time in the Project Schedule to second-guess the incorporated damage models in AASHTOWare Pavement ME Design®.***

Schwartz, Charles W., Rui Li, Sung Hwan Kim, Halil Ceylan, and Kasthurirangan Gopalakrishnan. Sensitivity Evaluation of MEPDG Performance Prediction. NCHRP Project 1-47, Final Report. TRB. December 2011. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP01-47_FR.pdf

The study systematically varied all the user inputs for the MEPDG model to determine the sensitivity of the pavement performance predicted by the model to the variability of the input factors for five types of pavements-- new HMA, HMA over a stiff foundation, new Jointed Portland Cement Pavemant (JPCP), JPCP over a stiff foundation, and new Continuously Reinforced Concrete Pavement (CRCP)-- and five climate types (the usual four, plus "temperate"). Although design inputs were varied, traffic composition was not-- only Annual Average Daily Truck Travel (AADTT) and operating speed were varied. The study derived normalized sensitivity indices (NSIs) for each distress for each input variable, expressing the percentage change in the normalized distress divided by the percentage change in the design input. Key findings were that design inputs for the surface layers were the most important; longitudinal cracking, alligator cracking, and Asphaltic Concrete (AC) rutting were *substantially more sensitive to inputs than were IRI and thermal cracking; design input sensitivities for thermal cracking had little overlap with the design input sensitivities for the other distresses; and little thermal cracking occurred when binder grades were properly matched to the climate.* ***The study will be helpful in designing base case pavement sections, but the lack of traffic variations make it less useful for the overall analysis for the current CTSW Study.***

Timm, David H., Rod E. Turochy, and Kendra D. Peters. *Correlation between Truck Weight, Highway Infrastructure Damage and Cost*. Auburn College of Engineering for FHWA, DTFH61-05-Q-00317, Subject No 70-71-5048. October 2007. http://www.eng.auburn.edu/files/centers/hrc/DTFH61-05-P-00301.pdf

Using Mechanistic-Empirical Pavement Design Guidelines (MEPDG) for a small sample of pavement sections, the study team determined the time until terminal pavement distress for a base case of traffic, then under three different loading scenarios: shifting entire weight distributions toward heavier axles, adding specific heavier axles, and changing the GVW from 80,000 to 97,000 lbs. while adding an axle to the rear tandem group. The first scenario showed very large decreases in pavement life (and increases in cost), the second showed significant cost increases when the number of added heavy axles exceeds 10% of the number of legally loaded axles, and the third showed "no practical difference". Mechanistic analysis outside of MEPDG showed only slight difference in pavement response, confirming the finding of insignificant changes in pavement costs. The authors noted that their findings represent a limited set of conditions and that results were pavement-specific. They recommended that future work identify other loading scenarios for MEPDG simulation and establish a methodology to more accurately predict changes in loading spectra. FHWA followed up on these recommendations and initiated a project that systematically varied axle loadings for a larger number of pavement sections, and derived a general set of findings that could apply to any set of traffic shift scenarios (see Nichols et al, above). ***If the team cannot successfully use the primary approach proposed in this work plan, based on the pilot pavement section, the findings of this study and especially the follow-up study are directly applicable to the proposed back-up approach.***

Timm, David, and Kendra Peters. *Effects of Increasing Truck Weight Limit on Highway Infrastructure Damage*. ICWIM 5, Proceedings of the International Conference on Heavy Vehicles: 5th International Conference on WIM of Heavy Vehicles, March 2013. http://road-transport-technology.org/HVTT10/Proceeding/Papers/Papers_WIM/paper_123.pdf

Using MEPDG, no change in pavement life was found under idealized vehicle loading conditions when the same weight of freight was carried on a 97,000-lb vehicle or an 80,000-lb. vehicle. ***The idealized loading assumption makes the study unusable for this analysis, since we will be using actual observed axle weights as the basis for analysis, and the results are likely to be very different.***

Tirado, Cesar, Cesar Carrasco, Jose M. Mares, Nasir Gharaibeh, Soheil Nazarian, and Julian Bendaña. "Process to Estimate Permit Costs for Movement of Heavy Trucks on Flexible Pavements." Transportation Research Record: Journal of the Transportation Research Board, 2154, pp. 187-196. TRB. National Research Council. Washington, D.C., 2010.

http://pustaka.pu.go.id/files/pdf/BALITBANG-03-C000066-610032011103843-process_to_estimate_permit_cost.pdf

The paper describes use of a primary-response model, coupled with damage predictions from a mechanistic-empirical analysis, to quickly estimate relative levels of distress caused by particular combinations of axle loads. It is interesting for the current study, since it does not vary traffic within the M-E model, but external to the model, thus allowing much more rapid estimation of the relative effects of axles based solely on their primary responses. ***The approach certainly has merit, but expanding it to this CTSW Study would require a fairly major research effort that is probably beyond the scope and schedule for the Project. There is not enough calendar time or resources under this Project to substantially extend the findings of AASHTOWare Pavement ME Design®. It is likely that considering actual axle groups, rather than arbitrarily dividing large groups of axles into tridems and tandems, would increase the accuracy of pavement damage analysis, and FHWA may consider a future research project that extends this analysis to other Pavement Analysis Tools, such as NAPCOM and PaveDAT, for example.***

Zapata, C., and C. Cary. Integrating the National Database of Subgrade Soil-Water Characteristic Curves and Soil Index Properties with the MEPDG. National Cooperative Highway Research Program Project 9-23B, Preliminary Draft Final Report, National Research Council, Washington, D.C., 2012. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP09-23B_FR.pdf

Findings of this report, and, more importantly, the associated ASU Soil Maps software tool can be used to establish what the substructure properties will be for any of the sites analyzed in any (and within any) of the four LTPP climatic regions evaluated. ***This report contains information that will be used in compiling the data necessary for each pavement analysis section that will used under this Project.***

129,000 Pound Pilot Project: Report to the 62nd Idaho State Legislature. Idaho Transportation Department (IDT). January 2013.
http://itd.idaho.gov/newsandinfo/Docs/129000%20Pound%20Pilot%20Project%20Report.pdf

*Idaho raised the operating GVW limit from 105.5 kips to 129 kips as a pilot project on selected routes in the state in 2003, 2005, and 2007. The 105.5 kip trucks typically operated with 8 axles, while the 129 kip trucks typically operated with 10 or 11 axles. The state legislature asked Idaho Department of transportation (IDT) to study the impact of the pilot on safety, bridges, and pavements and report to the legislature every three years. Participating trucking companies reported making 264,169 trips by 1,359 trucks between 2004 and 2012, and ITD did not observe any significant effects on safety, bridges or pavements, while participating trucking companies reported great savings in costs and number of trips****. Normal maintenance and repair activities occurred during the pilot, but ITD did not tabulate their relative frequency on the pilot and non-pilot routes, so one cannot conclude that there was no effect on pavement or bridge deterioration, only that regular maintenance and repair activities were able to compensate for any change in deterioration rates. That lack of data, plus the small sample size of routes, trips, and pilot duration make any conclusions from the project somewhat tentative at this point.***

1997 Federal Highway Cost Allocation Study (HCAS) Final Report, FHWA. http://www.fhwa.dot.gov/policy/hcas/final/index.htm

New pavement costs were allocated to vehicles based on the same "minimum pavement" approach used in the 1982 HCAS, wherein costs of pavement thickness above a sidewalk or bikeway standard are assigned to vehicles based on traditional ESALs. Costs for pavement reconstruction, rehabilitation, and resurfacing (about 25% of all federal obligations) were allocated using the latest version of NAPCOM, following the 1982 approach of assigning costs to vehicles based on their estimated contribution to each pavement distress weighted by the importance of each distress to the need to repair or replace a pavement. For both types of cost, FHWA developed estimates of travel by vehicle class and operating weight group. Unlike in 1982, however, FHWA used a simplified version of estimating axle weights for each operating group and vehicle configuration, rather than using an array of all observed axle weights. ***There may be merit in following such an approach for the cost responsibility analysis aspect of this CTSW Study but it appears to be more reasonable to use an array of axle weights for each weight group and configuration rather than a regression equation describing the average weight of each axle.***

Estimating Truck-Related Fuel Consumption and Emissions in Maine: A Comparative Analysis for a 6-axle, 100,000 Pound Vehicle Configuration, American Transportation Research Institute, September 2009.

*The performance of a 6-axle vehicle configuration operating at a maximum GVW of 100,000 pounds was analyzed over two roughly parallel routes between Augusta and Brewer, Maine. The existing route (Route 9) reflects current conditions where trucks greater than 80,000 pounds GVW are not allowed on I-95 north of State Route 3 due to federal weight restrictions. The alternative route (I-95) assumes trucks up to 100,000 pounds GVW would be allowed to travel on I-95 north of State Route 3****. This report relates only very limited information that relates to the impact of increased truck loads on pavement response. It deals instead with energy consumption and emissions.***

Highway Cost Allocation Study: 2013 - 2015 Biennium, Final Draft. Prepared for Oregon Department of Administrative Services, Office of Economic Analysis by ECONorthwest, with R.D. Mingo and Associates, Jack Faucett Associates, HDR Engineering, and Mark Ford. January 2013. http://www.oregon.gov/DAS/OEA/docs/highwaycost/2013report.pdf

Every two years, Oregon evaluates its anticipated highway program and its current highway usage patterns to determine how to adjust user fees to match highway user cost responsibilities. As in 2011, a new version of NAPCOM / PaveDAT was adapted to vehicle classes weight categories, and simplified highway classes, was updated to include the most recent Oregon WIM and pavement condition data, and was used for pavement cost allocation. ***A similar process for estimating cost responsibility will be used in the damage comparisonaspect of this CTSW Study.***

"How Vehicle Loads Affect Pavement Performance." Wisconsin Transportation Bulletin No. 2, Undated. http://epdfiles.engr.wisc.edu/pdf_web_files/tic/bulletins/Bltn_002_Vehicle_Load.pdf

Explains ESALs and the basics of pavement fatigue and pavement strength to a lay audience. ***The ESAL assumption makes the findings of only general interest to this CTSW Study, but the explanation of why pavement damage goes up faster than axle weight could be helpful in summary reports intended for a non-technical audience***

Research Projects – Multiple documents. Multimodal Transportation & Infrastructure Consortium. Available at http://www.mticutc.org/research/research-projects/

Several projects underway appear to have some possible relevance, but all of the final reports for these projects are listed as "Coming Soon" so will not be available soon enough for this CTSW Study.

"Section 5 - Truck Weight Monitoring", Traffic Monitoring Guide. Federal Highway Administration, May 1, 2001 http://www.fhwa.dot.gov/ohim/tmguide/tmg5.htm

Describes the truck weight monitoring program under which states collect and report WIM data. ***Excellent reference material for using and understanding the WIM data that will be used in this Study.***

Study of Impacts Caused by Exempting Currently Non-exempt Maine Interstate Highways from Federal Truck Weight Limits, Appendix C: Pavement Cost Impacts, Development Process for the Study Network, Wilbur Smith Associates Study Team, June 2004.

This report assumed that all pavement damage is related to ESALs, so has limited information useful to this CTSW Study, for the reasons cited above.

Trucks and Infrastructure Maintenance Costs. State Smart Transport Initiative. Undated

http://ssti.us/wp/wp-content/uploads/2011/11/Trucks%20and%20Infrastructure%20 Maintenance%20Costs.pdf

Compiles truck estimated per-mile pavement costs from a variety of cited sources, including Congressional Budget Office and FHWA reports. ***May be of general interest to this CTSW Study as a point of comparison for baseline per-mile pavement cost estimates.***

U.S. Department of Transportation Comprehensive Truck Size and Weight Study, FHWA. August 31, 2000. http://www.fhwa.dot.gov/reports/tswstudy/

The study found that pavement wear is an important area of interest in conducting truck size and weight studies because rough pavement affects the cost of travel via vehicle operating costs, delay costs, and crash costs. Pavement wear increases with axle weights and the number of axle loadings applied to a pavement. To analyze the magnitude of changes in pavement wear given alternative mixes of weights and axle configurations, the study used the same version of NAPCOM that was used in the 1997 HCAS, using the same baseline estimates of travel by vehicle class and operating weight group and the same simplified version axle weight distributions. ***The team recommends using an array of axle weights for each weight group and configuration for this CTSW Study, but will attempt to modify the older study's approach of***

using axle weights and types as the primary units of analysis in favor of considering all the axle weights and types in each operating weight group as a single unit. The backup approach, however, would revert to the 2000 CTSW Study's traditional approach of analyzing each weight and type of axle separately.

Vermont Pilot Program Report, FHWA Report to Congress Required by P.L. 111-117, 2012. http://www.ops.fhwa.dot.gov/freight/sw/reports/vt_pilot_2012/vt_pilot.pdf

Vermont raised size and weight limits on its Interstate highways for one year beginning in December 2009. This study estimated traffic and infrastructure impacts and energy consumption and compared them to the pre-pilot (control) case. For pavements, the study team used an expanded version of the PaveDAT model, with its newly derived, distress-specific LEFs. Since traffic shifted mostly to 4-axle single units and 6-axle combination trucks as a result of the temporary allowance of 51 kip tridems on the Interstate system, pavement damage attributable to these vehicle classes increased considerably. Pavement damage on the Vermont Interstate system increased by 12 percent, which translates to significant increases in pavement maintenance and repair costs and more frequent work zones. There was a negligible decrease (less than 0.5%) in pavement damage off the Interstate system. ***If the preferred approach proposed in the Project Plan cannot be successfully implemented, the findings of this Study and especially the follow-up study are directly applicable to the proposed back-up approach.***

Wisconsin Truck Size and Weight Study: Final Report. Prepared for Wisconsin Department of Transportation by Cambridge Systematics with National Center for Freight and Infrastructure, University of Wisconsin- Madison and Others. June 15, 2009. http://www.topslab.wisc.edu/workgroups/tsws/deliverables/FR1_WisDOT_TSWStudy_R1.pdf

Pavement analysis considered differential effects of traffic under various temperature and moisture conditions, and effects of load and non-load factors, but assumed that all vehicle related damage is measured by and related to traditional ESALs and that the Road Test ESALs can be extended to tridems by extrapolating a dummy variable from a regression equation. ***The ESAL assumption makes the findings of only general interest to this CTSW Study, for the reasons cited above.***

1.3 Additions Suggested During May 29, 2013 Webinar

Di Cristoforo, R., Regehr, J.D., Germanchev, A., and Rempel, G. (2012). "Survival of the Fittest: Using Evolution Theory to Examine the Impact of Regulation on Innovation in Australian and Canadian Trucking," Heavy Vehicle Transport Technology 12, Stockholm, Sweden. ***This publication is not directly related to pavement issues. It examines the impact of regulation on trucking in Australia and Canada by applying evolution theory and deals more with regulatory issues.***

Jablonski, B., Regehr, J.D., Kass, S., and Montufar, J. (2010). "Data Mining to Produce Truck Traffic Inputs for Mechanistic-Empirical Pavement Design," 8th International Transportation Specialty Conference, Canadian Society for Civil Engineering, Winnipeg, Manitoba. ***This presentation is related to the overall CTSW Study, but not overly useful for our task.***

Jablonski, B., J.D. Regehr, G., Rempel, T. Baumgartner, A, Nuñez, K. Patmore, M. Moshiri, H. Hernandez, and J. Montufar, J. (2010). "Traffic Data Requirements for the Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures in Manitoba," prepared for Manitoba Infrastructure and Transportation by UMTIG in association with Regehr Consulting. ***This paper is useful from its title but is propriety (a consulting report) and therefore not publicly-available.***

Malbasa, A., Regehr, J.D., and Clayton, A. (2005). "A Performance-Based Approach to On-Road Regulatory Compliance of Commercial Vehicle Operations in Manitoba," UMTIG, prepared for the Compliance and Regulatory Services Branch, Manitoba Transportation and Government Services. ***This paper seems related more to compliance from its title, plus it is propriety (a consulting report) and therefore not publicly-available.***

Montufar, J., J.D. Regehr, G. Rempel, T. Baumgartner, and B. Jablonski (2008). "The Impacts of Increased Truck Gross Vehicle Weights: Environmental Scan," Montufar & Associates and UMTIG, prepared for Alberta Infrastructure and Transportation. ***This paper may be useful from its title but is propriety (a consulting report) and therefore not publicly-available.***

Montufar, J., J.D. Regehr, C. Milligan, and M. Alfaro (2011). "Roadbed Stability in Areas of Permafrost and Discontinuous Permafrost: A Synthesis of Best Practices," prepared for Transport Canada – Surface – Prairie and Northern Region by Montufar & Associates in association with Regehr Consulting and UMTIG. ***This paper is actually most pertinent to railroads in the northern Canadian context and a publicly-available paper is forthcoming in ASCE Journal of Cold Regions Engineering.***

Radstrom, B., Regehr, J.D., Arango, J., Steindel, M., Rempel, G., Jablonski, B., Montufar, J., and Clayton, A. (2007). "Traffic on Manitoba Highways 2006," University of Manitoba Transport Information Group, prepared for the Traffic Engineering Branch, Manitoba Infrastructure and Transportation. ***This paper may be marginally-useful for its Level 1traffic data, specifically the percentages and load range for 3-S2 and B-train truck types.***

Regehr, J.D. (2012). "Truck Exposure to Inform Size and Weight Policy Decisions," presentation prepared for the Transportation Research Board Annual Meeting, Washington, D.C. ***This presentation is related to compliance.***

Regehr, J.D. (2011). "Understanding and Anticipating Truck Fleet Mix Characteristics for Mechanistic-Empirical Pavement Design," Transportation Research Board Annual Meeting CD-ROM, Washington, D.C. *This paper analyzes vehicle classification data to support the implementation of the Mechanistic-Empirical Pavement Design Guide (MEPDG). A cluster analysis and expert judgment are applied to vehicle classification data from Manitoba to produce six jurisdiction-specific truck traffic classification groups (TTCGs). These groups are used to estimate truck volumes by class at locations where no site-specific classification data exist.* ***The unique vehicle classification distributions evident from these groups, particularly the relative predominance of six-axle tractor semitrailers and multiple-trailer trucks within the fleet, demonstrate the importance of developing truck traffic data inputs based on local***

conditions and expertise. This publication is relevant to pavements, but specifically looks at vehicle class rather than weight.

Regehr, J.D. (2010). "Leveraging Truck Traffic Data from Mechanistic-Empirical Pavement Design to Support Other Transportation Engineering Decisions," presentation prepared for the North American Travel Monitoring Exposition and Conference, Seattle, Washington. ***This presentation is related but not overly useful for this CTSW Study as it is not detailed enough.***

Regehr, J.D. (2009). "Truck Loading on Highway Infrastructure in the Canadian Prairie Region," presentation prepared for the Vehicle-Infrastructure Interaction Workshop, Winnipeg, MB. ***This presentation is related by not detailed enough to be useful for this CTSW Study.***

Regehr, J.D. (2003). "Estimating Live Truck Loads for Roads and Bridges: A Sectoral Approach Applied to Grain Transport," presentation prepared for the Institute of Transportation Engineers (Manitoba Section), Winnipeg, Manitoba. ***This presentation is related by not detailed enough to be useful for this CTSW Study.***

Regehr, J.D. (2002). "Aspects of Agriculture-Related Trucking in Manitoba," UMTIG. ***This presentation is related by not overly useful for this CTSW Study.***

Regehr, J.D., Baumgartner, T., Nuñez, A., and Montufar, J. (2009). "Measuring and Estimating Recreational Traffic in Manitoba," presentation prepared for the Recreational Traffic Monitoring Workshop, Lakewood, CO. ***This presentation is related by not detailed enough to be useful for this CTSW Study.***

Regehr, J.D., Jablonski, B., Rempel, G., Baumgartner, T., Nuñez, A., Patmore, K., Moshiri, M., Hernandez, H., and Montufar, J. (2010). "Traffic Data Requirements for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures in Manitoba," presentation prepared for the MEPDG User Group, Transportation Association of Canada Spring Technical Meetings, Ottawa, ON. ***This paper seems useful from its title, perhaps for the traffic classification, but it is propriety (a consulting report) and therefore not publicly-available.***

Regehr, J.D. and Montufar, J. (2007). "Classification Algorithm for Characterizing Long Multiple Trailer Truck Movements," Transportation Research Board Annual Meeting CD-ROM, Washington, D.C. ***This presentation is related but not overly useful for this CTSW Study. It deals with development of an algorithm that provides the core dataset for modeling long-truck exposure in terms of the volume of trips, and their weight and cubic characteristics. It is embedded within a modeling approach in which exposure is an explanatory variable needed for predicting transportation system impacts related to long-truck operations. Table 2 may be useful in that it contains WIM data related to long trucks from highways between Winnepeg and Brandon, MB, and Figure 3 includes the load spectra.***

Regehr, J.D. and Montufar J. (2012). "Traffic Data and the State of the Practice in Canada," presentation prepared for the North American Travel Monitoring Exposition and Conference, Dallas, Texas. ***This presentation is related by not overly useful for this CTSW Study.***

Regehr, J.D., Montufar, J., and Clayton, A. (2009). "Lessons Learned about the Impacts of Size and Weight Regulations on the Articulated Truck Fleet in the Canadian Prairie Region," Canadian Journal of Civil Engineering, vol. 36, no. 4, pp. 607-616. ***This publication is not directly related to pavement issues. It deals more with the state-of-the-practice and policy issues, but includes some information on the shift in traffic percentages related to articulated trucks. This paper is not useful for this CTSW Study.***

Regehr, J.D., Montufar, J., and Clayton, A. (2009). "Options for Exposure-Based Charging for Long Multiple Trailer Truck Permits," Transportation Research Record: Journal of the Transportation Research Board, no. 2097, pp. 35-42. ***This presentation is related by not overly useful for this CTSW Study as it appears to deal more with compliance issues.***

Regehr, J.D., Radstrom, B., Arango, J., Isaacs, C., Han, K., Rempel, G., Montufar, J., and Clayton, A. (2006). "Traffic on Manitoba Highways 2005," UMTIG, prepared for the Traffic Engineering Branch, Manitoba Transportation and Government Services. ***This presentation is related by not overly useful for this CTSW Study.***

Reimer, M. and Regehr, J.D. (2012). "Clustering of Vehicle Classification Data to Support Regional Implementation of the Mechanistic-Empirical Pavement Design Guide," presentation prepared for the North American Travel Monitoring Exposition and Conference, Dallas, Texas. ***This presentation will soon be published as a TRB Transportation Research Record Journal article. It is relevant to pavements, but specifically looks at vehicle class rather than weight.***

Transportation Research Board of the National Academies. All Motor Carrier Publications. http://www.trb.org/MotorCarriers/Publications1.aspx ***The relevant projects shown in this publications list appear to have already been included in this desk scan.***

1.4 Wide-Tire Studies

General Comment: Although moving from narrow dual tires to single wide base tires (WBT) does create the potential for exacerbating certain distresses such as top-down fatigue cracking, thermal cracking, and other durability distresses, the model AASHTOWare Pavement ME Design® currently handles only dual tires. To include WBT in this CTSW Study, an approach must be developed to adjust dual tire spacing/pressure within the design tool to simulate WBT. This approach might not provide accurate results. Analysis of the relative effects of WBT would have to be done outside Pavement ME using a mechanistic model. Such analysis requires a greater research effort and time than is available for this CTSW Study. Also, there is not enough evidence that the larger trucks we are considering in this study would make greater or less use of WBT than current vehicles. Therefore, we will not be using the results of the studies discussed below in CTSW Study.

Al-Qadi, I., and Wand, H. Pavement Damage Due to Different Tire and Loading Configuration on Secondary Roads. Final Report. NEXTRANS Project No. 008/Y01, 2009.

Due to the different contact stress distributions at tire-pavement interface, the impact of the new generation of wide-base tire (455/55R22.5) on secondary road pavements varies when compared to the impact of the conventional dual-tire assembly. Results showed that the 455 wide-base tire *causes 1.9-2.5 times more fatigue damage, 1.31-2.35 times more subgrade rutting, and 1.35-1.77 times more HMA rutting (densification) compared to the conventional dual-tire assembly when carrying the same load. On the other hand, the 455 wide-base tire caused 19%-78% less HMA rutting (shear) and had 4%-31% less potential for base shear failure than the conventional dual-tire assembly. These damage ratios vary with different base thicknesses, temperatures, and possibly loading. The findings indicate that wide-base tires' impact on pavement damage on secondary roads depends on the roads' predominant failure mechanisms. Therefore, a combined damage ratio was used to consider the overall effect of different failure mechanisms on pavement serviceability and to conduct a simplified pavement cost analysis. In general, the results show that using the 455 wide-base tire results in 1.12-1.38 times more damage compared to the dual-tire assembly and thus greater costs for designing and maintaining secondary road pavements. This cost ratio provides state pavement agencies a basis for implementing appropriate load regulations and road pricing for trucking operations that use wide-base tires on secondary roads. It should be noted that an earlier study concluded the wide-base tire causes less or similar damage to interstate highway pavements when compared with the dual-tire assembly. The report includes simple design examples that describe how to consider the effects of the wide-base tire in pavement design and rehabilitation practice by using the damage ratio obtained from this study.*

Al-Qadi, Imad. Impact of Wide-Base Tires on Pavement and Trucking Operation. International Workshop on the Use of Wide-Base Tires, Presentation to Federal Highway Administration Turner-Fairbank Highway Research Center, October 25-26, 2007

Imad Al-Qadi, of the University of Illinois at Urbana-Champaign gave two presentations In the first presentation, he provided a review of wide-base tires research study findings over the years and explained the differences between the 425 and the new generation of wide-base tires as well as the confusion in using the research outcome of the 425 tire to explain the performance of the new generation of wide-base tires. Some key points of his presentation include the following:
-Wide-base tires have been used in Europe since the 1980s.
-Early research in all cases indicated that more pavement damage was produced by traditional wide base tires; 385mm and 425mm in width.
-Later wide-base tire designs have wider footprints and lower aspect ratios that produce a more uniform contact pressure distribution.
-Discussed the impact of wide-base tires on fuel, emission, handling, stability, comfort, repair cost, recycling, noise, braking, hydroplaning, rolling resistance, etc..
-Research into modeling and accelerated pavement loading is needed to determine how the new designs affect pavement performance.
-He shared the progress of work over the past seven years on testing of the new generation of wide-base tires at the Virginia Smart Road and the APT at University of Illinois and the pavement response to loading using load-response instruments.
-He showed that the steering axle caused more damage to pavement than tandem axles and the difference in tire pressure between tires in dual-tire system can be detrimental to pavement.
-He illustrated the modeling approaches of pavement response to tire loading and its evolution from using elastic theory to HMA viscoelastic properties in finite element analysis.
-He discussed a comparison technique between tire effects on pavements considering several failure criteria.

-He provided a summary of the pros and cons of wide-base tires with respect to several parameters.
-He concluded that advanced modeling is the only approach to quantify pavement damage due to various tire configurations including the use of continuous moving load, layer interface friction, and dynamic analysis.
In the second presentation, he focused on advanced modeling and research direction. He discussed the following:
-The fine-tuning of the finite element modeling.
-Use of dynamic analysis procedure.
-Modeling of Smart Road and other pavement sections at various HMA thicknesses.
-Showed the 3D stress distribution for each rib of wide-base and dual tires.
-3D finite element modeling indicates that high shear stresses developed approximately 50 mm (2 in.) below the pavement surface may be the source of crack initiation.
-For thick pavements, cracks initiate near the surface.
-He presented preliminary analysis of calculated potential damage due to dual tire and wide-base tires.
-He discussed the research needs in this field and suggested directions.
-A pool fund on wide-base tires was initiated and the tasks of the proposed research were presented.
Wang, H. and Al-Qadi, I. (2011). "Impact Quantification of Wide-Base Tire Loading on Secondary Road Flexible Pavements." *J. Transp. Eng.*, 137(9), 630–639.

There is a need to evaluate the damage caused by the new generation of wide-base tires on low-volume secondary roads because of their increased use on trucks. In this study, a three-dimensional (3D) finite-element (FE) model was built to simulate the realistic tire loading on secondary road pavements. The model allows for predicting pavement responses to loading applied by various tire configurations. In addition, the model incorporates the measured 3D tire-pavement contact stresses, models hot-mix asphalt (HMA) as linear viscoelastic material, simulates continuous moving load, and utilizes implicit dynamic analysis. The analyzed pavement structures comprised a 76-mm HMA layer and an aggregate base layer with various thicknesses (203, 305, and 457 mm). The impact of a wide-base tire on secondary road pavement damage was analyzed using available damage models and was compared to that resulting from conventional dual-tire assemblies. It was found that the new wide-base tire (455/55R22.5) caused greater fatigue damage, subgrade rutting, and HMA rutting (densification) but less HMA rutting (shear) and base shear failure compared to the conventional dual-tire assembly when carrying the same load. The findings indicate that wide-base tires' impact on secondary road pavements depend on the roads' predominant failure mechanisms. Hence, calculated combined damage ratios can be used for road usage pricing and pavement design practice when wide-base tires are used.

Myers, L. A., R. Roque, B. E. Ruth, and C. Drakos, (1999), Measurement of Contact Stresses for Different Truck Tire Types to Evaluate Their Influence on Near-Surface Cracking and Rutting," Transportation Research Record: Journal of the Transportation Research Board, No. 1655, TRB, National Research Council, Washington, DC, pp. 175-184.

Two pavement distress mechanisms have become more prevalent in recent years: near-surface rutting and surface-initiated wheel path cracking. Some possible factors causing these failure *mechanisms include higher traffic volumes, use of lower-quality materials, and changes in tire type and structure. Although all of these factors may play a role, this study concentrated on the effects of changes in tire type and structure on surface distress. Within the last decade, trucking companies have shifted from operation on bias ply tires to an exclusive use of radial tires and the gradual introduction of wide-base (super-single) radial tires. This prevalence of radial tires causes a major change in pavement surface loading characteristics and is shown to help explain the development of surface rutting and cracking. Tire contact stresses were measured for bias ply, radial, and wide-base radial truck tires at various loads and inflation pressures to investigate the effects of tire structure, loading, and inflation pressure on surface loads applied to pavements. It was determined that contact stresses vary significantly for the different types of tires investigated. The observed variations were explained by the differences in tire construction. In fact, tire structure appeared to have a greater influence on contact stresses than variations in either load or inflation pressure for a given tire type. It was shown that the specific characteristics of the complex contact stresses under truck tires have a strong influence on asphalt pavement cracking and rutting and must be considered for proper design and evaluation of asphalt pavements.*

Prozzi, J. A. and R. Luo, (2005), Quantification of the Joint Effect of Wheel Load and Tire Inflation Pressure on Pavement Response, Transportation Research Record: Journal of the Transportation Research Board, No. 1919, Transportation Research Board of the National Academies, Washington, DC, pp. 134-141.

Most pavement design and analysis procedures predict performance on the basis of expected pavement damage under traffic loads expected during design life. Some failure criteria are primarily dependent on wheel loads and almost independent of contact stresses. Others are primarily dependent on normal and shear stresses, not on load magnitude. Wheel load is used as a proxy for tire pressure to account for the effect of contact stresses indirectly. In most pavement design methods, tire-pavement contact stress is assumed to be equal to tire inflation pressure and to be uniformly distributed over a circular area. A methodology that explicitly accounts for the effect of tire inflation pressures and the corresponding contact stresses on pavement response is not available. In this research, pavement responses of typical pavement structures under the combined actions of variable wheel loads and tire pressures were evaluated. A multilayer, linear-elastic computer program was used to estimate three critical pavement responses: longitudinal and transverse tensile strains in asphalt and compressive strains in the subgrade. The differences of the strains estimated by the two models were statistically analyzed to quantify the effect of the assumption of uniform stress over a circular shape. The traditional model proved to be reliable to estimate compressive strains in the subgrade layer. The tensile strains in the asphalt layer under actual contact stress, however, were quite different from those under uniform constant stress. Contrary to initial expectation, for the general case, the assumption of uniform stresses is a conservative approach.

Priest, A. L., D. H. Timm, and W. E. Barrett, (2005), Mechanistic Comparison of Wide-base Single vs. Standard Dual Tire Configurations, Final report, National Center for Asphalt Technology (NCAT), Auburn, AL.

In an effort to increase trucking efficiency, the commercial tire industry has produced wide-base single tires that can replace the standard dual-tire configuration. Although wide-base tires can *offer benefits like increased fuel economy and cargo capacity, previous studies have shown that they may cause premature highway distress. Many agencies have restricted the use of wide-base single tires to preserve the integrity of their highway infrastructure. The following can be concluded regarding the layered elastic theory analysis and its comparison to the field data:*

- *The predicted responses using linear layered elastic theory for the standard dual-tire assembly agreed reasonably well with the field-measured responses.*
- *The theoretical model overestimated the horizontal tensile strain in the asphalt layer when compared to the field-collected data for the wide-base single tire. This was likely due to the inaccurate assumption that the tire load is distributed evenly in a circular footprint calculated from the tire load and inflation pressure. The following can be concluded regarding the field-measured methodology and pavement responses of the two tire configurations:*
- *The test method of collecting 15 passes of each tire configuration over two testing dates at equal pavement temperatures was effective in creating two equal testing conditions.*
- *The field-measured horizontal strain at the bottom of the asphalt layer was indistinguishable between the standard dual- and wide-base single-tire configurations. This indicates that the predicted fatigue life is equivalent for the two tire configurations for the given testing conditions and pavement cross-section.*

Perdomo, D. and B. Nokes, (1993), Theoretical Analysis of the Effects of Wide-Base Tires on Flexible Pavements Using Circly, Transportation Research Record, No. 1388, TRB, National Research Council, Washington, DC, pp. 108-119.

Many state highway agencies across the nation are concerned with the effects of wide-base tires on flexible pavements. This concern is supported, in many cases, by legislative regulations that try to limit the extent of damage caused by wide-base tires. A study was done by the California Department of Transportation to characterize and predict the effects of wide-base tires and to evaluate a tentative regulatory limit. The primary objectives were (a) to provide an extensive literature review summary about previous research in the area, including the wide range of regulatory limits, and (b) to perform an improved mechanistic analysis that includes effects of actual temperature gradients and nonuniform contact stress (normal and shear) distributions. The literature review summary indicates that the overall wide-base tire issue cannot be quantified reliably with a single regulatory limit. The reason for this lies in the various factors and assumptions involved in any experimental or theoretical evaluation (e.g., temperature and load conditions). Previous studies assume simple and incomplete loading conditions that are known to differ from actual circumstances. The mechanistic analysis, using a computer program called CIRCLY, shows that the effects of these simplifications significantly alter predicted pavement response. Future evaluations should continue to model the actual nonuniform vertical and shear forces that tires exert on pavement structures. The full influence of these factors should be verified by laboratory and field measurements.

Al-Qadi, I. L., A. Loulizi, I. Janajreh, and T.E. Freeman, (2002), Pavement Response to Dual and New Wide-Base Tires at the Same Tire Pressure, Transportation Research Record: Journal of the Transportation Research Board, No. 1806, Transportation Research Board of the National Academies, Washington, DC, pp. 38-47.

Although concern was raised about the introduction of radial tires due to their higher inflation pressure compared with that of bias tires, radial tires have been proven to reduce the strain at the bottom of the hot-mix asphalt (HMA) layer. However, conventional wide-base single tires have been shown to be more damaging to pavement than dual tires. The damage mainly depends on the tire tread width and inflation pressure. It has been suggested that wide-base tires may produce damage equivalent to that of dual tires if the maximum load per tire is limited to 11.6 kilogram per millimeter (km/mm) of tire tread width. Recent advances in tire design and material have led to the design of a new wide-base tire that is wider and flatter in the crown area to provide a uniform contact stress distribution. It operates at an inflation pressure of 690 kilopascals (kPa) for 151-kilonewtons (kN) tandem axle load. An experimental program studied the effects of the newly developed wide-base tire on a flexible pavement section at the Virginia Smart Road under different loading and environmental conditions. Testing results have shown that the newly developed wide-base tires induce approximately the same horizontal tensile strains under the HMA layer as do equivalent dual tires. Hence, the fatigue damage expected from these newly developed wide-base tires is the same as that produced by dual tires. However, the vertical compressive stresses induced by the wide-base tire are greater on the upper HMA layers of the pavement. The difference in stresses diminishes with depth and becomes negligible at the bottom of the subbase layer.

Akram, T., T. Scullion, R. E. Smith, and E. G. Fernando, (1992), Estimating Damage Effects of Dual versus Wide Base Tires with Multidepth Deflectometers, Transportation Research Record, No. 1355, TRB, National Research Council, Washington, DC, pp. 59-66.

Multidepth deflectometers (MDDs) were successfully used to assess the relative damage of dual and wide base single tires. In this study MDDs were installed in two in-service asphaltic concrete highways (one thick, one thin) to measure the pavement response to vehicle loading. A specially configured 3S2 truck was used in the study. It is an 18-wheel water tanker that was converted to a 14-wheel tanker for this study. For the first set of data collection, dual tires were used on the tandem drive axle with wide base single tires on the tandem trailer axle. For the second set, wide base single tires were used on the tandem drive axle and dual tires on the trailer axle. Deflections measured at several depths within the pavement by MDD under dual and wide base single tires were used to calculate average vertical compressive strains. The Asphalt Institute subgrade limiting strain criteria were used to estimate the reduction in pavement life that will occur by using the wide base single tires in place of duals. Wide base single tires were found to be more damaging on both tandem drive and tandem trailer axle positions. At a speed of 55 mph and equivalent axle loading, it was found that the wide base single tires (trailer axle) reduced the anticipated pavement life on the thin and thick sections by a factor of between 2.5 and 2.8 over that predicted for standard dual tires.

Dessouky, S. H., Al-Qadi, I. L., and Yoo, P. J. Full-Depth Pavement Response to Different Truck Tire Loadings. Presented at the 86th Transportation Research Board Annual Meeting, Washington D.C., 2007.

The objective of this paper is to investigate the potential indication of distress in medium-volume, full-depth flexible pavement when exposed to loading conditions under accelerated pavement testing at various speeds, inflation pressures, and loads, under three different tire configurations: dual-tire (11R22.5), and old and new generations of wide-base tires

(425/65R22.5 and 455/55R22.5), respectively. In addition to longitudinal strain measurements at the bottom of hot-mix asphalt, a three-dimensional finite element model was developed in order to evaluate pavement response to loading at various critical locations in the pavement after being calibrated with field-measured data. Field measurements showed that the new generation of wide-base tires, 455/55R22.5, yields 7% more longitudinal strain than a dual-tire assembly at the same tire pressure. The dual-tire assembly shows differential longitudinal strains of 13 to 66% if the very common difference in inflation pressure between the two tires in the dual-tire assembly ranged from 140 and 555kPa, respectively. Using calculated parameters indicative of pavement distresses, the study found that for medium-volume, full-depth flexible pavement under the same loading and environmental conditions, the 455 wide-base tire has the potential to cause similar secondary rutting and fatigue cracking as the dual-tire assembly. In addition, less potential for primary rutting and significantly less potential for top-down cracking are expected when a wide-base tire is used.

Timm, D.H., and A.L. Priest. Mechanistic Comparison of Wide-Base Single Versus Standard Dual Tire Configurations. In Transportation Research Record: Journal of the Transportation Research Board, No. 1949, Transportation Research Board of the National Academies, Washington D.C., 2006, pp.151-163.

Wide-base tires are gaining renewed interest in the U.S. trucking industry as tire and rim technology and design continue to improve. First introduced in the early 1980s and termed "super-singles," new generation, wide-base tires have been developed to allow for lower inflation pressures and larger contact areas than their predecessors. Single tires are of interest to freight haulers because with fewer tires and lighter rims, cargo capacity can increase. Early theoretical and physical modeling studies of super-singles largely found them to be more damaging to highway pavement structures than standard dual tire configurations. However, in light of new tire advancements, the impact on pavement response and performance of the wide-base configuration should be reevaluated. In addition, the accuracy of theoretical models in predicting pavement response under the new wide-base tires should be evaluated because models are often used by agencies to determine single-tire weight limits and permitting. A conventional dual tire assembly (275/80R22.5) was evaluated versus a newly developed single wide-base tire (445/50R22.5) at the National Center for Asphalt Technology Test Track. Embedded asphalt strain gauges and earth pressure cells allowed for direct pavement response measurements and comparisons between the two configurations. In addition, theoretical modeling using layered elastic theory was used to evaluate both configurations. The pavement response measurements indicated no statistical difference between the two configurations. The theoretical model tended to over-predict the response under the wide-base configuration. Future studies should attempt to model the tire-pavement contact area precisely to improve accuracy under the wide-base tire.

Elseifi, M.A., I.L. Al-Qadi, P.Y. Yoo, and I. Janajreh. Quantification of Pavement Damage Caused by Dual and Wide-Base Tires. In Transportation Research Record, Journal of the Transportation Research Board, No. 1940, Transportation Research Board of the National Academies, Washington D.C., 2005, pp.125-135.

A study conducted in 2001 on the heavily instrumented Virginia Smart Road measured pavement responses to a new generation of single wide-base tire (445/50R22.5) and to dual tires

(275/80R22.5). The new single wide-base tire has a wider tread and a greater load-carrying capacity than conventional wide-base tires. The potential fatigue damage resulting from different tire configurations was evaluated. After successful field testing, a finite element (FE) parametric study was conducted to investigate different failure mechanisms that were not evaluated in the field. In this study, dual tires and two new generations of wide-base tires (445/50R22.5 and 455/55R22.5) were evaluated. The main difference between the two generations of wide-base tires is that the 455/55R22.5 is wider than the 445/50R22.5; hence, it further reduces the contact stress at the pavement surface under the same nominal tire pressure. In the developed FE models, geometry and dimensions were selected to simulate accurately the axle configurations typically used in North America; actual tire tread sizes and applicable contact pressure for each tread were considered; laboratory-measured pavement material properties were incorporated; and models were calibrated and properly validated against stress and strain measurements obtained from the experimental program. Four failure mechanisms were considered: fatigue cracking, primary rutting, secondary rutting, and top-down cracking. Results indicated that the new generations of wide-base tire would cause the same or relatively greater pavement damage than conventional dual tires. Because overall truck weight is reduced by approximately 450 kilograms (kg) when wide-base tires are used, it is reasonable to implement the load limits currently applied to the dual-tire assembly on the 455/55R22.5 wide-base tire.

Ponniah, J., R. Haas, Z. Jiang, R. Madill, and A. Adedapo. Wide Base Single Tires vs. Dual Tires: Assessment of Impact on Asphalt Pavements. Presented at the Advances in Pavement Design and Construction Session of 2009 Annual Conference of the Transportation Association of Canada, 2009.

The Ontario Ministry of Transportation initiated a research project in 2006 with the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo to assess the potential impact on pavements and the associated cost if the axle load on the second generation single wide-based tires (SWB) was increased to 9000 kg. The scope of this study included a comprehensive experimental investigation using the instrumented pavement sections. The objectives of the experiment were: 1) to determine the axle load on dual tires that would be equivalent to a 9,000 kg single axle load on the SWB tires and 2) to examine the effects of unequal tire pressure, wander and tire types on pavement response.
The results showed that the axle load on dual tires causing the equivalent damage as the 9000 kg axle load on SWB tires could range from 10,700 kg to 12,300 kg depending on the pavement structural strength. The weaker the pavement, the greater the damage due to SWB tires. The analysis based on ESAL indicated that the SWB tire could potentially cause 2 to 3.5 times the overall damage caused by dual tires. The fatigue cracking analysis showed that the SWB tires could cause 1.7 to 1.9 times the damage associated with dual tires. The study indicated that the combined adverse effects of unequal tire pressure on dual tires, wander, dynamic load and speed do not give SWB tires any advantage over dual tires in terms of reducing the overall pavement damage.

The findings of the experimental investigation carried out in Phase 1 and Phase 2 are summarized as follows.

Phase 1 Study

Pavement temperature had an unexpected high impact on the test results. There was a strong correlation between the tensile strain readings and the sub-surface temperature.
Additional, more focused field testing was therefore conducted to minimize or eliminate the impact of the temperature fluctuations and to provide additional data readings to help fine-tune the original calibration.
Preliminary test results indicated that SWB tires at 9,000 kg axle load could potentially cause more pavement damage than the best-performing dual tires at 10,000 kg axle load.
Imbalanced loading due to unequal pressure had no effect on maximum tensile strains. However, the average strain was slightly increased when the tire pressures were not equal. More tests are needed to determine the effects of such difference on pavement performance. According to the European study, unequal tire pressure has the potential to increase rutting by only 1% relative to SWB tires [11].
The vehicle lateral wander appears to have no beneficial effect on SWB tires in terms of reducing the potential damage. On the contrary, the dual tires showed a significant reduction in the tensile strain due to wander in comparison to SWB tires.
The dual tires produced lower strain than the SWB tire at 40 kph and higher strain at 5 kph when surface temperature was 40oC during the summer.
Dynamic loading tests showed that the dual tire under dynamic loading produces less strain than SWB under normal and dynamic loadings.
Contact stress test results indicated SWB tires produce 20% higher stress than the dual tires under the same axle loading.

Phase 2 Study
The single axle load on dual tires equivalent to the SWB tires at 9,000 kg appears to vary with pavement strength. The weaker the pavement, the higher the equivalent axle load on dual tires (EALDT).
The results identified two EALDT values (10,700 kg and 12,300 kg) for WBL and EBL sections, respectively. The average EALDT value is 11,500 kg.
Based on the analysis of ESAls, the SWB tire could potentially cause 2 to 3.5 times the damage due to dual tires.
Based on Fatigue analysis, the damage due to SWB tire could be 1.7 to 1.9 times the damage caused by dual tires.

TPF-5(197) - The Impact of Wide-Base Tires on Pavement Damage: A National Study (This study is still in progress)
Various research studies in the past have investigated the potential pavement damage of wide-base tires as compared to regular dual-tire assemblies, with many drawing the conclusion that wide-base tires are more damaging to pavements. However, until five years ago, all the research studies documented in the literature were conducted on early generations of wide-base tires, which may or may not have been intended for highway use. The early research results may, in part, account for the lack of wide-base tire adoption in the United States due to inconsistent State restrictions on these tires, which hinder interstate commerce. Recent advances in tire technology have led to the design of wide-base tires that have wider tread than previous designs, resulting in a load distribution more comparable to that of dual tires. Therefore, an evaluation of these new tire designs is needed to determine their contribution to pavement damage and other factors, such as safety and economic impacts, with respect to dual configurations. There is also

the issue of the discrepancy between the reported width of the tire and the actual tread width. From an enforcement perspective, it is much easier to read the width of the tire than to measure it. From the pavement's perspective, all that contributes to the damage of the pavement is the width of the tire that it contacts. The United States Environmental Protection Agency (EPA) Smartway Transport Partnership promotes the use of wide-base tires as a way to improve fuel economy by reducing weight, aerodynamic drag, and rolling resistance. Other potential benefits they cite are reduced driveby noise and improved stability. Trucking operation factors that directly affect pavement damage can be classified into three major components: vehicle-generated load, axle and tire configuration transferring the load, and pavement carrying the load. To fully characterize the damage induced by different tire and axle configurations, the effects of vehicle, tire, and pavement and their interaction must be considered. Vehicle and tire factors include axle loads, axle spacing, speed, tire inflation pressure, and tire configurations. Pavement parameters include surface roughness, materials properties, layer thicknesses, and subgrade strength. The recent introduction of the Mechanistic-Empirical Pavement Design Guide (MEPDG) has shifted the emphasis in pavement design from empirical methods to more rational approaches. Therefore, the impact of different vehicle tire factors on the pavement damage needs to be determined using rigorous theoretical modeling capable of simulating field conditions, and should be validated utilizing field test response measurements.

The key project objectives are:

- *Quantify the impact of vehicle-tire interaction on pavement damage using advanced theoretical modeling validated via full-scale pavement testing. This includes the determination of the relative effects of wide-base tires and dual-tire assemblies on pavement performance. This should also include the determination of the relationship between the reported tire width and aspect ratio, load, inflation pressure, and actual tread width.*
- *Develop a tool and methodology that allows the States to assess the impact of wide-base tires on the pavement network.*
- *Perform an analysis of the economic, safety, and environmental effects of using wide-base tires relative to the impact on pavement performance.*

Scope:

- *Limited to flexible pavements*
- *Only tires greater than 425mm in width and available in USA market*
- *Economic, safety and environmental analysis using available data*

1.5 Concluding Summary

The review of previous studies and techniques for analyzing pavement costs associated with changes in traffic loads reveals several basic approaches. The most prevalent approach involves calculating the number of ESALs before and after the changes, calculating the cost per ESAL through either a micro or macro approach, and simply multiplying the two factors. Since this approach doesn't reflect the most current approach, we will concentrate on the other approaches reviewed.

Most of the studies that did not use ESALs used another form of load equivalence factors (LEFs), using either that name or an equivalent name, that were typically derived for a single particular distress to describe the relative damage by one axle weight and type compared to the damage of a standard axle. Some of the LEFs were based on mechanistic primary-models, and some of these were calibrated to a small amount of observed empirical data. The most promising approaches based their LEFs on the MEPDG model in its various versions. Some of the studies used reduction in time-to-failure as the variable that determined LEFs, and some used distress levels.

Only one study, the Timm et al work for FHWA, used an approach of using a class of vehicles as the unit of analysis. That study used an idealized weight distribution for each of two specific vehicle weights and configurations, and simply ran MEPDG with base traffic and with a shift in travel from vehicle to another. The answer was inconclusive, and the authors recommended development of a more generalized approach that allowed a more comprehensive analysis of changes in operating weights, and axle weights and types. Further, the CTSW Study will use actual distributions of axle weights and types rather than an assumed idealized vehicle loading, and will consider a range of operating weights for each vehicle type, so it is not yet clear that this approach will be workable in the study, but it has the advantage of bypassing the need for calculating LEFs for the impact assessment phase of the study.

The studies by Chatti et al and Tirado et al used primary response models to extend analysis to axle groups with more than three axles in the group (tridems), a current limitation of the *AASHTOWare Pavement ME Design*® model. The Project Schedule does not afford sufficient time and there are not sufficient resources under this Project to apply the approach in this study but it may be informative to tabulate the prevalence of multi-axles in the WIM data analysis and apply a rudimentary approach for considering the likely effect of considering quadrem and larger axle groupings, rather than arbitrarily dividing them into tridem and tandem groupings.