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16. Abstract

The objective of this research project was to produce a synthesis of available information to support specific areas related to pavements for the safe, economical development of the Trans Texas Corridor (TTC). This synthesis is divided into nine sections, each of which deals with a specific topic or topics. These specific areas include (1) pavement design for heavy vehicles, (2) pavement design for light vehicles, (3) skid resistance issues on high-speed corridors, (4) issues related to traffic characterization, (5) smart pavements for high-speed corridors, (6) pavement material response to dynamic loads and performance prediction, (7) safety issues related to splash and spray, and (8) ride quality for high-speed corridors.

Regarding these stated issues, this synthesis recommends state-of-the-art technology to the Texas Department of Transportation (TxDOT) for use during development of the TTC. It provides recommendations for future research to fill gaps in knowledge and to take emerging technology to the stage where it can be implemented during the design and construction of the TTC pavements.

This is the first synthesis study to address issues related to the TTC. A secondary objective of this project was to determine if additional synthesis studies in other areas of transportation related to the TTC should be conducted and, if so, how the process might be improved. This synthesis recommends that future syntheses should be more focused on specific, maybe critical, issue(s); the researcher should be instructed to present only those findings that are really new, innovative, and potentially implementable. One element of the study should pursue non-transportation related technology that might be adapted to transportation issues.

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SYNTHESIS
OF
PAVEMENT ISSUES RELATED TO HIGH-SPEED CORRIDORS

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation. Not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Joe W. Button, P.E. # 40874.

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Mr. Gregory S. Cleveland, P.E., Technical Operations Manager, Materials and Pavements Section of the TxDOT Construction Division, served as project director (PD) for this research effort. Mr. Randy Hopmann, P.E., Lubbock District Engineer, served as project coordinator (PC). The project management committee included Mr. Randy Hochstein, P.E., Area Engineer in the Amarillo District and Maria Burke, P.E., of the Design Division. Their suggestions to guide this synthesis and support in the accomplishment of this project are gratefully acknowledged.

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INTRODUCTION

The Transportation Research Board's (TRB's) "Critical Issues in Transportation 2002" (TRB, 2001) states that congestion in the United States (U.S.) transportation system is worsening as demand for passenger travel and freight movement outstrips the ability to add capacity. The Texas Department of Transportation (TxDOT) has responded to this critical need with the most innovative concept in transportation since the conception of the interstate highway system. The project is termed the Trans Texas Corridor (TTC) project (Figure 1) (See http://www.dot.state.tx.us/ttc/ttc_report_summary.pdf).

According to TxDOT (2002), the TTC will be a multi-modal transportation system that includes separate lanes for passenger vehicles and trucks, high-speed passenger rail, commuter and freight rail, and a dedicated utility zone for water, petroleum pipelines, electricity, and data. The futuristic concept of the TTC is to intra-connect Texas by a 4200-mile network of corridors up to 1200 feet wide with separate lanes for passenger vehicles (three in each direction) and trucks (two in each direction) (Figure 2). The corridor will include six rail lines (three in each direction), one for high-speed passenger rail between cities, one for high-speed freight, and one for conventional commuter and freight. The third component of the corridor will be a 200-foot wide dedicated utility zone. The estimated total cost for the TTC ranges from $145 billion to $184 billion. The TTC is the largest engineering project ever proposed for Texas. It is a world-class concept.

World Highways (2003) reports that the proposed TTC investment over three decades underpins Texas's position as a major transport center for North America. As an example, 79 percent of all US-Mexico trade passes through Texas ports of entry, and this will increase under the North American Free Trade Agreement (NAFTA). The article concludes that the TTC will enable Texan infrastructure to meet its increasing trade requirements and projected population growth from 21 million today to 40 million over the next 30 years.

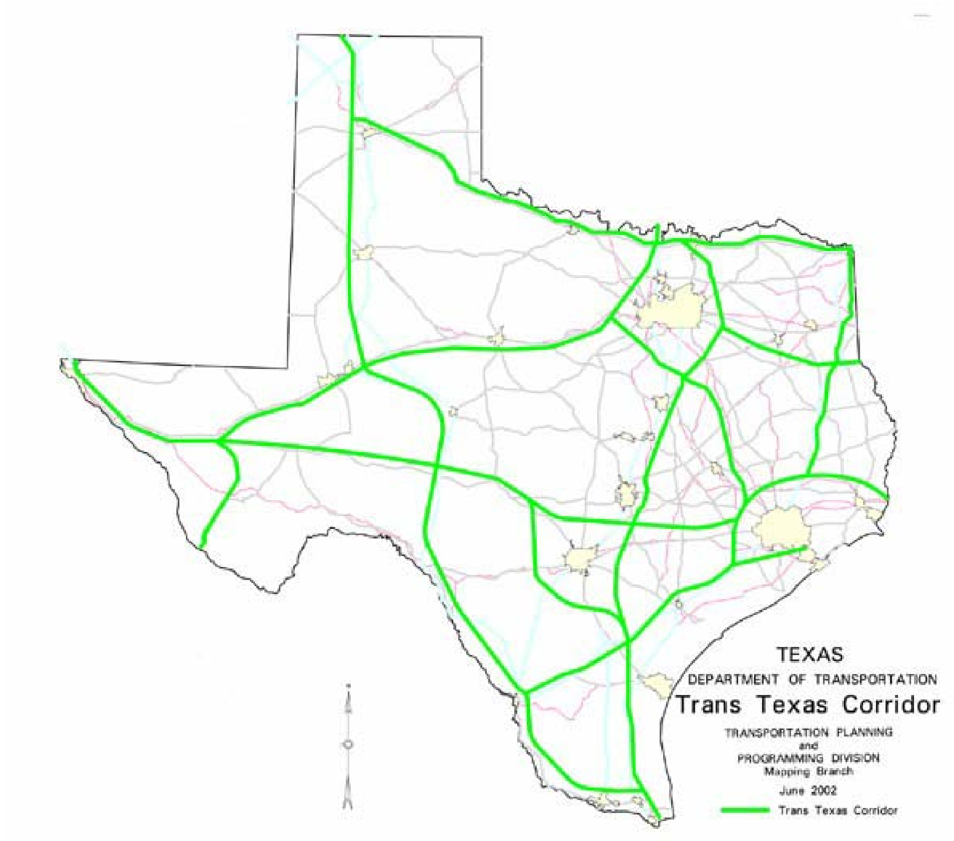

Figure 1. Planned Locations for Trans Texas Corridor (after TxDOT, 2002).

Figure 2. Conceptual Image of the Trans Texas Corridor (after TxDOT, 2002).

The objective of this research project is to prepare a synthesis of available worldwide information to support specific areas related to pavements for the safe, economical development of the TTC. This synthesis is divided into nine sections, each of which deals with a specific topic. These specific areas include:

- Pavement Design for Heavy Vehicles,
- Pavement Design for Light Vehicles,
- Skid Resistance Issues on High-Speed Corridors
- Issues Related to Traffic Characterization,
- Smart Pavements for High-Speed Corridors,
- Pavement Material Response to Dynamic Loads and Performance Prediction,
- Safety Issues Related to Splash and Spray,
- Ride Quality for High-Speed Corridors, and
- Miscellaneous Pavement Related Issues.

Regarding the above issues, this synthesis recommends state-of-the-art technology to TxDOT for use during development of the TTC. It provides recommendations for future research to fill gaps in knowledge and to take emerging technology to the stage where it can be implemented during the design and construction of the TTC. Further, this is a pilot synthesis project related to the TTC; therefore, it provides recommendations regarding how to conduct any future synthesis projects that may be requested by TxDOT.

PAVEMENT DESIGN FOR HEAVY VEHICLES

Introduction

The TTC will have lanes dedicated to trucks only. Designing pavements to accommodate trucks is nothing new. For practical purposes, most current structural design procedures disregard the effects of passenger cars because, by comparison, loading from private cars has a negligible effect (Buiter, 1989). However, heavier and larger trucks than presently allowed on Texas highways may be permitted for operation on the TTC. The question arises; do design methods for flexible and rigid pavements exist that are capable of addressing 100,000 to 150,000-lb. truck-only pavement designs?

TxDOT is already studying the impact of very heavy trucks on the condition of highway pavements. Due to recent legislative action, trucks with gross vehicle weights (GVWs) of up to 125,000 lbs are now routinely permitted to use a portion of SH4/48 near Brownsville to transport commodities to and from Mexico. The payloads carried by permitted trucks are mostly coiled metal sheets, oil, and powder mineral (fluorite), which are transported from the Port of Brownsville to Mexico and vice versa. Figure 3 illustrates the types of payloads transported along the route, which was established in response to the need expressed by truckers to haul cargo at the operating capacities of their trucks to improve operational efficiency. This need meant hauling loads in excess of legal limits, thus requiring permits to be issued. Table 1 presents the weight limits used along the route. The permitted weights shown are expected to be similar to the axle weights that will be applied on dedicated heavy weight truck lanes proposed for the TTC.

Deflection data from asphalt concrete pavements instrumented with multi-depth deflectometers (MDDs) suggest that these heavy trucks can produce two to four times more damage than trucks operating within current legal load limits (80,000 lbs GVW). Further, evaluation of different models using the MDD deflections suggests the need for considering the stress and directional dependency of pavement materials in predicting pavement response to traffic loadings (Ramos et al., 2004). While the data are particularly valid for the sections tested, these preliminary findings reveal the importance of using a mechanistic (or analytical) approach rather than empirical approaches to evaluate design requirements for overweight truck lanes.

Figure 3. Types of Loads Carried by Permitted Trucks on SH4/48 in Brownsville.

In this regard, a number of mechanistic and mechanistic-empirical design methodologies have already been developed from previous research. These are available for use in design of the truck-only lanes in the TTC system. The task of designing pavements for the TTC will involve using existing methodologies to develop pavement designs that are the most cost-effective for the projected truck loads, available pavement construction materials, and climatic conditions. Researchers anticipate that all design work on the TTC will involve new pavements; therefore, this synthesis deals primarily with the design of new pavements.

Table 1. Weight Limits Used for Permitting Trucks along SH4/48.

Weight Criterion	Weight Limit (kips)
Single axle	25
Tandem axle	46
Tridem axle	60
4-axle group	70
5-axle group	81.4
Gross vehicle weight	125

TxDOT currently uses or approves use of FPS-19, 1993 American Association of State Highway and Transportation Officials (AASHTO) Design Guide, or Modified Texas Triaxial for design of flexible pavements and AASHTO Rigid Pavement Design Procedure to design rigid pavements (TxDOT, 2003). The AASHTO design procedures currently used by TxDOT are empirically based and utilize an equivalent single axle load (ESAL) of 18 kips in the pavement layer thickness design process. Unless data are available to convert the effects of heavy trucks up to 150,000 lbs into ESALs, this limitation may preclude use of these procedures for rational design of truck-only lanes for the TTC. A fundamental limitation of any empirical design method is that extrapolation beyond the database used to calibrate the method cannot be made with confidence (Rodway and Wardle, 1998).

A comprehensive pavement design method should address the following items (AASHTO, 1993):

- traffic,
- subgrade,
- materials of construction,
- pavement performance,
- environment (climate),
- drainage,
- life-cycle cost,
- reliability, and
- shoulder design.

Some design methods incorporate specific input or calculations of all of these items while others may only consider some of the items in a cursory manner. The new National Cooperative Highway Research Program (NCHRP) 2002 Design Guide (hereafter referred to as the 200X Mechanistic-Empirical Design Guide) considers all of these items plus several others.

200X Mechanistic-Empirical Design Guide

The most current, practical pavement design methodologies in the U.S. are those found in the so-called National 200X Mechanistic-Empirical Guide for the Design of Pavement Structures, which should be completed by NCHRP Project 1-37A and made available in the summer of 2004. It is anticipated that AASHTO will adopt this new design guide. These design procedures for both flexible and rigid pavements are based on mechanistic-empirical principles, and the Guide emphasizes rehabilitation.

The new Guide is not actually a design procedure; it is essentially a design check, as pavement layer thicknesses are a required input for the design software. That is, once the pavement layer thicknesses have been determined using the method of choice by the designer, the Guide can be used to estimate pavement performance under given conditions of traffic, climate, reliability, etc.

The Guide can accommodate single axles weighing up to 41,000 lbs, tandem axles up to 82,000 lbs, and tridem and quad axles up to 102,000 lbs. Therefore, using the desired axle configuration, the Guide software can be used to estimate the performance of a pavement's structural design exposed to trucks weighing up to 150,000 lbs. ESALs do not serve as input to the new Guide; it is designed to receive data from weigh-in-motion devices.

The new 200X Design Guide software uses linear layered elastic theory for pavement design and provides a finite element analysis procedure for detailed investigations. Ullidtz (2002) explained that linear elastic theory often results in incorrect moduli when used for backcalculation of layer moduli from deflection testing, and in questionable stresses and strains when used for forward calculation. He further indicated that including non-linear materials characteristics may improve the theoretical model, but no theoretical model has yet been conclusively verified with experimental data. Use of non-linear or finite element analyses drastically increases computer run time. Furthermore, the empirical relationships used to predict pavement deterioration from critical stresses or strains are equally problematic.

The National Highway Institute now offers a Federal Highway Administration (FHWA) course titled "Introduction to Mechanistic Design of New and Rehabilitated Pavements" to familiarize users with the new design Guide (www.tfhrc.gov/focus/june02/course.htm).

Advanced Design and Analysis Methods

There are no really new pavement design procedures. However, there are a few advanced pavement design procedures that can accommodate realistic tire loads, loading configurations, and pavement responses. Examples of these include Visco-Elastic System (VESYS) (http://www.volpe.dot.gov/sbir/sol03/docs/vesys-intro.doc) developed by Dr. Bill Kenis and Mechano-Lattice developed by Dr. Bill Yandell.

VESYS is a well-developed probabilistic and mechanistic flexible pavement analysis computer program series (Kenis, 1977). The VESYS series is based on the elastic model of layered homogeneous material in half infinite space with some viscoelastic-plastic theory applications. This system uses a mechanistic N-layer elastic probabilistic primary response model, which can be used to analyze the primary response. It can also predict the development of distress in flexible pavements based on rutting, roughness, and cracking criteria. TxDOT is currently making use of VESYS through National Pooled Fund Study Number 2(205) (and TxDOT Project 9-1502) examining the effects of heavy loads coming from Mexico and Canada resulting from the North American Free Trade Agreement (http://tti.tamu.edu/researcher/v38n1/heavier_loads.stm).

Most pavement design methods make no attempt to simulate one directional translating wheel loads, which may be particularly important in flexible pavements. According to Yandell (1971), the Mechano-Lattice elastoplastic three-dimensional sequence dependent stress-strain analysis prediction process does address this issue. In 1979, Mechano-Lattice was further developed into a three-dimensional elastic-energy absorbing gross stress-strain analysis and mechano-lattice plain strain pavement performance prediction program (Yandell and Lytton, 1979). The mechano-lattice stress-strain analysis has been used extensively to solve a variety of problems in pavement technology, tire-road friction, and geotechnology (Yandell and Behzadi, 1999).

Leonard and Francken (2002), of the Belgium Road Research Center, pointed out that the present capabilities of computers do not justify the continued use of the ESAL. A number of these design procedures are available from both the public and private sectors. Some are capable of designing flexible, rigid, and composite pavement structures within the same tool.

As mentioned earlier, the 200X Design Guide provides a finite element procedure for detailed structural analyses. White et al. (2002) proved that finite element analysis is an effective tool for studying the contributions of flexible pavement layers to rutting. They stated that, unlike any other analytical approaches, finite element analysis is able to fairly represent layer and pavement geometry, material characteristics, boundary conditions, and loading. In particular, failure strains in a layer are promulgated and captured in surface deformations. They produced a computer program to assist users in calculating surface distortion parameters and drafted a procedure in AASHTO format. Calculated surface deformations compared very well with the surface deformations of pavements subjected to prototype scale truck loading.

International Pavement Design Procedures

According to Sebaaly et al. (2002), the majority of highway agencies in the United States use the 1993 AASHTO design guide, which is based on the AASHO Road Test and uses the 18-kip ESAL concept. The AASHTO design guide has the ability to convert heavier axle loads into ESALs using load equivalency factors that were developed at the AASHTO Road Test. However, only heavier loads that use standard single, tandem, or tri-axle configurations can be converted to ESALs using the AASHTO load equivalency factors. Heavier loads that do not conform to standard axle configurations cannot be converted to ESALs using the AASHTO factors. They deduced that this presents a problem to highway agencies that are faced with an increasing use of heavy loads on non-standard axle configurations such as heavy construction and agricultural equipments.

Nearly every country has adopted a different method for structural design of pavements, and they are based on methodologies that are likely 20 to 30 or more years old.

Several can be traced back to the AASHTO Road Test. Essentially all of the design procedures use standard design loads (18 kip to 20 kip axle load) similar to the USA standard ESAL to characterize traffic loadings. This is the case for Canada (He et al., 1997); United Kingdom (The Highways Agency, 2001); Australia (Austroads, 2001); New Zealand (Pidwerbesky et al., 1997); South Africa (Theyse, 1996); Finland (Saarelainen et al., 1999); China (Menyu and Qisen, 1997); and the International Civil Aviation Association (or ICAO) (Thompson, 2002). Germany (Werkmeister, 2001), Sweden, India (Bagui, 2002), and Hungary (András, 2000) use 22 kips. France uses an ESAL of 29 kips (Corte and Serfass, 2000). Therefore, these design methods would offer no significant advantage over those currently in use in the USA for characterizing trucks weighing up to 150,000 lbs.

He et al. (1997) reported that a new, comprehensive pavement design procedure (OPAC, 2000) had been developed for Canada's Ontario Province. The procedure is mechanistic-empirically based with separate load-associated and environment-associated performance models. It includes a reliability analysis. The models have been calibrated from an extensive, long-term performance database incorporating items such as age vs. pavement condition index (PCI), layer thicknesses, and ESALs, and have been regionally adjusted and validated. The researchers suggested that, even though the calibration has been performed using the Ontario database, the approach is generic and could be calibrated to other regions.

Recent Pertinent Research Findings

Although NCHRP Report 505 (Harwood et al., 2003) provides little regarding pavement structural design, it presents the latest information on highway geometric design and characteristics of the U.S. truck fleet.

Flexible Pavements. Hunter (2000) stated that the Directorate for Transport of the European Commission recognized the need for more comprehensive analytical pavement design methods and, consequently, is supporting two initiatives (COST 333 and Advanced Models for Analytical Design of European Pavement Structures [AMADEUS]). These involve up to 20 countries in an effort to establish an integrated pavement design method. He explained that COST 333 involves development of a new asphalt pavement design method, which deals with information gathering and selection of key parameters (performance requirements, traffic, climate, materials, and models). COST 333 will take into account the future uniform maximum axle loads of trucks in European Union countries and the standardization of requirements for road materials. The main objective of AMADEUS is the evaluation of existing, advanced, analytical pavement design models by comparing their predictions using standard inputs. Table 2 lists the methods being examined and the factors attributable to each (De Lurdes Antunes and Francken, 1999). Findings from these studies may offer valuable information related to design methods for truck-only pavements for TTC.

Recent work in the United Kingdom by TRL Limited (Nunn et al., 1997) showed that the concept of "indeterminate" design life is applicable to thick asphalt pavements with heavy traffic. Hunter (2000) explained that the term indeterminate life is associated with flexible composite pavements that have a cement-bound base; they can provide long but indeterminate design life. Such pavements often experience transverse shrinkage cracking, but these do not generally have adverse effects on structural performance, as long as the pavement is protected from the ingress of water. He asserted that many thick pavements designed to have mid-life strengthening have exhibited very stable structural characteristics and have not needed the expected treatments and consequent delays associated with major maintenance activities. Nunn et al. (1997) evaluated four thick pavements between 11 and 23 years old and found that fatigue and structural deformation were not present. They concluded that, if the pavement is well constructed and has sufficient strength to withstand structural damage in early life, a structural life of more than 40 years might be expected.

Based on his work in the United Kingdom, Nunn (1997) reported that a longer design life for flexible pavements, which carry the heaviest volumes of traffic, will yield a lower life-cycle cost. He demonstrated that the deterioration of thick, well-constructed, fully flexible pavements is not structural, and that deterioration generally occurs at the surface in the form of cracking and rutting. His evidence suggested that fatigue and structural deformation originating deep within the pavement structure are not the prevalent modes of deterioration. In the USA, these types of pavements are termed perpetual pavements, and much has been written about them in recent years.

Table 2. Inventory of Existing Models and Design Software Products (after De Lurdes Antunes and Francken, 1999).

Software Name	Method Used as Response Model	Type[2]	Non Linearity	Rheology	Anisotropy	Interface	Climatic effects	Dynamic loading	Axle spectrum	Tire characteristics	Stochastic	Crack propagation	Thermal effects	Cumulated damage	Fatigue	Permanent Deform.
APAS-WIN	Multi-layer	3					Y		Y	Y			Y		Y	
AXYDIN	Axisymetric FEM[1]	1						Y								
BISAR/SPDM	Multi-layer	3				Y	Y		Y						Y	Y
CIRCLY	Multi-layer	3			Y	Y			Y	Y				Y	Y	
CAPA-3D	3D-FEM	3	Y	Y	Y	Y		Y		Y		Y	Y			
CESAR	3D-FEM	3	Y	Y	Y	Y	Y	Y		Y	Y	Y		Y	Y	Y
ECOROUTE	Multi-layer	1				Y				Y				Y		
ELSYM 5	Multi-layer	1														
KENLAYER	Multi-layer	2	Y	Y		Y		Y		Y				Y	Y	Y
MICHPAVE	Axisymetric FEM	1	Y												Y	
MMOP	Multi-layer	2	Y				Y	Y	Y	Y	Y	Y				
NOAH	Multi-layer	3			Y	Y	Y		Y		Y				Y	Y
ROADENT	Multi-layer	2				Y	Y		Y	Y						
SYSTUS	3D-FEM	2	Y	Y	Y	Y		Y		Y		Y				
VAGDIM 95	Multi-layer	3					Y						Y	Y	Y	Y
VEROAD	Multi-layer	1		Y					Y	Y	Y					
VESYS	Multi-layer	3					Y		Y	Y	Y			Y	Y	Y

[1] FEM = finite element method

[2] Type 1, response models (i.e., those that provide results only in terms of stresses and strains); Type 2, response + partial performance (i.e., those that consider the effects of loading, climate, etc. on rutting, crack initiation, etc. but do not provide a full design procedure); Type 3, full design procedure (i.e., those that provide a recommended structure (thicknesses, materials) and long-term performance predictions.)

Huang et al. (2001) claimed that a true mechanistic pavement design procedure should be able to correctly predict pavement response and the development of pavement distresses (such as rutting and fatigue cracking) under various traffic and environmental conditions. They developed a three-dimensional (3-D) numerical simulation procedure with realistic material models and moving wheel loads at the Louisiana Accelerated Loading Facility. Rate-dependent viscoplastic models were incorporated into the 3-D finite-element procedure. A creep model was used to predict rutting of the asphalt pavement. The results indicated that the 3-D finite-element procedure with viscoplastic models was capable of reflecting the pavement responses and predicting pavement rutting with reasonable accuracy.

Rigid Pavements. A source of current information on design procedures for concrete pavements is the American Concrete Institute's SP-181, "Recent Developments in the Design and Specification of Concrete Pavement Systems" (Zollinger, 1999). Owusu-Antwi and Darter (1999) maintained that concrete pavement design is still largely empirical, although there are instances where analytical methods based on theoretical principals have been used. Zollinger (1999), the editor of SP-181, anticipated that future design developments will most notably center on the use of mechanistic concepts and utilize important material properties that affect the performance of concrete pavement structures. One of the more widely accepted and used design procedures for rigid pavement structures is the PCA Thickness Design for Concrete Highway and Street Pavements (Packard, 1984), which is a mechanistic-empirical procedure.

Ceylan et al. (1999) trained an artificial neural network (ANN) model with results from the ILLI-SLAB finite element program and used it to predict stresses and deflections in jointed concrete airfield pavements serving Boeing B-777 aircraft. The trained ANN model produces stresses and deflections with average errors of less than 0.5 percent of those obtained directly from the finite element analyses. They found that use of the ANN model was very effective for correctly predicting ILLI-SLAB stresses and deflections in less than one second and with no requirements for complicated finite element inputs. Further, they are using elastic layered programs (ELPs) in mechanistic-based pavement design procedures for analysis of jointed concrete pavements. Corrections are required to ELP solutions to account for the effects of finite slab size, load location on the slab, and load transfer efficiencies of the joints. They demonstrated that this could be accomplished by using the ANN model, which is being expanded to handle all possible aircraft gear configurations with multiple-wheel loading conditions by using the superposition principle. As demonstrated for the solution of the B-777 aircraft gear loadings, trained neural network models eventually will enable pavement engineers to easily incorporate current sophisticated state-of-the-art technology into routine practical designs.

Other Design Issues. According to Salgado and Kim (2002), super-single tires are gradually replacing conventional dual tires in the trucking industry because of their higher efficiency and economy. Super-single tires generate much higher vertical contact stresses than do conventional dual tires, resulting in larger deformations and more severe damage to the pavement structure. The analyses suggest that current flexible pavement design methods are not conservative for the increased loads imposed by super-single tires on the pavement system. They offer load equivalence factors and damage factors for super-single tires and suggest their use in design practice.

Design Methods for Heavy Duty Pavements

Procedures used for design of runways and aprons that carry heavy aircraft or those used for design of industrial pavements at intermodal container terminals may have application for design of truck-only pavements (Rodway, 1997; Knapton and Meletiou, 1996; Nixon, 1996) in the TTC. The Asphalt Institute and others discussed below offer methods for designing heavy-duty pavements (The Asphalt Institute, 1986).

It is shown at http://www.mincad.com.au/container_BrisbaneCaseStudy.htm that designs have been produced to handle *axle* loads up to 154,000 lbs. Croney and Croney (1991) wrote a textbook on the design, performance, and maintenance of pavements. Part six deals with the design of heavy-duty port and industrial pavements operated by specialized lifting plants such as front-and side-lift trucks, rubber-tired gantry cranes, and straddle carriers. Part seven, by the way, discusses the riding quality and skid resistance of pavements and the design of anti-splash surfacings of friction courses.

McGillivray and Laurion (2001) point out that highway standards and specifications most familiar to engineers are often used when designing pavement systems for seaports. Yet the heavy loads that are transported and stored using seaport pavements usually require more rigorous design methods and construction details, similar to those developed for applications like major airports. In fact, the ASCE Ports and Harbors Committee is in the process of developing a pavement design guide tailored for the intensive loading conditions encountered in container terminals and intermodal yards (Smallridge and Jacob, 2001). The guide is intended to provide a comprehensive reference of alternative design procedures and material options available to engineers undertaking the design of heavy-duty pavements.

According to Wardle and Rodway (1996) of Australia, their Airport Pavement Structural Design System (APSDS) has unique features that will enhance and optimize the analysis and design of airport pavements. These include improved rational quantification of the effect of aircraft wander, graphical presentation of the damage profile across the pavement, and material anisotropy for improved modeling of unbound granular materials and subgrades. The system's transparency, speed, and flexibility enables design specialists to readily change all problem inputs including aircraft wander, aircraft numbers and mass, layer thicknesses and material properties and also the performance models. This allows rapid assessment of the sensitivity to each component input and for all design assumptions.

APSDS rutting criteria have now been developed from the observed performance of aircraft test pavements subjected to wheel loads of up to 30 tons (Wardle et al., 2003). These loads are comparable to those typically applied to heavy-duty pavements used at docks, container terminals, and on mine haul roads. An engineering firm used APSDS to estimate the damage caused by a certain mix of aircraft traffic during the 40-year service period on an airport in The Netherlands (De Bondt, 2002). The owners specified that, during this period, the pavement would experience about 4 million heavy wheel loads (between 27 and 33 tons) belonging to the aircraft types B747-400, B777, MD11, and NLA (new large aircraft such as the A380). He stated that a nice aspect of APSDS is that the overall influence of the entire mix of aircraft and the effect of the degree of lateral wander is fully taken into account, thereby saving engineering time and increasing accuracy. APSDS method may be worth examining for use in designing pavements for heavy trucks.

The computer program (Layered Elastic Design Federal Aviation Administration) LEDFAA (from U.S. Federal Aviation Administration) is a mechanistic method for designing pavements exposed to heavy loads (Wardle and Rodway, 1996). Although it specifically addresses the design of pavements to accommodate the Boeing 777, it is capable of designing flexible and rigid pavements and overlays of rigid pavements, and the concepts may have utility for designing truck-only lanes. The computer program operates under Microsoft Windows. (See http://ntl.bts.gov/data/5320-16.pdf.)

ILLI-PAVE, a structural axi-symmetric (i.e., single wheel) non-linear finite-element pavement analysis software with Mohr-Coulomb failure criteria, has been enhanced to characterize flexible pavement response under multiple wheel-heavy gear load aircraft using mechanistic-empirical concepts (Thompson et al., 2002). They used two different analysis techniques that utilize the principal of superposition to extend ILLI-PAVE single-wheel results to multiple-wheel configurations. ILLI-PAVE generates material moduli that incorporate the stress dependent characteristics of granular materials and subgrade soils and are thus considered more realistic than procedures that estimate granular material moduli as a function of subgrade modulus (Thompson and Garg, 1999). This new program can be used in a comprehensive flexible pavement design procedure for pavements experiencing heavy multiple-wheel loads. Elastic layer programs do not account for stress-dependent behavior.

In the United Kingdom, BAA (1993) identified a need for more onerous failure criteria and higher reliability than incorporated in previous design methods, primarily to reduce maintenance requirements. As a result, they developed design methods for rigid and flexible pavements to provide these criteria with known levels of design reliability.

Potential Solutions for Design or Analysis of Truck-Only Lanes

TxDOT should examine the findings of the European studies COST 333 and AMADEUS when they become available. Deliverables from these studies may offer valuable information related to design methods for truck-only pavements for the TTC. Websites describing these efforts are located at http://www.cordis.lu/cost-transport/src/cost-333.htm, http://europa.eu.int/comm/transport/extra/amadeusia.html, and http://europa.eu.int/comm/transport/road/research/2nd_errc/contents/11%20PAVEMENT%20DESIGN%201/pavement%20design%201.doc. In addition, TxDOT should examine design procedures used for runways and aprons that carry heavy aircraft and those used for design of industrial pavements at intermodal container terminals as these may have application for design of truck-only pavements in the TTC.

One potential aid in the design of heavy-duty flexible pavements is the use of large-stone asphalt mixtures (LSAMs). Most so-called LSAMs have historically been conventional mixtures with a few big rocks that are not designed to attain mutual contact of the largest stones. Mahboub and Williams (1990) pointed out that high resistance to deformation in properly designed LSAMs makes them attractive candidates for construction in heavy-truck traffic routes. They discussed problems often associated with LSAMs, including segregation, poor compaction, low density, and particle crushing and concluded that each can be avoided provided that appropriate countermeasures are employed during construction. Anderson et al. (1991) demonstrated that LSAMs offered better resistance to rutting than conventional mixtures on Kentucky's coal-haul roads.

Button et al. (1997) provided detailed design and analysis procedures for LSAMs along with pertinent laboratory test methods and field construction guidelines. Use of the Bailey method (Vavrik et al., 2002) is also useful for design of rut-resistant LSAMs. The South Africans (Verhaeghe et al., 1994) developed a framework for linking mix design parameters for large stone asphalt mixtures with the structural design process.

FHWA sponsored development of a software analysis tool that can evaluate the relative performance benefits and costs associated with adding different design features to a Portland cement concrete (PCC) pavement design (Hoerner et al., 2004) (See also http://www.tfhrc.gov/pavement/pccp/pubs/04045/.) The tool is for pavement designers who are interested in comparing costs versus performance associated with the selection of design features during the PCC pavement design process. This software is only a computational tool. It is not intended to provide absolute answers on the effect of different design features, but rather to offer insight into general performance and cost trends associated with the use of different design features.

According to Hoerner et al. (2004), various design features (such as dowel bars, tied shoulders, or drainable bases) may be added to a PCC pavement design to improve its overall performance by maintaining a higher level of serviceability or by extending its service life. However, the addition of these features also increases the initial cost of the pavement design, in some cases quite significantly. This then raises the question as to whether the improved performance benefits gained by adding the design features are worth the increased cost. Furthermore, the effects of adding more design features to a PCC pavement design may produce smaller performance gains, while significantly increasing the overall costs of the structure. Unfortunately, current design practices do not always consider this trade-off between performance benefits and costs when design features are added to a PCC pavement design.

Research Needs Related to Truck-Only Lanes

According to Cackler (2003), if Future-Strategic Highway Research Program (F-SHRP) comes to fruition, it will focus on studies of pavement rehabilitation, not design of or design methods for new pavements. Therefore, if officials determine that TxDOT needs new design procedures to accommodate truck lanes in TTC, a research project should be initiated promptly.

It is evident from Table 2 that a range of options is available for evaluating design requirements for dedicated overweight truck lanes. Thus, in terms of analysis procedures, the authors are of the opinion that work has progressed considerably, along with advances in computing technology, to model the complex behavior of pavements under in-service load and environmental conditions. The main challenge, in the authors' opinion, is in implementing current analysis procedures into a comprehensive methodology for designing and building dedicated heavy truck lanes to ensure that pavements are built according to the design. In this regard, the following research and development needs are identified:

- Quality control and assurance testing. The development of rapid, nondestructive, performance-related test methods is crucial in verifying that the as-built pavement satisfies design assumptions. Where feasible, these applications should be based on existing test methods already implemented within TxDOT, such as ground penetrating radar, (GPR), falling weight deflectometers, (FWD) seismic pavement analyzers, and inertial profilers. There are a number of research efforts already conducted or underway in this area. Examples include the use of GPR for longitudinal joint density testing, infrared sensors for identifying segregated areas during hot-mix asphalt laydown operations, and equipment instrumentation to determine effectiveness and uniformity of field compaction methods. Significant progress has been made in developing these applications, but more work needs to be done in getting applications implemented through development of standard test methods and specifications and training of TxDOT engineers and contractors. In addition to nondestructive in-situ test methods, standard test methods for laboratory characterizations of material properties are needed for quality control/quality assurance (QC/QA) testing based on measurements of material properties used in pavement design models.

- New material specifications. Researchers anticipate that changes in existing material specifications will be necessary to provide pavements intended to serve heavy truck traffic. In particular, researchers are of the opinion that the use of premium base materials will be important in achieving cost effective pavement designs for heavy truck lanes. In this regard, there are on-going TxDOT projects with Texas Transportation Institute (TTI) involving field testing of experimental base sections that are expected to provide useful information for evaluating existing material specifications. A key requirement is to provide durable materials. Several districts have already conducted experimental projects in this area. For example, the Corpus Christi district has constructed test sections to identify the structural benefits of triaxial class 1 base materials. The initial performance of these sections along US 77 has been excellent, as documented by both GPR and FWD data. In addition, the Fort Worth and Waco districts have evaluated test sections to evaluate the rut resistance of large stone asphalt stabilized base layers. It is important to document the benefits of improved materials and to monitor the performance of these materials under heavy truck traffic. A critical issue that must be addressed is the development of laboratory and nondestructive field test procedures that can be used as reliable predictors of expected pavement performance.
- New construction methods. The implementation of new material specifications will more than likely require changes in the existing practice of placing and compacting new pavement materials. In view of the possible lack of experience in the use of these materials, guidelines will have to be developed to assist engineers and contractors in successfully building pavements under new material specifications.
- Accelerated pavement testing. Application of existing models to evaluate the expected performance of pavements subjected to routine truck traffic and utilizing new materials will likely require verification and calibration before such models can be used with confidence to design and build heavy truck routes. In this regard, the use of accelerated pavement test methods can serve this purpose. In addition, accelerated pavement testing will be needed to verify potential pavement designs and evaluate the applicability of new materials for building pavements intended to serve heavy truck traffic. Through accelerated pavement testing, the authors believe that TxDOT can accomplish the verification and calibration of existing models, and the evaluation of suitable materials for heavy truck routes in a cost-effective and timely manner.

PAVEMENT DESIGN FOR LIGHT VEHICLES

Introduction

The TTC will be unique in that it will include separate roadways for passenger vehicles and trucks. Obviously, either flexible or rigid pavements designed for passenger cars only (i.e., excluding heavy trucks) can be thinner and thus less expensive than those designed to also carry truck traffic. The primary objective of this section of the synthesis is to identify methods for designing pavements reserved for light vehicles. Based on typical comparisons of initial costs as well as cost and speed of maintenance and current trends, it appears that these pavement structures will almost always be flexible. Nevertheless, this synthesis addresses both flexible and rigid pavements.

Fundamentally, all highways are designed to accommodate a certain level of predicted truck traffic with little regard to the effects of passenger cars and light trucks (Buiter, 1989). Hicks et al. (1998) explain that, although passenger cars make up the majority of the traffic volume, they do very little damage to the pavement structure compared to trucks. For example, a typical sport utility vehicle (GVW = 20 kN, [4500 lb]) has a total equivalent axle load of 0.0005. They conclude that nearly 4500 sport utility vehicles would have to pass over the pavement to do as much damage as one fully loaded moving van.

Many experts have questioned the accuracy of load equivalency factors in terms of ESALs for passenger cars and light trucks. Designing pavements dedicated to light vehicles using traffic input in terms of ESALs may be particularly problematic and may result in pavements that are too thin to provide adequate service.

During the writing of this synthesis, no new procedures for designing highway pavements limited to passenger cars were identified. Most light-traffic pavement design methods were developed for residential streets or parking lots. Therefore, the design of highway pavements reserved for carrying passenger cars only may offer designers the greatest opportunity for innovation. Further, development of new methods for designing such pavements offers significant opportunities for far-reaching research.

It currently appears that, when dealing with pavements dedicated solely to light vehicles, engineers must change their way of thinking about the structural design process, mixture design procedures, materials (aggregate, asphalt grade, mixture type) selection, materials test protocols and criteria, and construction specifications. Realistic procedures are needed to optimize performance and cost effectiveness for these light-traffic pavements.

Design Methods for Lightly Trafficked Pavements

Jahren (2000) indicates that Australia and New Zealand have much lower population densities and thus fewer resources to invest in their infrastructure. (e.g., Australia has a land mass 80 percent the size of the United States with a population 7 percent the size of the U.S.) As a result, both countries have developed systems for economically constructing and maintaining roads. Several of their products will be useful in designing pavements and selecting materials for lightly trafficked pavements.

According to Mulholland (1986), pavements for light traffic are typically designed using highway design procedures. His work provided municipal engineers with methods by which one can rationally design light-traffic pavements. He spelled out procedures for estimating design California bearing ratio (CBR) and design traffic values. His paper gives some indication of the quality criteria that should be specified for conventional pavement bases and subbases for residential street pavements. Schofield (1986) pointed out that extrapolations of the then current highway pavement design curves to very light traffic levels might result in under design, particularly for low-strength subgrades. Mulholland (1987) stated that the six most important phases in street pavement design are (1) subgrade assessment, (2) traffic assessment, (3) thickness design, (4) pavement materials, (5) pavement surfacing, and (6) construction standards. This appears to be about the same for highway pavements except that the base may be more important than the pavement surfacing, particularly for flexible structures.

Several design methods and guidelines for designing pavements for light traffic are available. Essentially all of them are based on a maximum number of truck axles (e.g., ESALs); however, the pavements in question here will receive almost zero truck axles. Some examples follow. Flexible pavement design procedures for light-traffic pavements are available from the National Asphalt Pavement Association (Eason and Shook, 1991), The Asphalt Institute (TAI, 1999), and Australian Pavement Association (AAPA, 2002; Austroads, 1998). Rigid pavement design procedures for light-traffic pavements are available from the American Concrete Institute (ACI, 2002 and ACI, 1990), Portland

Cement Association (PCA, 1984), and Canadian Portland Cement Association (CPCA, 1984). A design catalogue published by NCHRP may also provide useful pertinent design information (NCHRP, 1998).

The NAPA publication (Eason and Shook, 1991) presents a method for designing hot mix asphalt (HMA) pavements for low-volume roads and other areas that are not subject to large or frequent heavy loads and for which traffic counts are often estimated. It describes alternative layer systems and construction strategies that may obtain better quality, economy, or construction efficiency, depending on the circumstances of the project. Fundamentals of specifying asphalt mixtures are explained, and recommended tolerances and construction guidelines are provided as an aid to the specifier. Part One addresses the selection of materials and construction methods and includes a checklist of items to consider. Part Two presents the structural design procedure, which covers both multi-layer systems and full-depth asphalt. Part Three contains technical guidelines for designing and specifying pavements, based upon concepts introduced in Parts One and Two. AAPA (2002) provides only general guidelines for very light duty pavements such as residential streets, parking lots, and even cycle ways and pedestrian paths.

The ACI guide (ACI, 2002) provides a perspective on a balanced combination of pavement thickness, drainage, and subbase or subgrade materials to achieve an acceptable pavement system for light-traffic roadways. Such concrete pavements designed for low volumes of traffic (typically less than 100 trucks per day, one way) have historically provided satisfactory performance when proper support and drainage conditions exist. Recommendations are presented for designing a concrete pavement system for a low volume of traffic and associated joint pattern based upon limiting the stresses in the concrete or, in the case of reinforced slabs, maintaining the cracks in a tightly closed condition. Details for designing the distributed reinforcing steel and load transfer devices, if required, are given. Thickness design is based on principles developed for analyzing an elastic slab over a dense liquid subgrade, as modified by field observations and extended to include fatigue concepts.

According to Potter et al. (1987), the U.S. Army Corps of Engineers' pavement design procedures (Corps of Engineers, 1992) are particularly appropriate for low-volume road applications because they were developed from traffic tests using relatively low traffic volumes and thin pavement sections on low-strength subgrades. The large loads and low volumes of traffic used in their development are especially analogous to situations encountered in mining, logging, and similar industrial applications, or in port facilities. The flexible pavement criteria are most appropriate for thin asphalt concrete pavements on granular base courses and subbases. Generally, rigid pavements have not been associated with low-volume roads because of their cost. However, they continue, development of roller-compacted concrete pavement construction has made rigid low-volume pavements feasible in many situations, and the Corps design method is capable of addressing roller-compacted concrete pavement characteristics. They conclude that these design procedures, published in Army technical manuals, have been computerized; therefore, the Corps of Engineers' design criteria can be applied quickly and efficiently to design economical pavements for low-volume facilities, even by pavement engineers unfamiliar with the Corps criteria or programs.

Structural and Mixture Design Philosophy for Light Vehicle Pavements

AAPA (1990) noted that HMA pavements are generally designed for optimum performance under medium to heavy loadings and traffic volumes. HMA mixtures designed in this manner are not necessarily optimal for lightly trafficked pavement surfaces. They concluded that, in lightly trafficked pavements, factors such as flexibility, impermeability, workability, and durability are more critical than factors associated with high strength such as stability, stiffness, and resistance to deformation.

Engineers should develop an atypical philosophy for designing and building highway pavements for light vehicles. Obviously, any pavement structure must be strong enough to accommodate the relatively heavy loads of construction traffic and subsequent maintenance vehicles (Schofield, 1986). Even residential streets must be designed to carry occasional heavy vehicles (e.g., school bus, garbage truck, and concrete truck), and typical design methods consider these loads. These loads are particularly critical when the base and/or subgrade are weak (e.g., when at or near saturation with water or during the spring thaw). Consequently, the pavement structure must have some minimum strength, which is greater than that needed for passenger car traffic.

Foley (2000) predicted that, for pavements limited to light vehicles, the negative effects of the environment are more likely to produce pavement distresses and ultimate failure than vehicular loads. Therefore, pavements designed for light vehicles must be designed for long life in the environment in which it is placed. Fatigue cracking and rutting should not be the anticipated modes of failure. To address some of these issues, NAPA (1995) and AAPA (1990) recommended designing HMA for lightly trafficked streets using a 35-blow Marshall process (i.e., higher asphalt contents than standard 50-blow or 75-blow mixtures). This is equivalent to using relatively low design gyrations with the Superpave gyratory compactor.

In the case of asphalt concrete surfaced pavements, mixtures should be designed to contain more asphalt and lower air voids than historically used on highway pavements. Lower voids will minimize intrusion of water and air and thus provide improved resistance to damage by stripping and oxidative hardening. Pavements limited to light vehicles will experience less densification due to traffic than conventional highways. Higher asphalt contents and lower voids will provide a more compliant mixture with higher tensile strength that is resistant to thermal cracking. Since these pavements will not have to accommodate heavy trucks, softer grades of asphalt than in conventional mixtures can be used. Soft asphalts will enhance the resistance of these mixtures to aging and thermal cracking. NAPA (1995) supports this basic philosophy.

Potential Solutions for Design of Pavements for Light Vehicles

Mixture design should be integrated with pavement design. That is, because of the relatively light loads, HMA mixes could be designed with higher asphalt contents and possibly lower grades of asphalt and still resist rutting and, further, be more resistant to moisture damage, cracking (fatigue and thermal), and oxidative aging. Expensive modified binders will not likely be needed. In a related issue, with no trucks, one may expect less and/or slower densification of the mat following construction. (Surface mixes are typically designed at about 4 percent air voids and placed at about 8 percent air voids and depend on traffic to further densify the mat to about 4 percent in a few years.) Therefore, it may be necessary to require lower air voids at construction for these types of pavements.

Due to high volume but light loads, friction and the preservation thereof may be a significant issue. Due to the relatively light loads, lightweight aggregate should not be subject to crushing and may provide good wet weather friction.

In western Texas, where climates are dry and subgrades are often of relatively higher quality, a two-course surface treatment may provide adequate service for these pavements while minimizing initial construction costs. Although such pavements may produce more noise than HMA pavement surfaces, most of western Texas is rural, and few areas will be affected. Surface treatments could be applied in a planned stage-construction process where the pavements may later receive overlays. However, a combination of loose stones and high speeds might lead to unacceptable incidents of windshield breakage unless lightweight aggregate is used. Examples of other potentially more acceptable thin pavement surfacings include cape seals, microsurfacing, Novachip, and the like. Incidentally, prime coats and tack coats will be particularly important for thin pavement surfaces because the horizontal stresses at the interface will be greater than those beneath thicker layers.

Stabilization of subgrade soils is often a source of cracking in asphalt pavements; this may be particularly true with thin pavement structures. With the lighter loads, these types of pavements may not require subgrade stabilization or may suffice with only enough soil modification to support construction traffic.

Pavements for light vehicles appear to be the logical place to use lower quality local construction materials, recycled materials, and industrial by-products and save the higher quality and more expensive materials for the truck-only lanes. NAPA (1995) suggested that sand asphalt could be used for low and medium traffic categories. Sand asphalt can provide a highly workable mixture and a smooth, quiet pavement surface with low permeability. Its disadvantage might be wet weather skid resistance on a high-speed corridor; however, well-designed sand-asphalt mixtures might provide adequate service in certain dry climates of western Texas. NAPA (2000) can also assist in mixture type selection for lightly trafficked roadways.

For current high-traffic corridors, seal coats for pavement preservation and skid resistance restoration are often avoided due to the potential for flushing during hot weather. However, for pavements dedicated to passenger car traffic, seal coats may serve quite well without the danger of flushing. Again, high speeds might lead to unacceptable incidents of windshield or headlamp breakage unless lightweight aggregates and/or small stone sizes are used.

These and other issues need to be studied in a well-designed and sequenced research program to specifically address issues related to pavements designed to carry passenger cars only at high speeds.

Research Needs Related to Design of Light Vehicle Pavements

No new design procedures for pavements dedicated to passenger cars were found during the writing of this synthesis. In recent history, TxDOT has been designing pavements primarily for heavy vehicles using a certain number of ESALs as the design input for traffic. Pavements devoted to passenger cars will not be exposed to loads near 18 kips except during construction and maintenance. Research is needed to develop a completely new overall design strategy for pavements devoted solely to passenger cars. Researchers need to adopt a new philosophy (as discussed above) during the development of structural design procedures, mixture design procedures, materials (aggregate, asphalt grade, mixture type) selection guidelines, materials test methods and criteria, and construction specifications to optimize performance and cost effectiveness for light-traffic pavements.

Current tests to evaluate paving materials (e.g., Hamburg for HMA mixes and flexural strength for concrete mixes) may be too severe for pavements reserved for passenger cars. These issues need to be studied, and appropriate criteria need to be developed for the current tests, or new tests and criteria need to be formulated.

SKID RESISTANCE ISSUES ON HIGH-SPEED CORRIDORS

Introduction

General. Current TxDOT skid testing standards (basically, AASHTO T 242 or ASTM E 274) recommend 50 mph using a smooth (AASHTO M 286 or ASTM E 524) tire. It is well known that wet skid resistance decreases as vehicle speed increases and that the rate of this decrease (or speed gradient) depends on the microtexture (which is a function of surface roughness of individual aggregate particles) and macrotexture (or texture depth which is a function of aggregate gradation) of the pavement surface. Macro texture or high texture depth becomes more important as speed increases because higher macrotextures typically yield lower speed gradients.

For corridors designed for speeds potentially up to 100 mph, the suitability of skid testing at 50 mph needs to be reexamined. The main objectives of this portion of the synthesis are to determine if new technology is available to address skid testing for high-speed corridors or if testing at 50 mph will be acceptable and to identify any applicable research needs.

The most recent summary related to wet pavement friction is NCHRP Synthesis 291, "Evaluation of Pavement Friction Characteristics," (Henry, 2000). This synthesis reviews the models used for evaluating the results of wet pavement friction testing methods and discusses the methods used to measure friction and texture. The discussion includes the International Friction Index (IFI), which consists of two numbers based on friction and texture measurements. Finally, methods for construction and restoring the surfaces of pavements to achieve desired levels of skid resistance are presented. The basis of the study is a questionnaire to determine current practices in the USA and selected other countries. Henry (2000) concluded that it was important to provide both microtexture and macrotexture parameters to assure appropriate frictional characteristics on wet pavements. He did not identify any new test methods, analysis procedures, surface materials, or criteria for specifically high-speed corridors.

Background. One contributor to wet-pavement crashes is uncontrolled skidding. Vehicle crashes on wet pavements are a major concern of all U.S. highway agencies. In 1980, the National Transportation Safety Board (1980) reported that fatal crashes occur on wet pavements at a rate of from 3.9 to 4.5 times the rate of occurrence on dry pavements.

In a subsequent nationwide study, the Federal Highway Administration (1990) reported that 18.8 percent of almost 25 million reported crashes occurred on wet pavements. Moore and Humphreys (1973) indicated that surfaces with skid numbers (SN_{speed}) below SN_{40} of 40 had more than the average number of wet pavement accidents, while surfaces with SN_{40} of 40 or above had fewer than the average number of wet pavement accidents. Abrupt maneuvers will increase the probability of initiating skidding action (Veith, 1983). Skidding occurs most frequently when the pavement surface does not provide adequate friction (Luo, 2003). Others have reported similar findings regarding surface friction or texture depth (Phillips and Kinsey, 2000; Roe et al., 1991; Wambold et al., 1986; Williams, 1975; The Netherlands Institute for Road Safety Research, 1970). Roe (1999) and Cenek et al. (2000) stated that new pavement surfaces on high-speed roads in the United Kingdom and New Zealand, respectively, are required to have a minimum texture depth.

These findings were reported for pavements with "normal" highway speed limits (55 to 70 mph). The question is, how will these findings relate to relate to pavements with speed limits of 80 mph or possibly higher. Kummer and Meyer (1967) indicated that their study of driver deceleration patterns during braking and cornering suggested that an SN_{40} of about 33 apparently satisfies the frictional needs of all normal vehicle maneuvers during acceleration, driving, cornering, and deceleration, and does so over a wide speed range (except toward the end of braking maneuvers that lead to a full stop). Gargett (1990) commented that, no matter how high the skidding resistance, because of the difficulty with which vehicles stop from high speed without skidding, high-speed roads would usually have a higher proportion of skidding accidents than low-speed urban roads.

Most of the skidding accident data was collected before mid-1990s and involved a majority of passenger cars without antilock brakes. Antilock brakes should significantly reduce wet weather skidding accidents and thus provide safer driving at high speeds, particularly on wet roads. Cenek et al. (2000) concluded that vehicles fitted with antilock braking systems negate the influences of pavement texture depth. Of course, when hydroplaning becomes a factor, the advantage of antilock brakes is severely diminished. Tubas et al. (1975) evaluated the accident avoidance potential for antilock braking by analyzing 89 skidding accidents. They estimated that two-wheel antilock brake systems would have prevented or reduced the severity of about 2 percent of the accidents. The corresponding figure for four-wheel antilock braking was 9.3 percent.

Pavement Friction Measurement

The real objective in skid testing is to determine the contribution of the pavement to tire-pavement friction (Hegmon et al., 1973). Friction on dry pavements varies little (Moore and Humphreys, 1973) and is normally quite adequate for maneuvers necessary in normal driving circumstances. Therefore, pavement friction is typically measured on wetted surfaces. Measurement of pavement friction is a very complex issue that is related to many variables (Kummer and Meyer, 1967). Some of these variables include water film thickness, surface cleanliness or contamination (dust, oil film, etc.), type of rubber in the tire (adhesion and hysteresis), tire tread design and depth, tire inflation pressure, tire contact area, tire load, ambient temperature, pavement temperature, pavement roughness, macro texture, micro texture, vehicle speed, uniformity of speed during skid, and, of course, the device used to make the measurement (e.g., algorithms, calibration, suspension stiffness). In addition, the skid value will depend on the season of the year or, more specifically, how long since the last significant rainfall (Wambold et al., 1987).

Many and varied devices have been developed to measure pavement friction. A few of the more common devices are skid trailers (ASTM E 274), SCRIM (sideway-force coefficient routine investigation machine) (Hosking and Woodford, 1976), FAA Mu-meter, NASA DBV (diagonal braking vehicle), Saab friction tester (Sweden), and British pendulum tester (ASTM E 303) (Sigler, 1943). Henry (1986) described several other devices. Most researchers report poor correlations between the friction values measured by the different devices (Yager, 1990; Henry, 1986; Diringer and Barros, 1990).

In the past 20 years, there have been no major developments in the measurement of friction value or skid number for highway pavements. The device most widely used by U.S. state highway agencies to measure skid resistance of their pavements is the skid trailer (ASTM E 274, Skid Resistance of Paved Surfaces Using a Full-Scale Tire) using a ribbed tire (ASTM E 501). One requirement of this procedure is that “The vehicle with one test tire locked shall be capable of maintaining test speeds of 40 to 60 mph…during a test on a level pavement having a skid number of 50." TxDOT typically uses this method at a speed of 50 mph.

In a small wet-weather accident study, Wambold et al. (1986) found that skid resistance measured using the smooth tire (ASTM E 524) is not only lower than that measured using the ribbed tire (ASTM E 501), but it is also a better predictor of skidding accident potential. Wet-weather accident data from Florida that they analyzed reinforced this conclusion.

Skid Resistance Measurement at High Speed

Hegmon et al. (1973) pointed out that, if skid testing could be accomplished at higher speeds, this would eliminate the need for extrapolating standard SNs to higher speeds. It would also reduce sensitivity to speed errors, since SN-speed gradients (slopes of SN vs. speed curves) generally decrease with speed. They further stated that correlation between skid testers is usually worse at higher speeds, and the most probable reason is inadequate pavement wetting. Wind currents at high speeds greatly interfere with the application of water to the pavement surface.

Moore and Whitehurst (1970) developed a high-speed skid trailer (ASTM E 274) for Tennessee DOT capable of maintaining a test speed of 80 mph on a level pavement. However, they conducted skid tests at essentially three speeds (speed limit [maximum of 65 mph], 40 mph, and 30 mph). Based on statistical analyses of the resulting data, Moore and Humphreys (1973) concluded that the measurement of skid resistance at high speeds does not add appreciably to the evaluations made at 40 mph. That is, skid numbers at higher speeds can be accurately predicted from SN at 40 mph using readily available mathematical models. They recommended that Tennessee DOT confine skid evaluations to 40 mph. On wet pavements, slide braking and cornering traction coefficients are reduced by increased speed in an approximately linear manner. The required cornering forces to round a corner of fixed radius or the distance needed to bring a vehicle to a stop vary as the square of the vehicle speed. Therefore, Veith (1983) argued that the very strong influence of speed from both viewpoints dictates that high speeds be used for testing *tires;* however, high speeds cause safety problems. He concluded that a testing speed of 60 mph is a reasonable compromise.

During preparation of this synthesis, the authors examined several papers and reports dealing with wet skid resistance measurements on airport runways to determine if high-speed measurements were used for runways. Although some high-speed measurements have been made, runway friction measurements are typically made using methods similar to those used on highway pavements and only at slightly higher speeds. In fact, ASTM E 2100, "Standard Practice for Calculating the International Runway Friction Index," recommends conducting high-speed tests at 60 mph when the surface class allows (ASTM, 2002). TxDOT does not currently perform skid testing on airports (Oshinski, 2003).

Predicting Wet Friction Values

Many researchers agree that pavement surface friction data suitable for pavement inventories can be obtained from calculations made using texture depth (Viner et al., 2000; Lenke and Graul, 1986; Henry, 1986; Yandell et al., 1983; Moore and Humphreys, 1973; Phillips and Kinsey, 2000) or SN at 40 mph (Wambold et al., 1990). Models are available that consider speed, pavement texture and wetting condition, tread rubber properties, and tire condition.

Currently, TxDOT uses skid trailers to annually inventory approximately 50 percent their interstate highway system and 25 percent of all other highways. They are moving toward inventorying 100 percent of their pavements using laser-based texture measurements to predict wet SN at 50 mph. Whenever fully implemented, texture measurements will provide approximately 10 times more data on a given segment of highway than typical skid trailer measurements (Bertrand, 2003).

Hydroplaning

Hydroplaning is the separation of a tire from the road surface by a layer of water. Accidents caused by full dynamic hydroplaning are comparatively rare events (Hayes et al., 1983; Wambold et al., 1986).

Extensive laboratory and field investigations of hydroplaning have been conducted (Horne, 1968; Yager, 1974; Gallaway et al., 1975; Gallaway et al., 1979; Horne, 1998;

Hayes et al., 1983). Balmer and Gallaway (1983) summarized these data to show that applying the following controls can decrease hydroplaning.

1. Provide adequate pavement cross slope.
2. Construct and maintain pavements with a gritty coarse surface texture or finish.
3. Minimize pavement-surface, water-film thickness by effective drainage.
4. Minimize pavement-drainage-path length by roadway design and construction.
5. Provide adequate water removal facilities for sag-vertical curves.
6. Reduce ponding of water in pavement ruts by proper pavement evaluation and maintenance.

One place where adequate pavement cross slope cannot be maintained is at the entrance and exit of left curves on a super-elevated highway. When the cross slope transitions to and from the super elevation in the curve, there will be a flat spot that can allow water to accumulate in dangerously thick films. These are often the locations of skidding or "run-off-the-road" accidents.

Researchers (Horne, 1968; Yager, 1974; Gallaway et al., 1975; Gallaway et al., 1979; Horne, 1998; Gothie et al., 2001) have demonstrated, using different methods, that the typical minimum speed for dynamic hydroplaning of passenger cars is just over 50 mph. Therefore, traveling speed should be limited to 50 mph on wet pavement, particularly where water can accumulate to depths of 0.1 inch or more (Martinez et al., 1972). Hayes et al. (1983) reported that loss of pavement contact could occur between 40 and 45 mph in puddles of about 1-inch maximum depth and about 30 feet in length. For trucks with higher tire inflation pressures and heavier loads, the minimum hydroplaning speed may exceed 60 mph (Horne, 1998).

Page (1993) deduced that, for an economical analysis, the important item to examine is the additional cost per unit area to provide a pavement surface with desirable characteristics and concluded that an open-graded friction course is the only means to reduce high-speed hydroplaning potential.

Recommended Skid Resistance Requirements

Kummer and Meyer (1967) recommended the minimum skid numbers as a function of traffic speed, as shown in Figure 4. These skid numbers should be measured using an ASTM E 274 skid trailer during late summer or fall (when skid numbers are lowest) in or near the center of the most polished wheel track (usually the left wheel track) in the direction of traffic. Preferably, skid tests should be performed at the actual mean traffic speeds to eliminate the uncertainty of selecting speed gradients for projecting the skid numbers from the speed of testing to higher speeds. Figure 4 indicates that recommended minimum skid values above 65 mph are essentially a constant value. A United Kingdom researcher (Roe, 1999) basically supports the findings in Figure 4, stating that friction falls with speed and reaches its lowest value at about 100 km/hr (or 62 mph). Findings by Rizenbergs et al. (1973) support these data (Figure 5).

For speeds above 40 mph, Figure 4 also shows minimum skid values calculated from skid measurements at 40 mph using three different speed gradients (G). According to Kummer and Meyer (1967), with the exception of very smooth surfaces, gradients of 0.2 to 0.8 will bracket all conceivable surface types, the mean gradient being 0.5. When skid numbers measured at 50 mph must be projected to 70 mph or higher, this synthesis recommends testing at two speeds that differ from each other by at least 10 mph, with a lower speed of at least 40 mph, and use available models to estimate the skid number at the desired speed.

The Hong Kong Highways Department stated that, while a texture depth of 0.7 mm is adequate for concrete pavements to ensure high-speed skid resistance, the texture depth required for a bituminous surface must be almost twice as much to ensure the same degree of skid resistance (http://www.hyd.gov.hk/eng/public/publications/road_notes/doc/rn5.doc) (Hong Kong Highways Department, 1983).

Surface Aggregate Classification

No new aggregate classification methods specifically for high-speed thoroughfares were identified in this study. TxDOT is well aware of the latest methods for characterizing and classifying aggregates because they are sponsoring pertinent state-of-the-art research and thus leading the industry in this area of study.

General program information related to surface aggregates may be found in NCHRP Synthesis 263, "State DOT Management Techniques for Materials and Construction Acceptance," (Smith, 1998). This document describes the state of the practice of state DOT management techniques for materials and construction acceptance, including approaches to

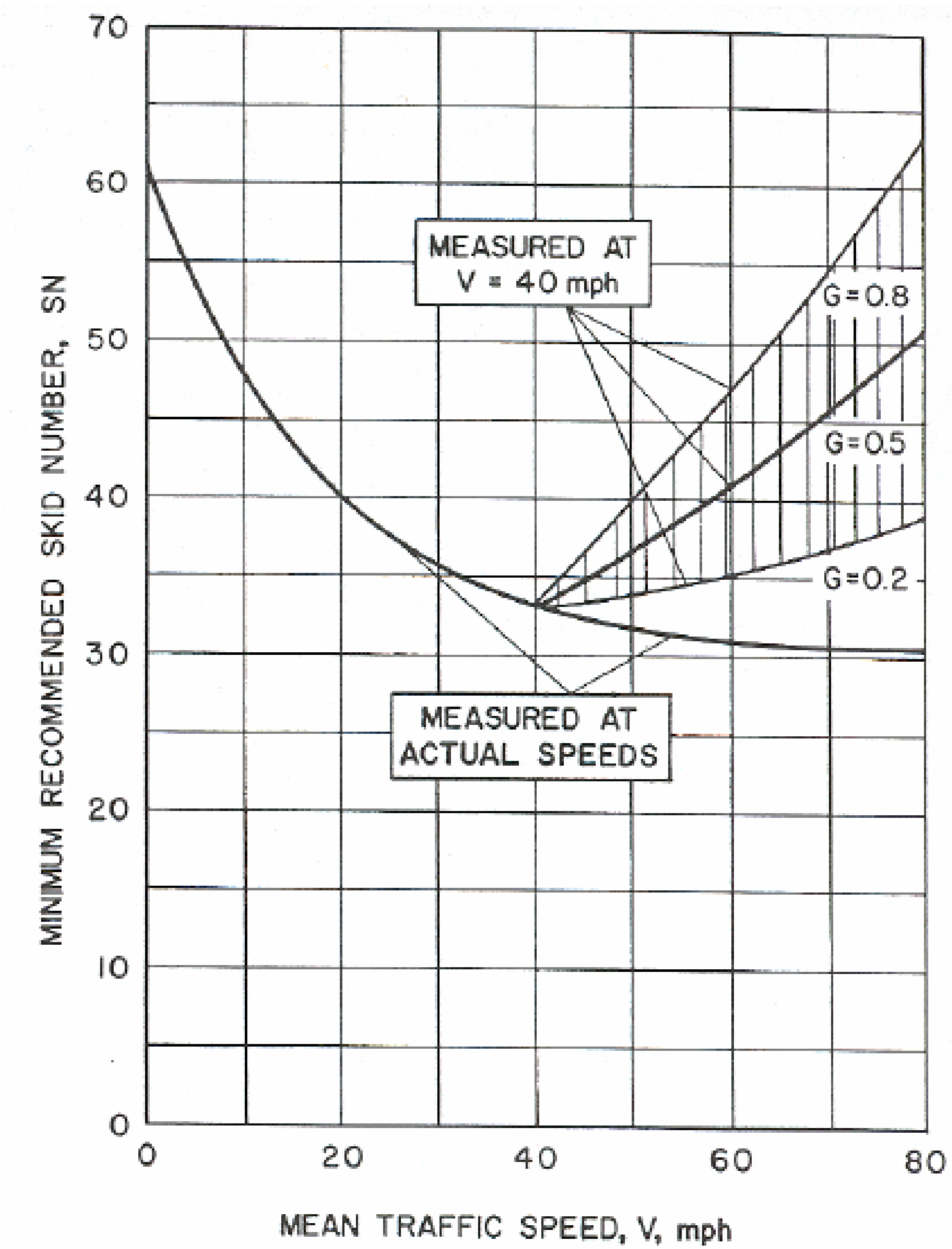

Figure 4. Recommended Minimum Skid Numbers as a function of Traffic Speed (wet skid using ribbed tire) (after Kummer and Meyer, 1967).

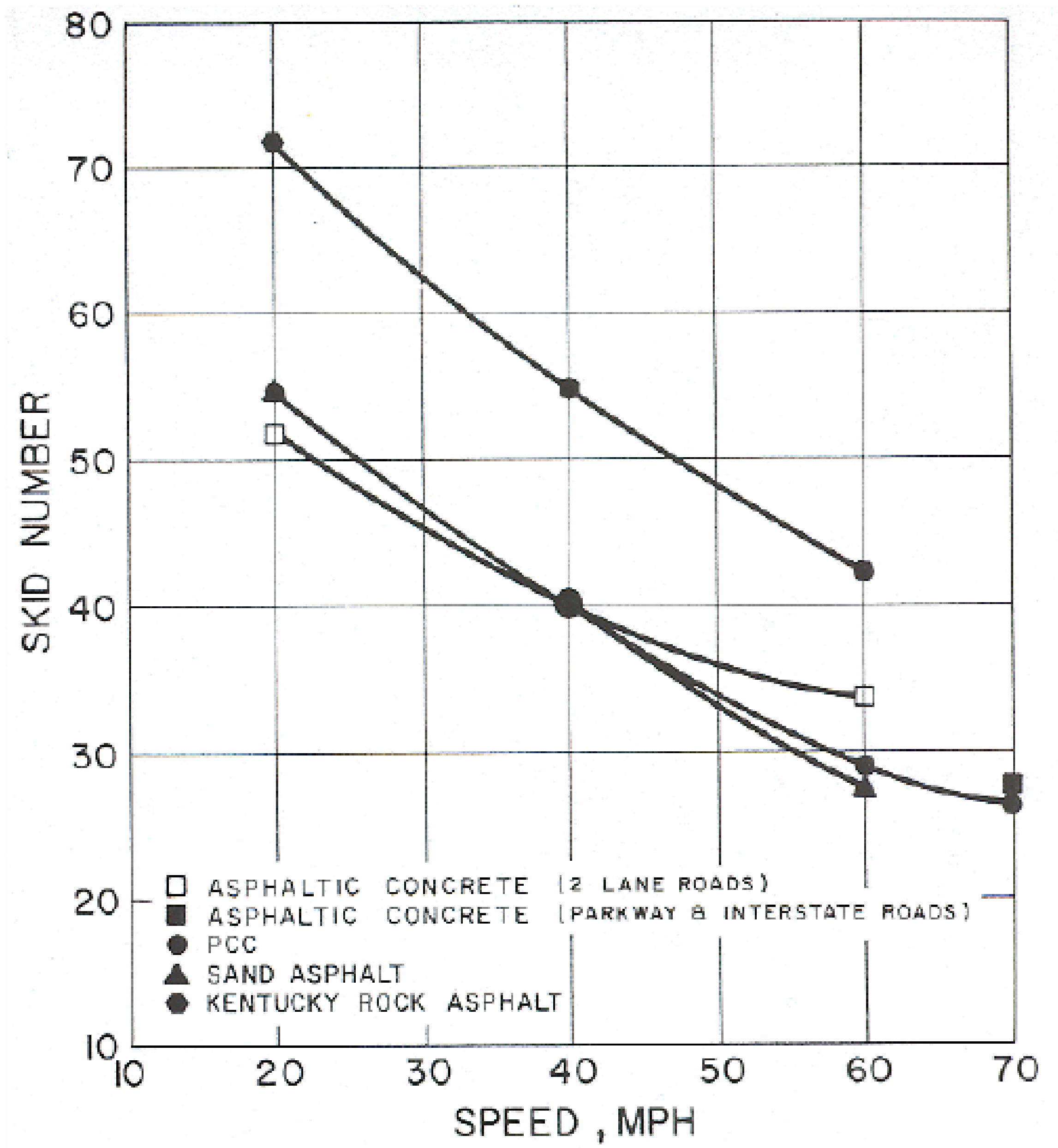

Figure 5. Skid Number Measured at Different Trailer Speeds (wet skid using ribbed tire) (after Rizenbergs et al., 1973).

inspection and testing. The associated requirements for maintaining adequate qualified personnel to operate the acceptance and testing programs are considered in the information reported. The information was collected by surveying state DOTs and by conducting a literature search. It presents background information on the changing role of specifications, quality assurance processes, warranties, material certifications, and personnel management regarding the state of the practice for state DOT management techniques for materials and construction acceptance.

NCHRP Project 4-20C, "Aggregate Tests Related to Performance of Portland Cement Concrete Pavements: State of the Knowledge," provided information on concrete pavement performance parameters and aggregate properties that affect these parameters and identified a set of tests that can be used to assess these properties (NCHRP, 2003). Similar information is available for asphalt pavements in NCHRP Report 405 (Kandhal and Parker, 1998).

Additional pertinent information may be found in research products from ongoing NCHRP Project 9-35, "Aggregate Properties and Their Relationship to the Performance of Superpave-Designed HMA: A Critical Review," which is due to be completed on June 30, 2004. The objective of this project is to conduct a review of the technical literature to identify consensus, source, and other aggregate properties that significantly impact HMA performance.

In 2004, TxDOT will complete a major study of aggregates, Project 0-1707, "Long-Term Research on Bituminous Coarse Aggregate." Early in the study, Little et al. (2001) concluded that there is a need to upgrade TxDOT's existing aggregate quality monitoring program and the aggregate classification system to improve long-term skid resistance.

Potential Solutions Related to Skid Resistance

Kulakowski and Harwood (1990) reported that as little as 0.05 mm of water on a pavement surface can reduce tire-pavement friction by 20 to 30 percent of the dry surface friction and, in special situations, a 0.025-mm water film can reduce friction by 75 percent of the dry surface value. This level of wetness is likely to be exceeded during any hour in which there is at least 0.25 mm of rainfall. Their results also indicated that the effect of a thin water film on tire-pavement friction increases with speed, and it was more pronounced on smooth surfaces than on high-texture surfaces. Based on this observation, they concluded that further limitation of speed on wet roads is the most effective safety measure.

Based on contacts with attorneys by the author, signing to indicate reduced speed limits when roads are wet can reduce the liability of the state for wet weather accidents on state-maintained highways. According to the Highway Research Board (1972), fixed warning signs (e.g., Slippery When Wet) for temporary hazards have low effectiveness; however, slight improvement may be obtained by posting an advisory speed. They suggest that variable signs, which display a warning and/or speed restriction only when the pavement is wet, may be somewhat better.

Adequate pavement texture depth on high-speed corridors is of utmost importance. Balmer and Gallaway (1983) stated that a pavement texture depth of 1.5 mm or greater will improve wet-pavement skid resistance and the cornering slip number, decrease hydroplaning tendencies, reduce splash and spray, and diffuse headlight glare, especially on high-speed highways. Higher texture depths may be accomplished by using coarse HMA surface mixtures (e.g., Type C CMHB, Type C or 19-mm Superpave), seal coats, or open-graded mixtures (e.g., permeable friction course [PFC]). Higher texture on dense-graded mixtures will normally produce higher traffic noise; however, this can be overcome by using a PFC. Balmer and Gallaway (1983) further stated that on portland cement concrete surfaces, transverse finishes or grooves provide better traction as compared to longitudinal grooves. They also indicated that traffic might decrease large texture depths 25 percent or more during the first six months.

Balmer and Gallaway (1983) found that the pavement surface-water layer thickness, which increases hydroplaning and decreases skid resistance, could be minimized by roadway design, construction quality control, and rehabilitation. Thickness of the water layer depends upon the pavement cross slope, texture depth, rainfall intensity, and the pavement surface drainage-path length. The drainage-path length, which should be minimized, is a function of the number of lanes and other roadway geometrics. They suggested that drainage facilities be provided to collect and rapidly remove water from sag-vertical curves to reduce hydroplaning susceptibility and improve traction.

Balmer and Gallaway (1983) concluded that a pavement cross slope of 2.5 percent will facilitate surface drainage, reduce tire hydroplaning, and improve traction during wet weather; yet it is not objectionable for vehicle steering or lane changing.

To maximize wet skid resistance and minimize hydroplaning, highly textured pavement surfaces are desirable. However, high texture usually comes with high noise. PFC provide asphalt pavement surfaces with excellent drainage, adequate texture, and low noise. PFCs produced by TxDOT using asphalt rubber have reportedly exhibited exceptional performance, reducing traffic noise levels by an average of 8 decibels, improving surface friction by more than 200 percent, and significantly improving ride quality (TxDOT, 2003; Kandhal, 2003).

Jackson et al. (2003) made similar observations and found that asphalt rubber (AR) binder demonstrated less reflective cracking than neat asphalt. The hotter, stickier AR may also provide better adhesion to concrete pavements. However, in much the same way that bridges are the first surfaces to ice over, air movement through porous PFC makes it susceptible to icing during wet freezing weather; therefore, climate must be considered when PFC is specified.

Further, Kamplade (1994) claims that porous asphalt surfaces soon experience significant loss of their acoustic efficiency, particularly in urban areas (Isenring, 1990). Alternative thin asphalt surfacing materials such as Novachip (Estakhri and Button, 1995; Fort, 1994), Millom Hitex (Nicholls, 1998), and Axoflex (Nicholls, 1997), UL-M (Parkinson, 1995), and Safepave (Parkinson, 1995) have shown promise in Europe and the U.S. Products similar to Novachip may be suitable for placement in northern climates where wet-freeze cycles might preclude the use of PFC. A seal coat may be suitable for passenger-only roadways, particularly in areas where PFC is not suitable or remote areas where noise is not an issue

Significant research to provide texture (and thus wet weather traction) and reduce noise on portland cement concrete pavements has been conducted. Some of the more promising surfaces include exposed-aggregate concrete (by washing or brushing), use of premium coarse aggregate in the top 1 inch of concrete, and longitudinal texturing using a plastic brush (Litzka, 1994 and Rocci, 1994). Exposed-aggregate concrete has been used on several sections of motorways in Austria. Their developments have solved the problems of initial production, and the surface is providing very good skid resistance with significant reductions in noise (Fuch, 1994 and Stinglhammer and Krenn, 1994). Sommer (1994), also of Austria, concluded that the exposed-aggregate technique is the cheapest way of building rigid pavements with a surface that is skid resistant, noise reducing, and durable. Germany (Kamplade, 1994), the United Kingdom (Franklin et al., 1994), Sweden (Hultqvist, 1994), and The Netherlands (Jurriaans et al., 1994) are also studying exposed-aggregate concrete with relatively small top-size aggregate in the top concrete layer, with promising results regarding friction and noise. In fact, Jones (1999) stated that "whisper concrete," a particular type of exposed-aggregate concrete, is the only rigid-surface option now permitted for all forms of construction on roads, whether high-speed or low-speed, administered by the UK Highways Agency.

Research Needs Related to Skid Resistance

TxDOT and other state DOTs are presently using laser-based systems to measure pavement surface texture and relate the findings to skid resistance. These relatively new technologies offer significant promise for estimating skid resistance at atypical high speeds. According to Bertrand (2003), TxDOT's current laser-based estimated skid number database is based on wet skid values (ASTM E 274) using a smooth tire at 50 mph. If the laser-based system is applied to high-speed corridors, it will be necessary to conduct additional testing (skid vs. texture) at higher speeds to recalibrate the algorithm. Skid testing at speeds much above 50 mph with the current pavement wetting systems may be impractical. Therefore, it may be practical to conduct skid tests at a speed lower than 50 mph and use the skid data at two speeds to predict skid values at the desired high speed. Recall that several researchers found that skid values measured on a given pavement at any speed above about 65 mph are approximately equivalent.

For high-speed corridors, highly textured pavement surface mixtures (e.g., PFC, stone mastic asphalt (SMA), coarse matrix high binder (CMHB), and exposed aggregate concrete) and/or new aggregate specifications requiring increased texture and polishing resistance values may be required to ensure adequate wet skid resistance. Research should examine the suitability of some of the new pavement surfaces, adequacy of current test methods for measuring the physical properties of coarse aggregates, and related aggregate specifications.

To maximize skid resistance of SMA pavement surfaces, the Germans use a process called gritting (in the USA, we would call it sanding) (Schreck, 2004). Skid resistance of SMA or any asphalt pavement is often at its lowest after initial placement, due to the heavy asphalt coating on the exposed aggregate particles. Gritting is the application of a uniform coating of 1-3 mm or 2-5 mm sized aggregate particles over the freshly placed SMA mat in advance of finish rolling. In Germany, most grit is coated hot with about 0.8 percent asphalt binder and stockpiled. The low binder content does not cause clumping, so it can be stockpiled like clean aggregate. Gritting not only enhances skid resistance but also reduces surface permeability and (depending on the color of the sand) can even make the surface white, thus improving night visibility. This promising process appears to deserve further study to optimize its benefits and develop field guidelines.

ISSUES RELATED TO TRAFFIC CHARACTERIZATION

Introduction

Design speeds of 100 mph and actual speeds exceeding 80 mph may be common on the TTC. Truck sizes and weights may also differ significantly from those currently allowed on Texas pavements. What will be the effects of these heavy, high-speed trucks on traffic characterizations needed to enforce legal load limits and/or support design and rehabilitation of pavement structures? As the damage to pavement structures is roughly proportional to the fourth power of wheel loads, highway agencies must detect vehicles with overloaded axles that contribute significantly to the expensive consequences of fatigue in pavements and bridges (Kistler, 2003).

Weigh-in-motion (WIM) is defined in the American Society for Testing and Materials (ASTM) Standard Specification E 1318-00 as "the process of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle." The idea of high-speed WIM systems is to provide continuous unbiased weighing of practically all vehicles passing over a system. They should be imperceptible, which means that truckers are not aware of the weighing operation and thus do not avoid them. Today, there are approximately 1000 working WIM stations around the world: approximately 450 in the United States, 300 in Europe, 150 in Australia, and others in South Africa, South Korea, Israel and a few other countries (http://wim.zag.si/general_WIM/).

According to ORNL (2000), approximately 500,000 carriers on U.S. highways are checked four times each day in the never-ending search for vehicles that are overloaded or otherwise unsafe. The cost to the motor carrier industry and, subsequently, to consumers of these mandated truck stops is estimated to be over $15 million/day! In addition, because weight enforcement activities are slow and cumbersome, weigh stations are often overcrowded. Law enforcement officials often face two choices that, together, can create unsafe conditions. They can allow vehicles to back up in long lines near weigh station entrance ramps. Or, they can let carriers bypass stations without being weighed or inspected.

According to Jacob and O'Brien (2002), the number of vehicles weighed is still far too small for enforcement to have a significant dissuasive effect. Furthermore, these operations are becoming more and more difficult, cumbersome, and expensive. WIM seems to be an ideal means of substantially increasing the number of vehicles checked. However, legal applications require higher accuracy in static weight estimation and a means of dealing with the dynamic interaction between vehicles and infrastructure.

Mamlouk (1996) pointed out that loads applied by trucks along pavements vary instantaneously and differently due to road roughness, truck speed, suspension type, tire pressure, and other factors. Kim et al. (2003) explained that two identical vehicles with the same weight will generate sensor signals that differ in shape and peak value, depending the tire pressure, vehicle speed, road roughness, and sensor characteristics.

Jacob et al. (2000) studied the accuracy of WIM systems. They described the European specification (http://wim.zag.si/reports/specifications/WIM_specs.pdf) for WIM, prepared by the COST-323 management committee. The specification gives an indication of the WIM accuracy that might be achievable from sites with particular characteristics. They provide a comprehensive review of methods for calibrating and testing WIM systems. Accuracy classes are defined on the basis of the width of the confidence interval within which the measured results lie. Confidence interval widths are specified for gross weights and weights of individual axles, among other things. The percentage of test results, which are required to fall within the confidence intervals, is a function of the test conditions and the number of test runs.

Collop et al. (2002) identified three sources of error in WIM measurements: calibration errors, random sensor error, and dynamic load effect. They reported that the effect of sensor/dynamic and calibration errors is likely to over-predict the loads by typically between 15 and 20 percent, which would result in a 5-mm to 15-mm over-design of pavement thickness for typical flexible pavement structures.

Important Recent Findings on Traffic Characterization

Skszek (2001) stated that, as safety, cost, increased traffic flow, complex road geometrics, and traffic disruption have become issues of concern, traffic counting professionals are looking more closely at alternatives to traditional methods of data collection. Such non-traditional traffic counting devices as video image detection, Doppler microwave, passive magnetic, passive acoustic, active and passive infrared, and active and passive ultrasonic are being considered due to their non-intrusive nature. Her report addresses information on available technology including cost, installation requirements, technical specifications, data retrieval, and limitations of the products. Her literature review indicated "little in the way of new technology."

ODOT (1998) described an operational test by the Oregon Department of Transportation of the Port-of-entry Advanced Sorting System (PASS), which uses a two-way communication automatic vehicle identification system integrated with WIM, automatic vehicle classification, and over-height detection tied into a heavy vehicle database. The purpose of this operational test was to demonstrate the feasibility of using this system to let trucks directly bypass the port and the static scale weighing process, thus resulting in significant benefits for both the carriers and the State. An additional purpose was to test the use of "double-threshold" bending plate type WIM scales to improve the weighing accuracy as compared to single WIM scales. Some problems with PASS caused interruptions. Most were software problems, which were resolved.

A survey indicated that truckers and trucking firms using the two-way transponders were pleased with the system. The project proved that the mainline sorting of heavy vehicles to bypass or enter a port-of-entry is workable with current technology. The variability of weight measurements using the double-threshold WIM scales was found to be less than the variability of measurements from the twin WIM scales when taken separately. Unfortunately, the weights provided by the WIM scales appeared to be biased toward the mean in spite of careful calibration. The complex dynamic forces at work on moving heavy vehicles require more study, and the new sensor-based WIM technologies may soon exceed the accuracy and precision goals of the PASS double-threshold bending-plate system at reduced cost.

Benekohal and Girianna (2003) conducted a national survey of all state DOTs on technologies used for truck classification and methodologies used for estimating truck vehicle miles travelled (VMT). DOTs use different procedures to classify trucks, to adjust truck data from short-term counts, and to calculate truck VMT. To classify trucks, the majority of state DOTs followed the FHWA F-13 scheme. The products from two manufacturers, Peek Traffic and Diamond Traffic Products with a variety of sensors, dominated the classification devices used by state DOTs. The duration and the number of truck classification counts (machine or manually) varied by state DOTs. With machine classifiers, state DOTs collected short-term (less and 24-hour as well as 48-hour counts) and continuous truck data for a variety of their highway coverage. Truck data were collected using machine classifiers unless certain conditions, such as congested highways, would demand collecting the data manually. To adjust truck data from short-term classification counts, most state DOTs developed their adjustment factors from continuous volume counts (not truck counts) and used them for adjusting truck volumes. Some state DOTs used adjustment factors for trucks that are different from those for cars.

Gonzalez et al. (2003) analyzed the performance of a multi-layer feed-forward artificial neural network algorithm applied to a multiple-sensor WIM. Unlike conventional WIM calibration algorithms, neural networks have the ability to identify underlying relationships, such as the spatial repeatability in axle dynamics, and they can efficiently remove noise and adapt to changing circumstances (e.g., traffic characteristics, road profile, or even sensor failure). Numerical simulations of the axle forces applied on a smooth road profile are used to train, validate, and test the artificial neural network algorithm. The artificial neural networks approach resulted in higher accuracy than the traditional average-based calibration method, particularly at high noise levels.

Piezoelectric Sensors. In a HITEC (Highway Innovative Technology Evaluation Center) activity, Alavi et al. (2001) evaluated piezoelectric sensors for collecting WIM data under controlled laboratory and field-loading conditions in both asphalt concrete (AC) and PCC pavements. The AC installation was performed at the WesTrack test facility near Reno, Nevada, and the PCC installation was performed at a CalTrans Heavy Vehicle Simulator test site. They conducted a compatibility study of the response of the WIM sensors with different data acquisition systems for the AC pavements. Various types of grouts were studied in the WIM installation process. Their results indicated that WIM sensor performance was most dependent on the ability of the data acquisition systems to process the raw sensor output accurately.

Quartz Sensors. According to their brochure (Kistler, 2003), the Lineas WIM by Kistler, which uses a quartz-sensing element, has been successfully used for WIM in Europe, the USA, and several other countries. It shows excellent stability of electrical and mechanical characteristics, exhibits no aging effects, is essentially insensitive to temperature changes, and accurately measures a wide range of vehicle weights.

Fiber Optic Sensors. Another technology that has received significant attention (but may not yet be as marketable as quartz systems) is fiber optic sensors for WIM. Florida DOT has sponsored most of the applied research on this system. Cosentino and Grossman (1996) reported that a rugged, reliable fiber optic sensor-based traffic classification system has been developed and successfully deployed in three locations in Florida. The fiber optic traffic sensors (FOTS) are immune to electromagnetic interference and do not provide a metallic conductive path to the electronic interface (this minimized the probability of lightning damage). Data from two field sites demonstrated accurate counts of vehicle axles and vehicle classifications. More than 250,000 axles were counted within one month after installation, and the devices gave results similar to those from piezoelectric loop traffic classifiers.

Cosentino et al. (2003) conducted a series of linear-elastic plane-strain finite element analyses on a FOTS that could potentially be used for traffic classification and WIM. These sensors performed well in a pavement when placed in 6-foot long narrow vertical grooves. Their objective was to determine how the sensor functions in this configuration. Results from three finite element models were correlated to laboratory and field results showing that, as tires load the pavement around it, the pavement groove closes, thereby squeezing the sensor. As the FOTS deforms, the intensity of the light passing through the fiber decreases, allowing roadside computer systems to use this intensity for vehicle classification or WIM. Comparison of predicted to measured pavement deflections agreed to within 5 or 6 percent, indicating the model was properly formulated. Results for both passenger car and high-pressure truck tires were encouraging, implying that the linear-elastic approach was suitable for typical applied pressures. They concluded that these FOTS are ready for implementation into traffic classification systems.

Udd and Kunzler (2003) found that a prototype sensor using the fiber Braggs gratings (FBG) technology was feasible for use in monitoring light and heavy traffic. They indicated that, with modification, the FBG strain sensor has potential for long lasting, cost-effective applications for WIM. The system is sensitive enough to detect adjacent lane traffic, opening possibilities of shoulder area monitoring for less traffic disruption and increased safety. With two sensors, the system can capture speed as well as weight of both sides of a vehicle.

Schulz et al. (1999) studied fiber optic sensors to monitor the strain state in structures. This monitoring assesses the health of the structure and provides useful data for traffic monitoring/control applications. They are working with Oregon DOT to develop a fiber optic based traffic detection sensor compatible with existing signal controller, classifier, and counter equipment. This system is expected to be less intrusive, more sensitive, more accurate, and more robust than conventional traffic loops.

Effects of Winter Weather. The Belgium Road Research Center (Jehaes, 1999) examined the effects of temperature and salt on different types of sensors, their calibration, temperature compensation, and the static weighing procedure. In one location, she found that the system lost accuracy during winter and spring but regained it during the summer; whereas, in another location, the systems yielded consistent results throughout the year. Two and three axle buses were measured far more accurately than two/three axle trucks. (This is likely due to the stiffer suspensions and heavier axle loads on loaded trucks.) Road surface condition and static behavior of the WIM can change during the year and with time and affect the calibration. The presence of snow makes the road surface uneven and causes vehicles to drive in a different transverse position. The presence of sand and snow on the static weighing area and frozen scales must be considered.

Sensor Selection Guidelines. Martin and Feng (2003) developed a systematic method to guide professionals in selecting detector technologies. The system leads buyers through a series of steps that prevents them from overlooking significant issues regarding any given detector.

WIM data collection devices collect both truck volume and load spectra; however, WIM devices are significantly more costly to purchase, install, operate, and maintain than equipment that only counts and classifies vehicles. Typically, highway agencies use a combination of devices to meet their traffic data collection needs. Their repertoire may include both permanent and portable, WIM and classification devices. Further, different technologies have different strengths and weaknesses, may work better in certain environmental conditions, or provide less accuracy but longer service life under harsh conditions. Therefore, one must make tradeoffs.

According to Hallenbeck and Weinblatt (2004), the required areas of knowledge and necessary decisions and/or actions to make these tradeoffs correctly include the following:

- understanding the equipment's capabilities and limitations;
- understanding the data collection characteristics of the site;
- choosing locations that optimize the opportunity for collecting accurate data;
- selecting equipment for each site that can operate effectively in the traffic and environmental conditions present;
- understanding how data collected from two different devices relate to each other (i.e., are the vehicle classes collected by two different classifiers the same, and if not, how do those classes relate to each other?);
- installing the equipment correctly;
- understanding how to test the equipment once it is in place to ensure that it is operating as intended and ensuring that these procedures are followed;
- calibrating the installed equipment properly;
- understanding preventive and corrective overall site maintenance;
- performing quality control checks on the data produced by the devices; and
- repairing, re-calibrating, or otherwise adjusting the equipment and site conditions if quality assurance checks indicate problems.

Hallenbeck and Weinblatt (2004) further stated that, while the choice of sensor technology can affect the accuracy of the data collected as well as the cost and longevity of the data collection installation, a wide body of research shows that technology is only one of many factors that affect reliability of data collected. In fact, FHWA (1997) concluded that the differences between devices from different manufacturers were more significant than differences between technologies and, further, that it is more important to select a well-designed and highly reliable product than to narrow a selection to a particular technology.

Sources of Current WIM Information Online

A wealth of state-of-the-practice information on traffic characterization devices can be found online. In 2004, NCHRP produced Report 509, "Equipment for Collecting Traffic Load Data" (Hallenbeck and Weinblatt, 2004). This report is a valuable and current resource for those responsible for specifying, installing, operating, and maintaining traffic characterization devices. Three tables in the report compare the different technologies available for (1) short-term vehicle classification equipment, (2) permanent vehicle classification equipment, and (3) WIM equipment. This written report is readily available to TxDOT personnel, or it may be accessed at http://gulliver.trb.org/publications/nchrp/nchrp_rpt_509.pdf.

The single most valuable document related to the items addressed in this synthesis may be "A Summary of Vehicle Detection and Surveillance Technologies used in Intelligent Transportation Systems" (Vehicle Detector Clearinghouse, 2003), the latest version of which can be found at (http://www.nmsu.edu/~traffic/Publications/VC/vdst.pdf). This almost 300-page booklet addresses over-roadway sensors, sensor technology comparisons, and their relative costs.

FHWA Demonstration Project 121 on WIM technology is located at http://www.ornl.gov/info/ornlreview/v33_3_00/weigh.htm and is maintained by Oak Ridge National Laboratory (ORNL). They maintain that commercial high-speed WIM systems are only 80 to 94 percent accurate and that this is not sufficient for law enforcement; therefore, the use of static scales is typically required at truck weigh stations. ORNL is addressing WIM-related issues using the latest technology. They are now developing a "weight enforcement on the fly" technology that they believe will weigh trucks much more accurately at high speeds. At their website, ORNL (2000) claims an error rate of less than 1 percent. When used with a license plate reader and wireless technology, this system could electronically identify and ticket overweight trucks passing by without making them stop at weigh stations.

The Long-Term Pavement Performance (LTPP) program is investigating verification of scale performance, pavement smoothness requirements, model WIM system specifications (including accuracy requirements and construction guidelines), and data collection processing (http://www.tfhrc.gov/focus/mar02/pilot.htm). FHWA (2002) indicated that the quality of the WIM data is highly dependent upon the pavement in which the system is installed, as smoother pavements provide more accurate and less variable measurements. The five pilot studies, held in Arizona, Florida, Maryland, Michigan, and Texas, demonstrated that the protocols were essentially correct as written. The equipment performance specifications in the protocols were shown to be achievable with current practice and technology, and the recommended field practices, including speed, temperature, and vehicle condition, were validated. It was noted, however, that the smoothness specification was too restrictive for actual field conditions, and it is now being revised.

This LTPP study led to NCHRP Project 20-51(3), "LTPP Product Development: Pavement Smoothness Specification for Approaches to WIM Equipment Sites," which is being conducted by FHWA. Current ASTM WIM smoothness specifications require closure of the traffic lanes. This project will use high-speed profile equipment measurements to determine acceptable ranges of smoothness that are essentially equivalent to the ASTM method. The proposed specification is an enhancement to the FHWA "States' Successful Practices Weigh-In-Motion Handbook" (McCall and Vodrazka, 1997) and the ASTM specification. The project will include a review and consideration of new technologies and measurement devices outside of the LTPP program. Highway agencies are investing increasing sums in WIM equipment to provide needed information. Existing smoothness specifications are difficult to implement. Lack of smoothness creates difficulties in calibrating equipment and is thought to be a leading cause of poor performance of WIM equipment. Decreasing smoothness may be a contributing factor to scale drift and increasing variability of load data. The guideline would provide states with a specification for use when installing equipment and reduce calibration check time. A description of the project is located online at http://www4.trb.org/trb/crp.nsf/0/f47c88550b8f4675852569c9006fb523?OpenDocument.

FHWA's "States' Successful Practices Weigh-In-Motion Handbook" (McCall and Vodrazka, 1997) is available online at http://ntl.bts.gov/data/wim.pdf. The purpose of the handbook is to provide practical advice for users of WIM technology and discuss pertinent systems, sites, and successful practices by other state DOTs. The handbook suggests the following guiding principles:

- Decide on the "site design life" and accuracy necessary to support the end user.
- Budget the resources necessary to support the selected "site design life" and accuracy requirements.
- Develop and maintain a thorough quality assurance program.
- Purchase the WIM equipment with a warranty.
- Manage the equipment installation.
- Conduct preventive and corrective maintenance on the site.

The National Transportation Research Center (NTRC) at Knoxville, Tennessee, (http://www.ntrc.gov/labs/photonics.shtml) designed an advanced high-speed WIM system and installed and tested it on I-75/I-40 near the Knox County, Tennessee, heavy-vehicle weighing station. The center is testing state-of-the-art technology to evaluate remote sensing of WIM and other traffic characterizations.

The Vehicle Detector Clearinghouse (VDC) at New Mexico State University (http://www.nmsu.edu/~traffic/) provides independent, impartial information on evaluations of new devices and technologies. They provide information to transportation agencies on the capabilities of commercially available vehicle detectors by gathering, organizing, and sharing information from research agencies concerning tests and test procedures. Equipment types included in the VDC database are devices that detect vehicle presence, speed, axles, classification automatic vehicle classifiers (AVC), and weight (WIM). The clearinghouse is designed to be a catalyst for developing standard test protocols. This could provide useful information to TxDOT during future development of related standards.

Researchers at the Minnesota test road (MnRoad, 2003) are collecting dynamic weight per vehicle axle using WIM devices. Nineteen data collection locations use vehicle classifiers (Piezo) in conjunction with automated data recording loops to provide vehicle class data. The loop detects vehicle presence and turns the piezo on/off to determine vehicle speed and length. A quartz piezoelectric WIM system was installed in 2000 about 1.5 miles upstream of a single load cell WIM system that had been in place since 1989.

The Minnesota Guidestar Non-Intrusive Traffic Detection Tests are described at http://www.dot.state.mn.us/guidestar/projects/nitd.html. Their original goal was to provide traffic data collection practitioners with useful information on performance of various non-intrusive traffic detection, counting, speed measuring, and classification technologies. The devices were considered non-intrusive if they could be installed, calibrated, and maintained without closing traffic lanes. Objectives of the research were to develop standardized evaluation and reporting procedures and conduct extensive field tests of non-intrusive technologies for use in a variety of applications. The project examined the traffic data collection capabilities of each device, the application to intelligent transportation systems (ITS), and traffic control purposes. Engineers evaluated devices in a variety of environmental and traffic conditions at both intersection and freeway test sites. The performance in various overhead and side mounting locations was examined. In addition to vehicular traffic detection, the detection of bicycles, pedestrians, and trains were considered.

The WIM of Axles and Vehicles for Europe (WAVE) project is described at http://wim.zag.si/wave/. WAVE indicates it is essential for road authorities to have at their disposal up-to-date and online measurements of axle and vehicle weights in order to:

- improve knowledge of the traffic (economic surveys, statistics, management);
- establish a technical basis for pavement design and maintenance;
- support legislation relating to road safety and fair competition in transport, leading to harmonization of enforcement across Europe; and
- provide to government authorities the information necessary for a harmonized tax system.

For legal purposes, static weigh stations are used at present, but the procedure is expensive and ineffective. It is the objective of this $1.8 million project to achieve a significant step forward for those responsible for road networks. It is of particular concern that heavy trucks are destructive to bridges and pavements and that a significant number of trucks are illegally overloaded. The WAVE project involves 11 partners and associate partners from a total of 10 European countries. The group includes research institutes and universities to assure the highest scientific standards, private industry for development and commercial exploitation, and transportation authorities to assure an end-result geared toward the needs of the users. Most of the partners are members of the COST-323 action in progress (i.e., WIM-LOAD) who organized, the first European conference on weigh-in-motion of road vehicles in March 1995. WAVE claims the partnership is well abreast of the latest developments in WIM techniques. Their executive summary is given at http://wim.zag.si/wave/.

Finally, a worldwide source of current information is the International WIM Users' Network (http://wim.zag.si/network.htm#top). At this writing, this organization has 234 members representing 42 countries and many different organizations. Members include users, producers, researchers, and consultants. The network administrator is Bernard Jacob of the LCPC in France.

Ongoing WIM Studies

AASHTO concluded that research is needed to develop guidelines for traffic data collection and forecasting to ensure state highway agencies' readiness for implementation of the 200X Design Guide. Therefore, NCHRP Project 1-39, "Traffic Data Collection, Analysis, and Forecasting for Mechanistic Pavement Design," was established and is due for completion in the summer of 2004. The objectives of this half-million dollar study are to (1) develop guidelines for collecting and forecasting traffic data to formulate load spectra for use in procedures proposed in the 200X Design Guide and (2) provide guidance on selecting, installing, and operating traffic data collection equipment and handling traffic data.

Al-Qadi (2004) indicated that the controlled traffic capabilities of the Virginia Smart Road allow testing to be conducted without the influence of public traffic and make this facility ideal to evaluate WIM systems. The facility permits testing using various simulated traffic loads, some of which would not be permitted on public highways. A fiber optic network provides transmission of digital data originating from on-site data acquisition systems and provides real-time monitoring capabilities. The Oy Omni Weight Control Ltd. Safe Load System™ WIM Dynamic Scale (OWC scale) is being evaluated. This system was chosen because it offers many unique characteristics aimed to reduce some of the common problems with existing WIM systems.

The design and construction of the OWC scale and its supporting software are thought to address the limitations associated with traditional WIM technologies. Among the advances made by the OWC scale are that the system is completely sealed from the environment; it is a multiple-sensor WIM system; it can be used in varying geometric conditions, and it is designed to be accurate for high-speed traffic. On the exterior of the top of the scale is a steel grid whose purpose is to interlock with the HMA during installation. On the underside of the top of the scale are four temperature sensors. The weighing element is attached to its concrete base by welding it to exposed reinforcing steel.

While the idea of a multiple-sensor WIM is not new (Mamlouk, 1996), the OWC scale and its software have advanced the technology by allowing trucks to pass over the scale at highway speeds with expected accurate readings. This is ostensibly accomplished using an array of 20 sensors installed in the scale and a neurological computer software system that constantly calibrates the scale. Only 10 sensors are functioning at any time, while the remaining sensors are spares. If for any reason a sensor malfunctions, one of the remaining sensors is actuated, which provides increased reliability. The high-speed accuracy that is offered by the scale's manufacturer promises to reduce the delay incurred by truckers at weigh stations. Results of this work should be published in 2004.

New Mexico State University is investigating emerging technologies to establish criteria for evaluating state-of-the-art fiber optic sensors to collect traffic data and measure actual dynamic loading of pavements and structures. For more information, see http://rip.trb.org/browse/dproject.asp?n=7367.

Potential Solutions Related to Traffic Characterization

Speeds above 75 mph will have a negative impact on current WIM scale accuracy, and the WIM errors will increase as speed increases. The most common way to mitigate some of these effects is by increasing the smoothness of the pavement before and after the WIM scale. Typically, a single load cell WIM can still achieve the accuracy required by ASTM E 1318 for a Type III in-motion scale with speeds as high as 75 mph. With proper preparation of the pavement surface, including grinding smooth the approach and departure slabs around the WIM, good performance is possible.

The best way to maximize accuracy is to provide a length of smooth pavement in front of the scales equal to a distance of 2 seconds travel time and 1 second after the scales. At 100 mph, smooth pavement to meet the ASTM E 1318 specification must be provided for distances of 300 feet ahead of and 150 feet after the WIM system. This approach will equate to an accuracy level in line with the ASTM Type III category.

Capacity of the WIM scales is the second consideration. As an example of the most accurate WIM scale, the International Road Dynamics, Inc. (IRD) Single Load Cell WIM scales have a working capacity of 35,000 lbs per axle and a maximum capacity of 55,000 lb per scale. IRD advertises a 10 to 100 mph speed of operation (http://www2.irdinc.com/irdwebapp/system/info/datacol_cvo/slc.asp?system=datacol). The axle configuration, spacing, and loading of trucks that might use the TTC are unknown, but researchers anticipate that additional axles will accompany the heavier gross vehicle weights being considered.

An example of a vehicle that is being used in Canada is a 135,000-lb GVW B-Train using 8 axles (12,500 lb steering and 17,500 lb singles). A vehicle that was proposed a few years ago was the so-called "Turner Double," which would have used slightly longer double trailers than the current Western Doubles, but would have utilized tandem axles where the current doubles use single axles – spreading the load applied to the highway infrastructure. Its gross vehicle weight was increased, but the weight of individual axles was decreased. If the axles are actually heavier, the negative effect on WIM is on the fatigue life of the scale. So, instead of lasting 10 or more years (in the case of the IRD Load Cell), they may only last seven or eight years. But, if the axle weights are lower, then the durability will likely remain similar to what it is with current loads.

Research Needs Related to Traffic Characterization

This search for information on new traffic characterization devices suitable for use on the TTC did not reveal any emerging technology or equipment that was not previously known. Therefore, it appears that those devices to be used on the TTC will be similar to those that are currently available. So the question remains, what will be the effects of heavy, high-speed trucks on traffic characterization devices to be placed on the TTC? A research project is needed to address these issues. It may be possible to perform the research (or a portion thereof) as a laboratory study using fatigue-type loads on certain WIMs. A more realistic field study of heavy, high-speed trucks on WIMs will be very expensive and time consuming. Since this is a national, and even an international issue, it may be possible and will certainly be efficient to conduct this research as a national (NCHRP) or a pooled-fund study.

Typically, laboratory testing can be accelerated to examine long-term effects. Cosentino and Grossman (1996) suggested that better laboratory testing procedures for WIM devices are needed. Researchers should incorporate tests in their experimental designs that will yield classical engineering properties such as stress-strain response, elastic moduli, ultimate compressive strength, and tensile strength. Sinusoidal vibration should be used to study long-term sensor degradation characteristics. Environmental testing of a variety of sensors and sensor materials should be performed to determine the most suitable materials for a variety of climates.

Because of the potential capabilities of the FBG traffic sensors for WIM, Udd and Kunzler (2003) suggested further investigation of this leading-edge technology. Work may include improving the second-generation fiber grating strain sensors and packaging it to analyze capabilities for WIM by studying same-vehicle repeatability, vehicle calibration, and axle response/stability. A further effort with interface requirement should also occur, as an optimal interface for retrofitting with existing equipment would be hardware-convertible and not require the use of a computer. They should be characterized to determine any position-dependent effects related to tires crossing over the sensor. Further studies should include optimal installation depth, speed-related effects, and materials and procedures for installation.

There is research potential related to commercial vehicle weight and other enforcement along the TTC. Access points will probably be spaced much farther apart than existing rural interstate highways. WIM will undoubtedly continue to serve as a screening mechanism to identify overweight vehicles, but there will still need to be means of verifying axle and gross weights using static scales. The research would determine the optimum uses of WIM and static scales along with related technologies that could be used in scale bypass today such as automatic vehicle identification (AVI) tags. Investigation of other high-tech means of expediting safety inspections or related aspects of enforcement might also be included.

The Kistler Lineas piezo-quartz sensors might also be included in high-speed tests, either in a laboratory setting or in a controlled environment where trucks could exceed "normal" speeds. Research Project 0-4664, "Develop and Implement Traffic Monitoring Equipment Evaluation Facility," will conduct limited tests of the sensors for WIM at two locations in central Texas, but other supplemental tests should follow.

SMART PAVEMENTS FOR HIGH-SPEED CORRIDORS

Introduction

The condition of pavement structures is typically assessed by visual inspection and limited nondestructive testing. This is accomplished by site investigations and usually requires expensive, disruptive, and dangerous lane closures. Technology has moved to a point where reliable, durable sensors are available at a reasonable cost to monitor certain pavement and bridge conditions (e.g., pavement temperature and moisture content, dew point, stress, strain, deflection, and fracture) in real time and automatically transmit the sensor readings to a central management location. Researchers have developed micro-fabricated sensors for measuring position, acceleration, pressure, force, torque, flow, magnetic field, temperature, gas composition, humidity, and biological gas/liquid molecular concentration (Mehregany, 1993). This technology has been termed by some as "structural health monitoring" (Fuhr and Huston, 1998; Chong et al., 2003).

Additionally, non-pavement related highway environment measurements, such as wind speed/direction, relative humidity, visibility, and traffic congestion level, are accessible. Some of these are now in use in various state DOT Roadway Weather Information Systems (RWIS). Environmental data (pavement temperature/moisture) have been used to assess the potential for hazardous driving conditions due to icing or to detect weak and structurally unsound pavement or bridge structures. RWIS can be used in conjunction with changeable message signs to automatically provide warnings or adjust the speed limit.

Smart materials studies are being conducted around the U.S. very few of these are addressing pavements. In the colder regions of the U.S. and Canada, instruments are being used to monitor spring thaw conditions and to advise highway agencies of when to place and remove spring-loading restrictions. Perhaps the most relevant project is the Smart Road project being conducted by the Virginia DOT, where repeatability and durability of a whole range of sensors is being evaluated. This project will be discussed in some detail.

Infrastructure maintenance is undertaken based on the perceived "health" of the infrastructure, which is derived from information gathered regarding certain performance indicators. The need to collect data reflective of the true state of health of the infrastructure is therefore crucial for efficient management of the system. Condition-based or on-demand maintenance are gaining recognition due to the superior advantage they afford. Micro sensors can be embedded unobtrusively and inconspicuously in structures to monitor parameters critical to the safe operation and performance (Attoh-Okine and Mensah, 2002).

Note that most of the items referenced in this section of the synthesis are less than five years old. These describe the state of the practice. Additional information on smart systems for highways, bridges, and structures can be found at (http://www.spie.org/web/meetings/programs/ss98/3325.html).

The Virginia Smart Road

The Smart Road (www.vtti.vt.edu) in southwest Virginia is a unique, state-of-the-art, full-scale research facility for pavement research and evaluation of intelligent transportation systems concepts and products. The construction of the project has been made possible through a cooperative effort of several federal and state organizations, including Virginia's Center for Innovative Technology, Virginia Department of Transportation (VDOT), the Virginia Transportation Research Council (VTRC), the Federal Highway Administration, and Virginia Tech. The Smart Road is the first facility of its kind to be built from the ground up, with its infrastructure incorporated into the public roadway, and will surely produce valuable research products.

The Smart Road is currently a 2.2-mile, two-lane road with a banked turn-around at one end and a slower speed turn-around at the other end. The latest phase of construction was completed in May 2001 and includes a 2000-foot bridge and several thousand feet of concrete pavement. When completed, it will be a 6-mile connector highway between Blacksburg and IH-81 in southwest Virginia, with the first 2 miles designated as a controlled test facility. After construction, provisions will be made to route traffic around controlled test zones on the Smart Road to facilitate testing.

Roadway infrastructure research is focused on the performance, maintenance, and life cycle of pavement and bridges. Specific infrastructure research concerns are:

- in-pavement sensors that provide data regarding pavement performance under real loading conditions;

- monitoring pavement health and performance by measuring strains, stresses, deflections, moisture, and temperature on the heavily instrumented Smart Road;
- measuring pavement response to vehicular and environmental loading;
- measuring pavement thickness and performance using ground penetrating radar; developing and evaluating materials in the laboratory;
- assessing concrete technology in the laboratory;
- evaluating and developing new techniques to increase the efficiency and effectiveness of snow and ice control operations on public roads; and
- assessing the impact of vehicle weight, tire sizes, materials, and pressures on pavement damage.

Four miles of magnetic tape were installed to track vehicle location and serve as the infrastructure portion of an in-vehicle position information system. Two configurations have been installed, one in the center of a lane and one along the shoulder. The facility is capable of producing multiple intensities of rain (up to 2 in/hr), snow (up to 4 in/hr), and a fog-like-mist over a one-half-mile stretch of roadway. In addition, water can be sprayed onto freezing pavement to create icy conditions. A highway lighting test bed allows for evaluating different types of lighting systems at spacings of 40, 60, or 80 meters and different heights. This allows a multitude of visibility conditions to be created, on-demand, for testing purposes. A specially designed intersection will be useful for a variety of projects including design, signals, controllers, and driver reactions.

A complete video surveillance system, consisting of several permanently mounted, low-light color cameras and additional portable cameras, can be used to monitor or record activities to support roadway research. A visibility sensor and three weather stations provide data for operational conditions during studies of human reactions. Available data includes temperature, humidity, wind speed, wind direction, and visibility measured in miles. An underground conduit network with manhole access every 200 feet houses a fiber optic data network and interfaces with several on-site data acquisition systems via wireless communications. The facility has a complement of road weather information system sensors connected to the data network. The roadway is marked with UV-sensitive pavement markers and striping to study fixed roadway lighting.

One road section alongside the Smart Road, which will have no arch in the middle and will be as flat longitudinally as possible, will provide for research on wet visibility.

Movable pavement markings will be used to study driver response during wet-weather conditions.

With the vast testing capabilities of this state-of-the-art research facility, there was no mention of smart materials, extraordinary sensors, or new analysis techniques being incorporated into any pavement layers. Others, such as MnRoad (Baker and Buth, 1994), are conducting similar research projects.

According to Elseifi et al. (2001), advancing electromagnetic techniques permit measuring and monitoring moisture content in pavement systems. Two pavement sections were instrumented and constructed to quantify the effectiveness of an impermeable geocomposite membrane as a moisture barrier and as a strain energy absorber. All layers were instrumented to measure stress, strain, temperature, frost, and moisture. Moisture variations in the subbase layer under different precipitation rates were continuously monitored using time domain reflectometry (TDR). Ground penetrating radar was used periodically to monitor water movement in the pavement sections. Results indicated that use of the membrane underneath a drainage layer prevented saturation of underlying layers even in heavy rain and facilitated lateral drainage.

Smart Pavement Research

According to Attoh-Okine and Mensah (2002), researchers from diverse disciplines, especially electrical, computer, and mechanical engineering, have combined efforts to develop sensing technologies and nanotechnology in infrastructure condition assessment (Ansari, 1997), crack detection (Rossi and LeMaou, 1989), and construction monitoring (Fuhr et al., 1992). Some examples include embedded fiber optic sensors for detection of faults and cracks, resistivity and dielectric probes for monitoring moisture contents, piezoelectric stress/strain sensors, and of course, stress/strain gauges and thermocouples. Micro-electro-mechanical systems (MEMS) involve the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro-fabrication technology. Attoh-Okine and Mensah (2002) pointed out that application of MEMS has not reached its full potential in civil infrastructures.

The Virginia Transportation Research Council is conducting a study at the Smart Road to determine the material properties of paving concrete, to instrument the concrete pavement for strain and temperature resulting from environmental effects, to monitor the construction practices during paving operations, and to monitor the performance of the pavement over a period of five years (http://rip.trb.org/browse/dproject.asp?n=4380). The contact is N.J. Garber (804/293-1908).

The Center for Intelligent Materials Systems and Structures at Virginia Tech is developing wireless sensors that use the energy transmitted from vehicles to a bridge surface to power active sensors for damage detection (Personal communication with Dr. Dan Inman, 2004). These, however, are still in the research phase and have not been used in service.

The Federal Highway Administration is developing a smart sensor system. They will test it in both the laboratory and field on components of highway bridges to prove the systems' ability to detect and monitor early signs of distress (http://rip.trb.org/browse/dproject.asp?n=692). The contact is A. Lopez (202/202-2222).

Fiber reinforced polymer (FRP) has advantages such as high strength/low weight ratio and corrosion resistance that makes it a good candidate for use in bridge construction and retrofits. Intelligent Sensing for Innovative Structures (ISIS), in Canada (http://rip.trb.org/browse/dproject.asp?n=4951), plans to develop product specification and manufacturing guidelines for smart FRP reinforcements incorporating fiber optic sensors. The product under development and assessment is the smart FRP composite reinforcement, which incorporates one or a number of fiber optic sensors embedded into the host composite material during the "pultrusion" process. The program will focus on the design, manufacturing, testing, and application of the innovative strain gages using composite materials to encapsulate optical fiber sensors.

Composite materials have the unique ability to be designed and manufactured with a very wide range of mechanical and thermo-mechanical properties. Embedment of the fiber optic sensors into the specially tailored composite host material will ensure sensor protection, thermal compatibility with the host material, and proper integration of the concrete structures. The smart FRP reinforcements and innovative strain gages will be used for the monitoring of concrete bridges. The Composite and Intelligent Materials Laboratory at the University of Nevada's Department of Mechanical Engineering is studying FRP to improve the shear connection properties of the cross-section and to introduce a novel and effective bonding system (http://web.me.unr.edu/ciml/compbridge.pdf).

Perkins and Lapeyre (1997) examined the reinforcement role of geosynthetics to define the mechanisms of base course reinforcement, to define and quantify the effect of site-specific parameters on the level of improvement observed, and to devise a design tool that can be readily applied in practice. This program involved the instrumentation of a full-scale pavement subjected to moving traffic loads. The test section was chosen and constructed not necessarily to establish geosynthetic performance but rather to evaluate instrument installation techniques and subsequent instrument performance. Instrumentation measured strain in the geosynthetics, base course, and asphalt concrete.

The Utah State University Computer Science Department has developed computer vision and fuzzy logic technologies that can measure and categorize pavement cracking at highway speeds. According to the researchers, this product is ready to be mounted in a van for further analysis and implementation (http://rip.trb.org/browse/dproject.asp?n=7943).

The French LCPC (http://www.lcpc.fr/en/recherches/resultats_recents/index7.dml) is looking for something new to more effectively manage infrastructure projects. They are now studying new types of high-performance fiber-reinforced concretes for civil engineering structures and new concretes for road building. Another goal is to further knowledge on the behavior of more conventional materials, such as granular and porous materials or complex composite materials, particularly to track changes in their properties over time.

Sohn et al. (2004) developed and demonstrated the utility of a technique to detect delamination in composite structures. In particular, a wavelet-based signal processing technique was developed and combined with an active sensing system to produce a near-real-time, online monitoring system for composite structures. This technique may have application in pavements and bridges.

APL, Limited (http://www.jhuapl.edu/programs/trans/surface.htm) has developed the Smart Aggregate sensor system, which integrates conductivity and temperature sensors with a low-cost, highly reliable wireless embedded electronics platform. A sensor for chloride ion concentration in concrete will be integrated in the near term. Smart Aggregate sensors are attached to the reinforcement bars of the bridge deck during construction and later embedded in the concrete (Kuennen, 2004). A reader head on the deck surface transmits power to the sensor system, which collects and broadcasts the data back to the reader head. The data are stored for processing and analysis.

Dry (1996) assessed the feasibility of using self-healing concretes for bridges and pavements that may be damaged by dynamic events such as earthquakes or impacts. Self-healing concretes have embedded adhesives that are released from hollow fibers inside the concrete when and where cracking of the matrix and the fibers occur. She later found that the adhesive improves the strength of the cracked portions of the concrete, increases its ability to deflect under load, and improves the bond strength in structures (Dry, 1997). Further, laboratory tests showed the internal adhesive repair system improved the bond between the reinforcing steel and the concrete to prevent pullout failure or debonding at the interface. White et al. (2001) explained that autonomic healing is accomplished by incorporating a microencapsulated healing agent and a catalytic chemical trigger within an epoxy matrix. An approaching crack ruptures embedded microcapsules, releasing healing agent into the crack plane through capillary action. Polymerization of the healing agent is triggered by contact with the embedded catalyst, bonding the crack faces. The damage-induced triggering mechanism provides site-specific autonomic control of repair and even multiple healing events.

Chong and Garboczi (2002) reported that the National Science Foundation is supporting much cutting-edge research on concrete materials. Projects include self-healing smart concrete, fiber optic sensors in concrete, and automation/robotics related to concrete. They diagrammed a virtual cement and concrete testing laboratory (Figure 6), which is a computer-based virtual laboratory designed to reduce the number of physical concrete tests, whether for quality assurance or for expediting the research and development process. They indicated that computer models can replace many standard tests right now, and many more tests can be replaced in the future. These models can now or will soon be able to predict: degree of hydration, chemical shrinkage, heat release, diffusivity, set point, strength development, elastic properties, and rheological properties such as slump, yield stress, and plastic viscosity.

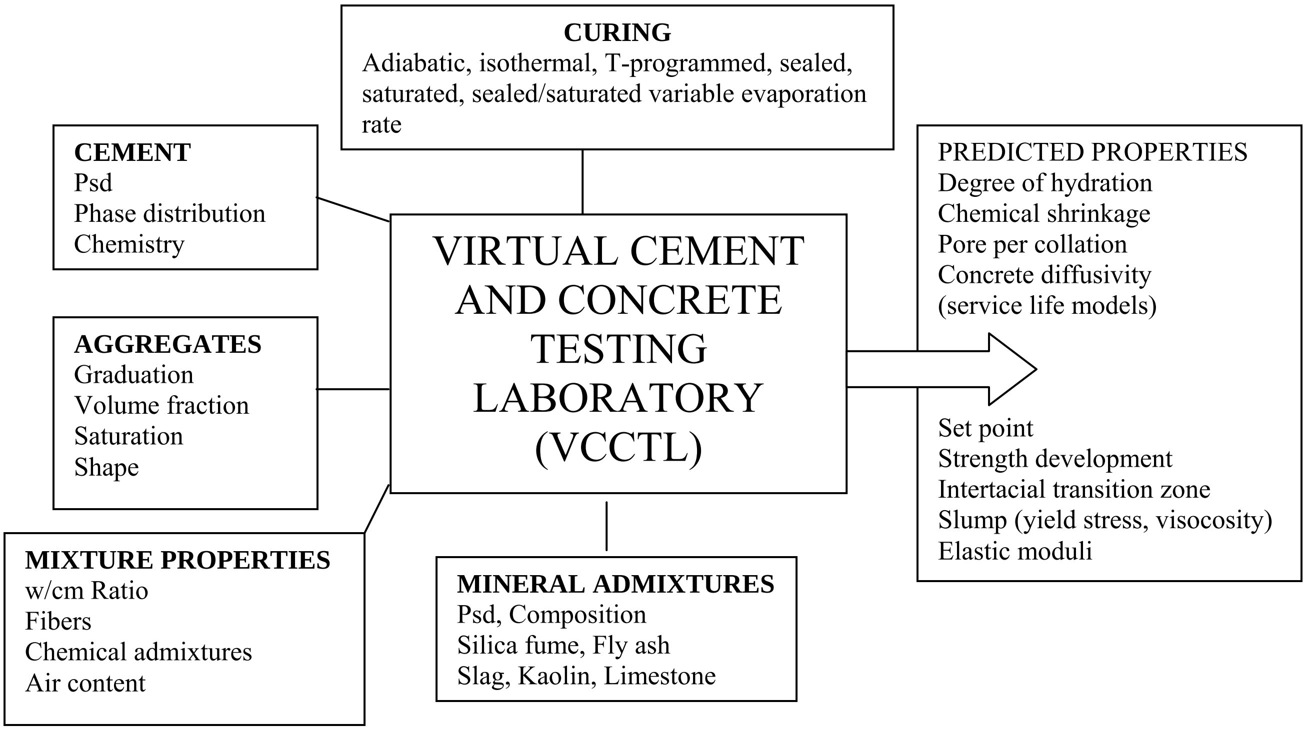

Figure 6. Schematic Overview of the Structure of a Virtual Cement/Concrete Testing Laboratory.

An FHWA website (http://www.fhwa.dot.gov/pressroom/nanotech.htm) forecasts that a future in which cracked bridges and potholes repair on their own, guardrails realign automatically after impact, bridges adjust their shapes to control movement caused by winds, and metal structures self clean to avoid corrosion are among the advances in highway technology. Further, sensors embedded into highways could allow engineers to continuously and remotely monitor the processes that contribute to deterioration and cracking without physical intervention. Similarly, sensors in bridges could monitor vibrations and loads and enable researchers to assess weaknesses and repair them long before they are apparent to human inspectors. Road sensor networks also could gather and provide data to transportation operators to manage congestion and incidents better and detect fast-changing weather conditions.

Kuennen (2004) reported that FHWA is also studying alkali-silicate reactivity (ASR), delayed ettringite formation (DEF), and cement hydration kinetics using nanotechnology and that their findings are advancing the fundamental understanding of the reaction of physics and chemistry.

Fiber Optics for Health Monitoring of Bridges and Pavements

Measures et al. (1995) described a two-span concrete bridge built in Calgary in 1993 as the first in the world to use carbon fiber composite prestressing tendons in several of its precast concrete deck support girders. Several of the girders were instrumented with an array of fiber optic intracore Bragg grating sensors to monitor the changes in the internal strain over an extended period. They demonstrated the feasibility of building, fiber optic long-term structural monitoring sensing technology into new bridges which will allow the use of these advanced composite materials to be monitored in a manner not previously practical. The strain information available from this type of monitoring system will assist engineers in their assessment of new materials and innovative design features and has a potential role in maintenance and repair activities.

In a steel-reinforced bridge, Idriss et al. (1998) reported findings similar those above. They used a multiplexed Bragg grating optical fiber monitoring system to measure strain throughout a bridge, with the sensors bonded to the tension steel in the slab and attached to the bottom flange of the girders. The load path in the structure was obtained using the built-in sensor system.

Fuhr and Huston (1998) presented multiple-parameter sensing using fiber optic sensors, which may be imbedded into portland cement concrete roadway or bridge structures. The sensors can provide internal measurements and assessment of cracking, as well as intrusion of deicing salts and/or degree of resultant corrosion of reinforcing steel.

Canada is using fiber optics and other techniques to monitor pavement response during spring thaw (Dore and Dupling, 2002). Specially designed strain gauges and multi-depth deflectometers were installed in test sections. These gauges were built using fiber-optic technology.

Pines and Lovell (1998) reported that the remote environment of many highways and bridges makes condition-based health monitoring for damage assessment difficult in the event of a natural disaster. During such disasters, electrical power is lost, and cellular phone lines are under heavy usage, thus limiting retrieval of important sensor data.

However, recent rulings by the Federal Communication Commission, coupled with advances in wireless communication products, have now made it possible to circumvent existing wired and cellular infrastructure to retrieve data from smart sensors remotely and more economically. They developed a remote health monitoring system using spread spectrum wireless modems, data communication software, and conventional strain sensors. Commands from as far as 1 mile away can be issued from a personal computer to instruct the system to either excite the structure or acquire data from sensors mounted externally to the structure. Resultant data can be transmitted wirelessly back to the computer for processing and analysis using damage detection algorithms.

Road Weather Management

Weather affects driver behavior, vehicle performance, pavement friction, and roadway infrastructure. Weather events and their impacts on roads can be viewed as predictable, non-recurring incidents that affect safety, mobility, and productivity. An easy-to-negotiate FHWA website on road weather management provides very current information (http://ops.fhwa.dot.gov/weather/index.asp). This is an extremely valuable resource. The site provides best practices with results of recent case studies regarding snow/ice, rain/flooding, low visibility, high winds, and hurricanes. It describes available training, equipment, publications, and many additional pertinent links. For example, one link on technologies available to help mitigate weather impacts on roads also addresses surveillance, monitoring, and prediction; information dissemination; and decision support, control, and treatment.

In 2002, Wisconsin DOT conducted a search of major transportation and municipal websites in the U.S. and Canada and discovered several working methodologies for measuring the efficiency and effectiveness of winter maintenance operations. Their synthesis is available online at the Wisconsin DOT website: http://www.dot.wisconsin.gov/library/research/docs/tsrs/tsrwinteroperationsmeasures.pdf.

TRB maintains a website on highway operations, which provides significant information (http://www4.trb.org/trb/onlinepubs.nsf/web/Highway_Operations_Reports) relevant to roadway weather management.

Smart Deicing Materials and Methods

A new anti-ice coating termed "Anti-Icing Smart Overlay" is being evaluated (Stidger, 2002) in Michigan (http://www.sas.it.mtu.edu/urel/breaking/2001/alger.html). A certain type of crushed limestone is epoxied to the pavement surface. The porous system absorbs some of the deicing salt during its first application. In subsequent icing situations, the material releases additional salt, thus minimizing the number of times deicing salt application is required and reducing the amount dispersed into the environment. Theoretically, one application of salt could last several weeks. The primary application would be bridge decks, particularly those in very remote locations. The crushed stone surface exhibits high-skid resistance, and the epoxy reportedly seals the surface from chloride intrusion.

A bridge that spans the Mississippi River on U.S. Interstate 35W in Minneapolis, Minnesota, was experiencing a high incidence of crashes due to icing (Johnson, 2001). The bridge is more susceptible to slippery conditions because of moisture from nearby waterfalls, power plants, and industrial facilities as well as heavy vehicle exhaust due to congestion on the bridge. It was fitted with a computerized system that sprays anti-icing chemical onto the bridge deck when data from sensors and a road weather information system determines that hazardous winter driving conditions are imminent.

Charlotte, North Carolina, installed a system that should limit snow and ice removal costs by identifying those roads and bridges that are likely to need preventive measures such as salt (Suchetka, 2001). Reduced salting would potentially bring significant savings to motorists by reducing auto repairs, injuries, and time lost at work.

Automated Distress Survey Methods

According to Bertrand (2005), TxDOT presently owns eight Texas Modular Vehicles (TMVs) and has plans to purchase eight more. TMVs contain subsystems that measure and record pavement surface conditions such as ride quality, rut profile, texture (to estimate skid resistance), and various categories of cracking, and they record synchronized video of the right-of-way and pinpoint the location using a global positioning system (GPS). TxDOT's current plan is to implement all sixteen TMVs in fiscal year 2005 to conduct statewide distress surveys. They will continue manual distress surveys for approximately one year thereafter and compare the results with those from the TMVs. Based on their findings, they may eliminate further manual surveys.

According to Chung et al. (2003), an automated in situ road surface distress surveying and management system, AMPIS, has been developed on the basis of video images within the framework of geographic information system (GIS) software. Video image processing techniques acquire, process, and analyze the road surface images obtained from a moving vehicle. This makes it possible to present user-friendly interfaces in GIS and to provide efficient visualizations of surveyed results. It can be used by transportation engineers to manage road surveying documentation, data acquisition, and analyses, and by financial officials to plan maintenance and repair programs and further evaluate the socio-economic impacts of highway degradation and deterioration. Chung et al. (2003) believe this technology will reshape pavement management systems (PMS) into a new technology-based information system providing convenient and efficient pavement inspection and management.

Wang et al. (2002) reported on the data analysis portion of a new automated system (University of Arkansas highway data vehicle) capable of collecting and analyzing pavement surface distress, mainly cracks, in real time through the use of a high-resolution digital camera; efficient image processing algorithms; and multi-computer, multi-CPU-based parallel computing. Features and performance of the automated system were surveyed. Three protocols for generating distress indices incorporated into the automated system were examined: AASHTO interim distress protocol, World Bank Universal Cracking Indicator, and the TxDOT method. They found that distress results from the automated system were consistent for multiple passes of the same pavement sections, thus demonstrating that the automated system produces very consistent results when compared to consistency of manual surveys.

Very soon, NCHRP Synthesis Project 34-04, "Automated Pavement Distress Collection Techniques," should be completed. The primary objectives of this study are to (1) review literature to catalogue methodologies and equipment available to highway agencies to capture surface feature images, and methods and algorithms used to interpret distress features from images; and (2) survey highway agencies to determine the current state of their practice in adopting automated distress collection techniques.

Smart Work Zone Technology

Tudor et al. (2003) reported on smart work zone technology deployed in Arkansas. The main goal was to provide a queue-detection system that prevents or reduces rear-end collisions and provides motorists with real-time information about potential backups caused by lane closures. The systems used were ADAPTIR from Scientex Corporation and CHIPS from ASTI Transportation Systems. These systems include all hardware, software, and other equipment necessary for collecting, displaying, and processing traffic condition data. A summary of the literature survey conducted by Tudor et al. (2003) is presented below.

The Midwest States Smart Work Zone Deployment Initiative is a pooled-fund study of new technologies for improving safety and efficiency of traffic operations in work zones. From this study, McCoy and Pesti (2001) found that a condition-responsive, real-time travel information system increased traffic diversion during congestion in work zones. Pearce (2000) described advanced technologies that monitor traffic entering and passing a work zone and provide pertinent information to local travelers. A smart work zone used in Iowa (Gent, 1998a; Gent, 1998b) was designed to monitor approaching traffic speeds and volumes, determine when traffic backups occurred, activate the warning devices, and inform surveillance personnel of problems.

Fontaine (2003) pointed out the need of objective information to make decisions on installation of portable smart work zone systems and provided guidelines for their deployment.

Non-Pavements-Related Smart Highway Technology

On certain roads in Finland, speed limits along specific sections are controlled by data at 5-minute intervals from unmanned road weather stations (Raemae et al., 2001). Speed limits are lowered automatically during adverse road conditions, and in some cases, signs for slippery road conditions are displayed as well. It appears that the high normal speed limit prevented drivers from taking into account the adverse road conditions; therefore, these advisory signs have demonstrated improved safety. Several state DOTs have reported similar findings (e.g., Goodwin and Pisano, 2003; Placer, 2001; Blomquist and Carson, 2001; Zwahlwn et al., 2003).

West Virginia (Zeyher, 2003) is using sensors to identify poor visibility in foggy conditions and warn motorists. The fog detector automatically activates beacons or variable message signs. Personnel at the control center can override the flashers if there is a malfunction. They installed six wireless traffic detectors into the pavement that employ vehicle magnetic imaging. In addition to counting vehicles, the detectors can measure speed and the overall length of the vehicles. Others are using similar technology (Perrin et al., 2002; Sanders, 2001).

Twenty-nine environmental monitoring stations placed at strategic locations on Houston freeways, frontage roads, high occupancy vehicle lanes, and arterial streets will provide advanced warning to government agencies and the traveling public when adverse weather conditions, especially high water, affect travel conditions (Benz et al., 2002). When the system fully matures, it will be integrated into the traffic management center's control room floor. The system is based on proven technology and is working well.

The Finnish National Road Administration uses a mobile monitoring station to gather information about driving conditions and transmits real time data and video images of roadway to a control center (Pilli, 2001). The mobile road weather-monitoring vehicle was developed to improve accuracy of information on weather and driving conditions on the road network. The vehicle measures temperature and humidity of the air and the surface temperature, as well as friction of the road surface. Resulting information is tied to a location using a satellite-based GPS. Measurements take place while the vehicle is driven in normal traffic.

Finland is testing the effectiveness of the weather-related use of intelligent speed adaptation (WISA) (Crawford, 2000). Test vehicles will use GPS and digital mapping for vehicle location and speed limit information, and sensors to register driving speeds, steering movements, and road surface friction. The vehicles will also have risk displays and haptic throttles (touch-screen computer) to alert drivers to dangerous road conditions.

Kuennen (2004) reports that existing coatings tend to accumulate grime, which reduces visibility of signs and contributes to degradation of materials over time. The lotus leaf, or water lily leaf, exhibits an extraordinary ability to keep itself clean and dry – termed the Lotus Effect. Nanotechnology is being used to mimic the lotus leaf surface and create new coatings that outperform existing no-stick products; it is clear that this technology will have immediate benefits for traffic and work zone signage. On a Lotus Effect surface, dirt and grime are collected by rainwater droplets and rinsed off. For more information, see www.botanik.unibonn.de/system/bionik_en.html.

Safety technology, in the form of automated guidance and warning systems, is advancing rapidly (http://www.casact.org/coneduc/spring/2000/handouts/bishop.ppt). For example, Bishop (2000) reported:

- development of automated systems to help the driver drive more safely, productively, and efficiently;
- in-vehicle information systems;
- automated during/after crash notification systems to summon assistance;
- detection of head/body proximity for optimum air bag deployment;
- lane departure warning systems;
- collision avoidance (intervening to avoid a crash; adaptive cruise control [e.g., controller senses a slower vehicle and automatically adjusts speed then resumes desired speed];
- radar-based systems to cover forward zone and right blind spot; and
- black boxes to record pre-accident data (available now in trucks).

He further stated that technology exists to monitor driver performance (e.g., lane keeping, steering wheel movements, blink rate, percent eye closure, head positioning). Work is in progress to measure driver fatigue, particularly for truck drivers. Liability issues are huge and must be resolved. Shared control of vehicle operation may increase liability of vehicle or system manufacturers; however, fewer crashes may reduce the existing litigation load.

The National Highway Traffic Safety Administration also provides information related to smart safety systems at their website: http://www-nrd.nhtsa.dot.gov/departments/nrd-12/research_areas.html#HEAVY%20VEHICLE.

Amato (1999) concluded that materials with an unprecedented combination of strength, toughness, and lightness will make all kinds of land, sea, air, and space vehicles lighter and more fuel efficient. Fighter aircraft designed with lighter and stronger nanostructured materials will be able to fly longer missions and carry more payload. Plastics that wear less because their molecular chains are trapped by ceramic nanoparticles will lead to materials that last a lifetime. Some long-view researchers are taking steps toward self-repairing metallic alloys that automatically fill in and reinforce tiny cracks that can grow and merge into larger ones, including catastrophic ones that have caused human tragedy. See http://www.wtec.org/loyola/nano/IWGN.Public.Brochure/IWGN.Nanotechnology.Brochure.pdf.

Research Needs Related to Smart Pavements

Research is needed to conduct field evaluations of the most promising "smart" materials, devices, and systems, with a particular focus on unique elements of the TTC. Full-scale implementation of these devices could decrease the cost of pavement and bridge condition surveys and resultant maintenance, reduce traffic delays, and improve safety. Smart systems will have particular value in remote areas where urgent conditions can be rapidly detected and transmitted to the central control group.

As indicated above, application of MEMS has not reached its full potential in civil infrastructures. Laboratory investigation on the behavior of embedded MEMS in asphalt materials under dynamic loading needs to be studied. Field and laboratory research is needed to establish both repeatability and long-term behavior of MEMS embedded in various types of pavements in different working and environmental conditions.

Clearly, technology is available to automatically detect overloaded trucks, trigger mechanisms to capture their license plate number, and transmit the data to enforcement officials (a process similar to that for identifying drivers who avoid tolls by going through the annual permit booth). Overloaded trucks are particularly destructive during spring when subgrade layers are wettest and where they may be thawing. The operational capabilities and legal issues related to this type of system need to be studied.

PAVEMENT MATERIAL RESPONSE TO LOADS AND PERFORMANCE PREDICTION

Introduction

For the TTC, it appears desirable to use materials with proven high quality to construct long-lasting, low-maintenance highways that will perform satisfactorily under the designated conditions. Once service has begun, minimizing lane closures on this facility will be imperative. TxDOT needs specifications (including materials and pavement test protocols and acceptance criteria) that will ensure the use of individual materials, paving mixtures, and constructed pavements that will provide long-term performance. In addition, TxDOT needs mathematical models that can use results from laboratory tests and accurately predict pavement performance. These specifications and tests need to define acceptable and unacceptable products.

Even with the highly advanced technology of the 21st century, accurate and precise prediction of pavement performance under the expected operational conditions has been elusive. The main reason for this is because pavement performance depends on so many difficult- or impossible-to-control factors (e.g., traffic, subgrade, weather, construction quality, and vehicle dynamics) and their variability. The latest predictive methods for pavement performance are included in the new 200X Design Guide (NCHRP Project 1-37A, "Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures: Phase II"), but these models have not been fully validated or calibrated. Further, even these "new" predictive systems incorporate materials evaluation procedures and mathematical models that have been used by highway engineers for many years. This is not to say that these procedures are bad; it merely demonstrates that a really new generation of improved test protocols to characterize pavement materials and models to predict performance is very difficult to create.

The main objective of this section of the synthesis is to examine and report current and emerging technology related to the response of materials to dynamic stresses and conditioning to support accurate prediction of pavement performance during its service life.

Pertinent Recent/Ongoing Research Projects

National Cooperative Highway Research Program. In addition to Project 1-37A, NCHRP has sponsored or will sponsor several studies to directly or indirectly support the forthcoming Mechanistic-Empirical Design Guide. These NCHRP Projects and their status at this writing are listed below. This multimillion dollar coordinated research effort will provide a locally calibrated and validated state-of-the-art structural design guide for flexible and rigid pavements, along with recommended test protocols and criteria control quality of materials.

- 1-37A(01) - Distribution Plan for the Recommended Mechanistic-Empirical Pavement Guide and Software (Active)
- 1-38 - Guide on Pavement Rehabilitation Strategies (This study has been completed, and the report is available as NCHRP Web Document 35 at http://gulliver.trb.org/publications/nchrp/nchrp_w35-a.pdf.)
- 1-39 - Traffic Data Collection, Analysis, and Forecasting for Mechanistic Pavement Design (Active: NCHRP Report 509 is available at http://gulliver.trb.org/publications/nchrp/nchrp_rpt_509.pdf; it describes equipment for collecting traffic load data.)
- 1-40 - Facilitating the Implementation of the Guide for the Design of New and Rehabilitated Pavement Structures (Anticipated)
- 1-40A - Independent Review of the Recommended Mechanistic-Empirical Design Guide and Software (Pending)
- 1-40B - Local Calibration Guidance for the Recommended Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (Proposal requested)
- 1-41 - Selection, Calibration, and Validation of a Reflective Cracking Model for Asphalt Concrete Overlays (Anticipated)
- 9-19 - Superpave Support and Performance Models Management (NCHRP Report 465 is available at http://gulliver.trb.org/publications/nchrp/nchrp_rpt_465.pdf.)
- 9-22 - Beta Testing and Validation of HMA Performance Related Specifications (Active)
- 9-23 - Environmental Effects in Pavement Mix and Structural Design Systems (Active)

- 9-29 - Simple Performance Tester for Superpave Mix Design (Findings are in NCHRP Report 513 at http://gulliver.trb.org/publications/nchrp/nchrp_rpt_513.pdf.)
- 9-30 - Experimental Plan for Calibration and Validation of HMA Performance Models for Mix and Structural Design (Completed. Results are summarized at http://trb.org/publications/nchrp/nchrp_rrd_283.pdf and http://trb.org/publications/nchrp/nchrp_rrd_284.pdf)
- 9-30A - Rutting Performance Model for HMA Mix and Structural Design (Anticipated)

Details of these projects are available at http://www4.trb.org/trb/crp.nsf/NCHRP+projects and therefore are not discussed here. Current information about the 200X Design Guide is available at http://www.2002designguide.com/. Collectively, in these studies, multiple researchers spent enormous efforts searching for laboratory tests on pavement materials that could be used to accurately predict their performance. The simple performance tests recommended for characterizing rutting, fatigue cracking, and low-temperature cracking of bituminous pavement materials (Witczak et al., 2002) are essentially refinements of tests that have been commonly used by researchers for more than 30 years. However, state DOT personnel have not normally used these protocols as specification tests.

In their initial evaluation, Witczak et al. (2002) examined 12 HMA materials properties and 12 test methods and concluded that there is no perfect test method for all types of HMA mixtures placed under varying traffic and climatic conditions. The next phase of this project will involve a field validation of the simple performance tests (SPTs) and the recommended criteria. A final recommendation will be made of SPT method-response parameter combinations to estimate the susceptibility of an HMA mix design to rutting and fracture. Recommendations will include proposed specification criteria developed with the HMA performance models in the 200X Design Guide (ERES Consultants, 1999) and recommended test methods in AASHTO standard format for potential adoption by highway agencies. The objective of additional work on this project will be to simplify the SPTs and make them as practical as possible (Witczak et al., 2002).

Strategic Highway Research Program (SHRP). In SHRP Project A-005, Lytton et al. (1993) developed and validated a sophisticated, mechanistic-based pavement performance model to define the relationships between asphalt binder and mixture properties and pavement distress. The objectives of the SHRP Project A-005 were to:

- Establish, on the basis of documented field performance data, criteria that may be used in support of the asphalt binder specification and for the design of asphalt-aggregate mixture systems; and
- Develop performance prediction models for asphalt binder and for asphalt-aggregate mixture systems.

The successful development of performance-based specifications required the validation of those properties identified as important determinants of pavement performance. SHRP and FHWA accomplished validation in three steps.

Lytton et al. (1993) developed a comprehensive pavement performance model that predicts the amount of fatigue cracking, thermal cracking, and rutting in asphalt concrete pavements with time, using results from certain accelerated laboratory tests. The model uses detailed environmental data and can be used to optimize the mixture design (combination of binder and aggregates) for specific conditions. The pavement performance models for each distress were used to confirm the relevant binder and mixture properties established by other SHRP contractors using accelerated laboratory tests and laboratory torture tests, and to establish the degree of correlation between those asphalt binder and mixture properties. Results from these model studies were used to confirm or make recommendations for revisions to the asphalt binder specification. In general, these analytical studies confirmed the material properties and specific limits used in the performance-based specification.

The model is simple, runs on a microcomputer, and can be used to evaluate or design asphalt concrete mixtures for particular applications. The model can minimize a specific distress or combinations of different distresses, or it can set specification limits for specific materials and environments. The model has three parts: (1) a mixture evaluation model, (2) a pavement response model, and (3) a pavement distress model. The mixture evaluation program calculates the relevant binder and mix properties from the accelerated laboratory tests. These properties are used with the pavement response program to evaluate the behavior of a mixture subjected to simulated traffic and/or environmental loads.

This state-of-the-art mixture evaluation program calculates the non-linear elastic, viscoelastic, plastic, and fracture properties of a paving mixture (Lytton et al., 1993). The pavement response program calculates the stresses and strains in an asphalt-aggregate system from applied wheel loads and temperature changes. The pavement distress program uses the relevant mixture properties and the appropriate stresses and strains to calculate the amount of cracking (from wheel loads and environmental loads) and rutting with time.

TxDOT Research. Some of the best research related to pavement responses to loads and predicted performance has been or is being conducted at TTI. According to Dr. Amy Epps Martin, at TTI, her research team is incorporating calibrated mechanistic surface energy (CMSE) into the previous SHRP-A-357 model (Lytton et al., 1993) in a study for TxDOT. Walubita et al. (2005) defines CMSE as a continuum micro mechanics approach based upon the fundamental theory that HMA is a complex composite material that behaves in a nonlinear viscoelastic manner, exhibits anisotropic behavior, ages, heals, and requires that energy be expended to cause load-induced damage in the form of cracking. Similarly, energy must be expended to close and mend these fractured surfaces, a process called healing. CMSE utilizes the viscoelastic correspondence principle, Paris's law fracture mechanics, and Schapery's work potential theory (Park et al., 1996) to remove viscous effects and monitoring of accumulated damage through changes in dissipated pseudo strain energy (DPSE) under repeated uniaxial tensile tests.

Walubita et al. (2005) indicated that the CMSE approach considers that HMA micro-fatigue damage consists of two processes that both change over time: resistance to fracture under repeated loading and the ability to heal during rest periods. The approach further assumes that resistance to fracture is governed by two processes, namely the number of repetitive load cycles for micro cracks to coalesce to macro crack initiation (N_i) and the number of repetitive load cycles for macro crack propagation through the HMA layer (N_p), the sum of which yields the number of cycles to failure (N_f). HMA material is thus characterized in terms of fracturing and healing processes. Analysis requires only relaxation tests in uniaxial tension and compression, strength and repeated load tests in uniaxial tension, and a catalog of fracture and healing surface energy components of asphalt binders and aggregates measured separately. In this approach, HMA fatigue behavior is principally governed by the energy stored on and/or released from crack faces that drive the fracture and healing processes, respectively (Kim et al., 1997a; Kim et al., 1997b; Lytton et al., 1993; Si, 2001).

The computation of the critical design shear strain within HMA pavement structure for N_p analysis constitutes the mechanistic part of this type of approach. This critical design shear strain is determined at the edge of a loaded tire using a layered linear-elastic or viscoelastic model of material behavior. The utilization of field calibration constants in modeling the healing process, N_i, and N_p, constitute the calibration part of the CMSE approach. This calibration simulates the field mechanisms of micro crack growth and propagation in the HMA layer thickness with respect to field traffic loading and environmental conditions, as well as simulating transfer functions relating mechanistically determined responses to specific forms of physical distress (Huang, 1993). Walubita et al. (2005) used the calibration constants developed by Lytton et al. (1993) in their extensive field calibration study of fatigue cracking through falling weight deflectometer (FWD) tests in the field and accelerated laboratory tests. These calibration constants were developed over a wide environmental spectrum of the United States.

Professor Robert Lytton and his team at TTI are improving accuracy of pavement response assessments from current performance models by addressing the anisotropic properties of pavement layers. The applicability of the cross-anisotropy model to pavement engineering originated from soil mechanics. The relevance of this subject is that most natural soils, as well as rocks, in their response to stresses exhibit some degree of anisotropy. In general, while an isotropic elastic material is characterized by only two independent elastic constants (e.g., Young's modulus [E] and Poisson's ratio [ν]), five parameters are needed to describe the stress-strain relationships in a cross-anisotropic material:

- Young's modulus, E_v, in the vertical direction;
- Young's modulus, E_h, in the horizontal direction ($E_h = nE_v$);
- Poisson's ratio, ν_{vh}, for the effect of vertical strain on horizontal strain;
- Poisson's ratio, ν_{hh}, for the effect of horizontal strain on complementary horizontal strain; and
- shear modulus, G, for distortion in any vertical plane, $G = mE_v$ (Gazetas, 1982).

Tutumluer and Thompson (1997) stated that an apparent anisotropy is induced due to aggregate orientation placement and compaction loading. The granular layer, therefore, becomes significantly stiffer in the vertical direction than in the horizontal direction, even before the wheel load on the pavement imposes further anisotropic properties. Adu-Osei (2000) performed laboratory tests to obtain cross-anisotropy properties of unbound granular materials with various moisture contents and densities. He modified a finite element program to incorporate nonlinear cross-anisotropy material behavior and stress dependent Poisson's ratio and analyzed different pavement sections using a finite element program. He observed that nonlinear cross-anisotropy modeling predicted self-confinement within granular layers.

Oh (2004) performed extensive analyses to model pavement responses due to overweight truck traffic near Brownsville, Texas. In this study, researchers installed multi-depth deflectometers in the pavements to obtain layer displacements. Oh compared measured displacements with predicted displacements using four different constitutive models: linear isotropic (LI), linear anisotropic (LA), nonlinear isotropic (NI), and nonlinear anisotropic (NA). In the NA model, granular materials and subgrade layers were modeled with an anisotropic condition based on anisotropic material properties obtained from laboratory tests. As anticipated, the NA model showed the least error between measured and predicted displacements.

Oh (2004) also verified application of the cross-anisotropic model by comparing measured rut depth and fatigue cracking with their predicted values. In this task, the application of cross-anisotropy in the asphalt concrete layer was introduced on the basis of the relationship between static and dynamic backcalculated modulus. The prediction of rut depth from the cross-anisotropic model was closer to the values determined using TxDOT's rut bar profilers. However, the differences in predicted rut depths among different models, i.e., nonlinear elastic, linear cross-anisotropic, and nonlinear cross-anisotropic were not of practical significance (< 2 mm).

ICAR Research. Masad et al. (2003) conducted a comprehensive study to evaluate aggregate characteristics that affect HMA performance. They assessed the sensitivity of HMA properties to aggregate shape characteristics. Aggregate shape was characterized through direct detailed measurements of angularity, form, and texture using the Aggregate Imaging System (AIMS).

They developed a microstructure-based viscoplastic continuum model for permanent deformation. Although the model was developed within the continuum mechanics framework, microstructure parameters were incorporated in the model to enrich it with virtues usually monopolized by discrete models. The model accounts for the anisotropic aggregate structure in the mix, which is related to the shape properties measured using AIMS, which also accounts for different HMA moduli in the vertical and horizontal directions. Masad et al. (2003) demonstrated the model capabilities by matching the results of tests on various mixes from the FHWA Accelerated Loading Facility using triaxial creep and strength tests. In addition, the model was used to predict the response of mixes that contain aggregates with different shape characteristics to develop relationships between the model parameters and aggregate shape characteristics.

Masad et al. (2003) included in the model a damage parameter based on the effective stress theory to reflect the initiation of cracks and the growth of air voids and cracks (voids) that cause a reduction in the material load-carrying capacity. A parametric study of the model response showed sensitivity to strain rate; anisotropy level, which was captured by the vector magnitude; and crack initiation and growth, which was captured by the damage parameter. The damage parameter gave the model the capability of predicting the tertiary creep and capturing the softening behavior of HMA, which occurs as soon as the damage mechanism overcomes the work hardening, resulting in a drop in the load-carrying capacity of the material.

As part of the model development, an experiment was conducted to capture and characterize damage evolution in HMA due to permanent deformation. Using a triaxial compression setup, HMA specimens were loaded to four predefined strain levels at three confining pressures. X-ray-computed tomography and image analysis techniques were used to analyze damage distribution. Results of the damage experiment supported the damage evolution function proposed by the viscoplastic model. These findings should be important to TxDOT as they are currently adopting AIMS for characterizing aggregates.

Their damage experiment revealed that the HMA specimens experienced some dilation due to air void growth (coalescence), particularly in the middle region. This dilation model was associated with the hardening mechanism described by the viscoplastic model they developed. As the deformation increased, micro cracks initiated in the critical section in the top region of an HMA specimen. These micro cracks grew and propagated to become macro cracks in the post-peak region, decreasing the load-carrying capacity of the material and leading ultimately to failure. Meanwhile, the middle region was dominated by dilation, and the bottom region did not experience significant micro structural change.

The Superpave volumetric mix design is based on bulk volumetric properties such as average air voids. However, two specimens with the same average air void content might have completely different air void structures and distributions and, consequently, exhibit distinct mechanical properties (Masad et al., 2002). Thus, for a composite material like HMA, which exhibits a complex non-uniform microstructure, a valid constitutive model has to account for the microstructure distribution. Currently, the effect of the microstructure is not considered in the mix design. The impact of the proposed model is contained in a better representation of the material and, hence, in the performance prediction. As soon as the mechanisms leading to the development of different distresses like rutting are understood, improved pavement and mix design procedures can be formulated, with the aim of improving pavement performance and reducing maintenance costs (Scarpas et al., 1997).

HMA Performance Tests

The national Mechanistic-Empirical Design Guide now being developed (Witczak et al., 2002) recommends the following so-called simple performance tests to evaluate HMA:

- Rutting – triaxial dynamic modulus term (E*/sin φ), triaxial static creep, and triaxial repeated load tests, conducted at 100 to 130°F;
- Fatigue Cracking – dynamic complex modulus (E*), determined from dynamic modulus test conducted at 40 to 60°F; and
- Low-Temperature Cracking – indirect tensile creep compliance [D(t)], determined at zero, -10, and -20°F.

These tests are being refined, and equipment purchase specifications have been or are being developed in ongoing NCHRP Project 9-29. Bonaquist et al. (2003) have reported their initial findings and recommendations from this study.

Probably, the most common torture test presently used to identify rut-susceptible hot mix asphalt mixtures in the U.S. is the Asphalt Pavement Analyzer (APA). About 35 state

DOTs have used APA, and several currently specify a minimum rut depth for the device (Bhasin et al., 2003). Some engineers have recently questioned the ability of the APA to accurately predict rutting in asphalt pavements. Kandhal and Cooley (2003) concluded that it is generally not possible to predict pavement rut depths from APA tests on a specific project using relationships developed on other projects with different geographical locations and traffic. They also stated that APA compared well with other performance tests, including the Hamburg wheel tracking device (HWTD), with respect to prediction of potential pavement rutting.

Colorado DOT, TxDOT, and Utah DOT currently use the Hamburg as a specification test to qualify HMA for use in pavements, Some engineers believe the Hamburg relates well to field performance; others avoid the Hamburg test because it intermingles rutting and stripping.

Permanent deformation may be the most important performance property to be controlled during mix design and construction. However, from a structural standpoint, most experts agree that designing long-life or perpetual pavements to resist fatigue cracking is more important than designing them to resist rutting (Monismith, 2004). Currently, there is no practical standard test to evaluate fatigue resistance of HMA pavement materials. TxDOT is addressing this issue through ongoing Research Project 0-4468 at TTI (Walubita et al., 2005).

According to Brown et al. (2001), predicting performance of HMA is very difficult due to the complexity of HMA, the complexity of the underlying unbound layers, and varying environmental conditions. Add to this list the variability of laboratory-prepared specimens. Presently, no nationally recognized methods are used to design and control HMA with regard to rutting, fatigue cracking, low-temperature cracking, and frictional properties. The HMA industry needs a set of simple performance tests to help ensure that a quality product is produced. Brown et al. (2001) conducted a study to evaluate available information on permanent deformation, fatigue cracking, low-temperature cracking, moisture susceptibility, and friction properties, and recommend performance test(s) that could be adopted immediately to ensure improved performance. They concluded that, for predicting permanent deformation, one should consider the APA, Hamburg, and French Rut

Tester in priority order. Of note, they made no recommendations regarding the other potential pavement distresses.

The Transportation Research Board is in the process of publishing an electronic circular on "New Simple Performance Tests for Asphalt Mixes." The objective of this circular is to identify practical and reliable laboratory tests that could be used for ranking the rutting potential of HMA paving mixtures. It will include discussions of field shear tester, hollow cylinder tensile test indirect tension test, and dynamic shear rheometer as potential SPTs. According to TRB, this publication should be available on their website by the end of 2004 (http://www.nationalacademies.org/publications/#newsletters).

Perpetual Pavements

The perpetual or long-life pavement design concept should be considered for TTC lanes dedicated to passenger cars. In summary, this process designs a strong pavement structure that should last for, say, 50 or more years with periodic maintenance and rehabilitation of the surface layer only. A wealth of information is available at no cost from the Asphalt Pavement Alliance (http://www.asphaltalliance.com/library.asp?MENU=8) including the Perpetual Pavement Concept Paper, PerRoad 2.4: Flexible Perpetual Pavement Design and Analysis Software; PerRoad 2.4 Instructional Brochure, Perpetual Pavements: A Synthesis; TRB Circular on Perpetual Pavements, and more. PerRoad is a software package developed specifically for designing perpetual pavements (Trimm and Newcomb, 2004). Selected TxDOT engineers have received training on this procedure.

Additional design maintenance information on long-life pavements is also available in reports from the European Long-Life Pavements Group (ELLPG) http://www.ellpag.com/), which has been formed under the auspices of the Forum of European National Highway Research Laboratories (http://www.fehrl.org/projects_fp6.php). One would need to contact the ELLPG chairman to obtain reports.

Flexible pavement design experts have deduced that 70 micro-strain is the fatigue endurance limit (Monismith et al., 2004; Thompson and Carpenter, 2004). That is, a pavement designed to experience a maximum 70 micro-strain under the expected conditions (loads, climate, and subgrade) will not fail due to fatigue. At the International

Symposium on Design and Construction of Long-Lasting Asphalt Pavements, Dr. Michael Nunn, of the United Kingdom, stated that he backcalculated strain in existing pavements that had exhibited very long, fatigue-free life and found them to exhibit about 67 micro-strain (Ferne and Nunn, 2004). Therefore, this criterion can essentially be used to define a perpetual flexible pavement.

Research Needs Related to Pavement Response to Loads and Performance Prediction

This synthesis immediately followed a multi-million dollar concerted NCHRP research effort in this area of study. In fact, several of these studies are still in progress. Therefore, much current information related to pavement responses to loads and environmental conditioning and prediction of pavement performance is readily available to TxDOT. During preparation of this synthesis, no other relevant emerging technology was identified. Since pavement response to loads and performance prediction are national and even international issues and topics that need further work, research supported by national or international funds may be in order as appropriate projects can be identified.

For both flexible and rigid pavements, a research program should address the use of locally available materials to keep TTC construction costs to a minimum. For example, the TTC segments that parallel the Rio Grande and the Gulf coast will require long haul distances for high-quality quarried aggregate materials. With proper structural and mixture designs, it should be possible to utilize the local gravel materials in some or all of the pavement layers, particularly for the dedicated passenger car lanes.

Flexible Pavements. During this reporting period, TxDOT is considering the use of flexible pavements for the TTC passenger car lanes and portland cement concrete pavements for the TTC truck lanes. For flexible pavement, TxDOT should examine the perpetual pavement concept, which is essentially mature technology. The perpetual pavement concept offers many alternatives. Already, TxDOT has experienced some problems related to permeability of certain layers in perpetual pavements. Poor construction quality threatens the anticipated long life of such pavements. Therefore, design and construction guidelines and specifications are needed to aid the pavement design engineer in optimizing the structural design for particular combinations of traffic, climate, and subgrade to ensure the long design life.

Rigid Pavements. Recent experience in the Houston District has shown that some continuously reinforced concrete (CRC) pavements develop a distress that is difficult to repair and that manifests itself in the form of widened longitudinal joints in the vicinity of the transverse construction joints after a period of 10 to 15 years of service. This widening results from the pavement system laterally displacing under stresses due to cyclic temperature changes in the longitudinal axis of the pavement, forcing the longitudinal joint to widen and, thus allow moisture to corrode the transverse tie bars. One approach to eliminate this type of distress is to eliminate the need for longitudinal control joints during the construction process by placing post-tensioned cabling transversely in the pavement and tensioning the cable prior to the formation of cracking stress. This measure would also significantly reduce the required pavement thickness for design and possibly eliminate short cracking intervals in the crack pattern. For the TTC truck lanes, TxDOT should examine the concept of a post-tensioned, continuously reinforced concrete pavement design. This process could provide practical construction of thinner (thus less expensive) concrete pavement, with no concern about longitudinal joint separation and minimal concern about loss of load transfer at the transverse cracks.

SAFETY ISSUES RELATED TO SPLASH AND SPRAY

Introduction

General. Many individuals, who are disabled in many ways, routinely drive vehicles on public highways. However, those with significantly impaired vision cannot safely operate a vehicle. Sight is perhaps the most important attribute of a vehicle driver, and anything that detracts from sight creates major hazards. When following other vehicles during and shortly after periods of rainfall, particularly large vehicles like trucks, splash and spray can diminish visibility and thus driver safety. To maximize driver safety, the high speeds that undoubtedly occur must be adequately taken into account during design of many features of the roadway.

According to Maycock (1966), splash and spray result from a complex interaction of the airflow, driver, highway, speed, vehicle, and water. Pilkington (1990) defines splash and spray (S&S) as two separable and identifiable phenomena and discusses the dynamics involved:

> (1) Splash is the mechanical action of a vehicle's tire forcing water out of its path. Splash is generally defined as water drops greater than 1.0 mm in diameter that follow a ballistic path away from the tire. (2) Spray is formed when water droplets, generally less than 0.5 mm in diameter and suspended in the air, are formed after water has impacted a smooth surface and been atomized. Several factors must be present: (a) water in the tire path (the thicker the water film, the greater the quantity of splash and spray generated); (b) pavement surface characteristics (thicker water films are retained on a nonporous surface); and (c) turbulent and high-velocity air masses generated by the combination of vehicle configuration and speed.

Placement of multiple adjacent wide lanes to accommodate the TTC in concert with high-speed traffic will create a particular need for rapid pavement surface drainage to avoid excessive S&S due to high-speed traffic. S&S dangerously diminishes driver visibility and thus creates a hazard. Trucks, because of their configurations, size, and the diameter of their wheels, generally create a larger and denser splash and spray pattern than do most passenger cars (Sherard, 1973). In this regard, a major advantage of the TTC is that trucks and passenger cars will travel on lanes separated by several feet. Although large trucks will produce S&S, trailing truck drivers are seated much higher off the pavement than passenger car drivers, and thus, under normal circumstances, their visibility is significantly less affected by S&S. Maycock (1966) deduced that spray density = constant x $(\text{speed})^{2.8}$. Therefore, at speeds well above 70 mph, truck spray could significantly affect the visibility of trailing truckers.

Related issues pertain to light reflection and glare principally related to night visibility, particularly on wet pavement surfaces. Reflected light and resultant glare can be minimized only by using a coarse-textured pavement that permits surface asperities to penetrate the water film (Henry and Dahir, 1979). Fortunately, coarse-textured surfaces are also required to improve S&S and resistance to skidding and hydroplaning. Sabey (1973) and Maycock (1966) agreed that all evidence points toward the need for macroscopically rougher textures to improve both visibility and skid resistance and that added benefits could be obtained from porous surfaces. They found that most of the water that fell onto the surface drained into the porous pavement very quickly. In summary, these researchers and others (AASHTO, 1976; Schreuder, 1988) agree that wet-pavement visibility can be improved and glare reduced by incorporating light-colored, nonshiny (nonglassy) aggregates in a coarse-textured, porous pavement surface.

Background. Henry and Dahir (1979) suggested that drivers would agree that S&S constitutes an important problem that impairs visibility, especially at night, and accordingly, any improvement that reduces S&S contributes to driving safety. On the contrary, Pilkington (1990) concluded that the adverse effect of S&S on highway safety is a perceived, rather than a real, hazard since S&S is seen by the driver and can reduce the driver's vision of the highway, but it does not cause driver guidance problems.

TxDOT engineers have been concerned about safety issues related to S&S on high-speed highways for many years. This will be a particular issue on the planned high-speed roadways of the Trans Texas Corridor. TxDOT has experimented with open-graded friction courses (OGFCs) and highly textured pavement surfaces for more than 30 years and, more recently, has investigated improved permeable friction courses. These second-generation PFCs have demonstrated improved performance (e.g., constructibility [less asphalt draindown], service life, noise, as well as void capacity and size and thus speed of surface water drainage) over standard OGFCs.

Truck Fixtures to Reduce Splash and Spray

Generally, S&S is not measurable until truck speed reaches about 30 mph and does not become objectionable until speed reaches about 50 mph (WHI, 1973). Henry and Dahir (1979) indicated that several investigators in the United States, the United Kingdom, and other countries have studied various types and configurations of mudflaps to alleviate the problem of vehicle splash and spray on wet surfaces.

About 25 years ago, FHWA's Federally Coordinated Program of Highway Research and Development conducted a significant study (Project 1U) of S&S (Weir et al., 1978). This study included wind-tunnel experiments, driver simulator experiments, full-scale experiments that included truck component tests and two series of operational tests with various truck configurations and truck-mounted devices to improve air flow around the truck and reduce S&S, cost effectiveness analyses, and over-the-road evaluations in coordination with manufacturers. Henry and Dahir (1979) briefly summarized FHWA's work and findings:

(1) the cab-over engine and van semitrailer produced the most critical truck combination causing the largest truck-induced aerodynamic disturbance effect and spray cloud;
(2) a mudflap/fender system was the most effective among other effective truck modifications in reducing S&S;
(3) the change in visibility caused by the various truck-mounted devices was a reliable indication of the changes in aerodynamic disturbances and spray;
(4) due to reduced vehicle drag, truck-mounted S&S reduction devices can result in annual savings of approximately $400 per truck;
(5) there was good correlation between the objective measures of the spray cloud (using lasers and a photometer) and the subjective observer ratings, and
(6) truck weight had little effect on S&S and aerodynamic disturbances.

Subsequent research (Sandberg, 1978) by the Swedish National Road and Traffic Institute essentially provided independent verification of the findings by FHWA.

From more than 100 laser transmissometer measurements of one truck configuration in a wide variety of wind conditions, Pendleton (1988) developed a regression model to predict S&S from trucks under several realistic conditions. Many others (Koppa et al., 1990; Johnson et al., 1985; Gorte et al., 1986; Mortimer et al., 1986; Tromp, 1985) have studied the complex relationships between the amount of spray generated and various vehicle aerodynamic characteristics. Based on all the available information in 1994, the National Highway Traffic Safety Administration (NHTSA, 1994), in their report to Congress, concluded that it is not necessary to initiate any new rulemaking action on splash and spray suppression for large commercial vehicles. Further, Pilkington (1990) had concluded four years earlier that the most effective and global countermeasures to reduce S&S are those applied at the pavement surface to reduce the amount of water in the tire path.

Pavement Surface Drainage

According to most researchers, surface drainage is the most logical and effective way to address S&S. Good surface drainage, of course, can also minimize skidding, hydroplaning, and glare. All of these are significant safety concerns. Anderson et al. (1998) provide the most recent comprehensive examination of pavement surface drainage. They offered an excellent description of water flow on pavements:

> Water films develop on the pavement surface during natural rainfall and tend to increase in thickness along the water drainage or flow path. At the onset of rainfall, the water first occupies the macrotexture on the pavement surface and is contained within the macrotexture of the pavement surface or is drained from the surface through grooves or internal drainage (e.g., porous asphalt surfaces). With increasing rainfall, a film of water forms above the macrotexture. The flow of water on the pavement surface under these conditions is referred to as sheet flow; the depth of the sheet flow tends to increase in the direction of the drainage path. The depth of the sheet flow is of critical importance because the depth of this flow controls the skid resistance of the pavement, the tendency for hydroplaning, and contributes to the intensity of S&S.

Anderson et al. (1998) identified models to calculate the depth of sheet flow as a function of four general pavement characteristics: pavement geometry, location and capacity of drainage appurtenances, surface texture of the pavement, and any internal drainage offered by a porous asphalt surface or grooved portland cement concrete pavements. They used these models and other information to develop an interactive computer program, PAVDRN, to predict water film thickness and the potential for hydroplaning. It may be possible to use this model to examine certain alternative pavement designs before they are constructed to predict water film thicknesses and avoid those that may yield hazardous situations regarding splash and spray.

Anderson et al. (1998) listed five broad categories of implementable techniques for improving surface drainage. These are:

- optimization of geometric design parameters such as cross-slope;
- reduction of the distance that the water must flow (flow path) by installing drainage appurtenances;
- use of internally draining wearing course mixtures;
- use of grooving (per hard cement concrete); and
- maximization of surface texture.

The AASHTO *Policy on Geometric Design of Highways and Streets* (2001) provides guidelines to promote safe and efficient movement of highway vehicles. Drainage capacity of a highway surface is determined primarily by its surface geometry, especially cross-slope. Geometric design criteria that enhance drainage are often in conflict with the design criteria for safety and driver comfort (Anderson et al., 1998). For example, pavement cross-slopes are a compromise between drainage (steep slopes) and driver comfort and safety (flat slopes). Further, a zone of high water film thickness is always created at each end of a left horizontal curve (the flat spot) when a normally crowned pavement is transitioned to a superelevated curve and back to the normal crown. If the cross-slope is toward the median, the flat spot will occur on a right curve.

According to Anderson et al. (1998), cross-slopes may be formed in a number of ways (Figure 7). Section 2 removes water from the roadway faster than Section 1, but more inlets are needed to collect the water at the edge of the pavement. These sections are recommended if freeze-thaw is common. Drainage can be directed in two ways, sloping toward the median or sloping toward the shoulder. If a highway slopes toward the median, more inlets will be needed, but less water will be in the outer travel lane, while more water will be in the inner, high-speed lane. Figure 7 shows a variety of drainage configurations including slotted drains located within the traveled way. Placing longitudinal drains between traveled lanes is especially effective in reducing the flow path length, particularly for multi-lane pavements.

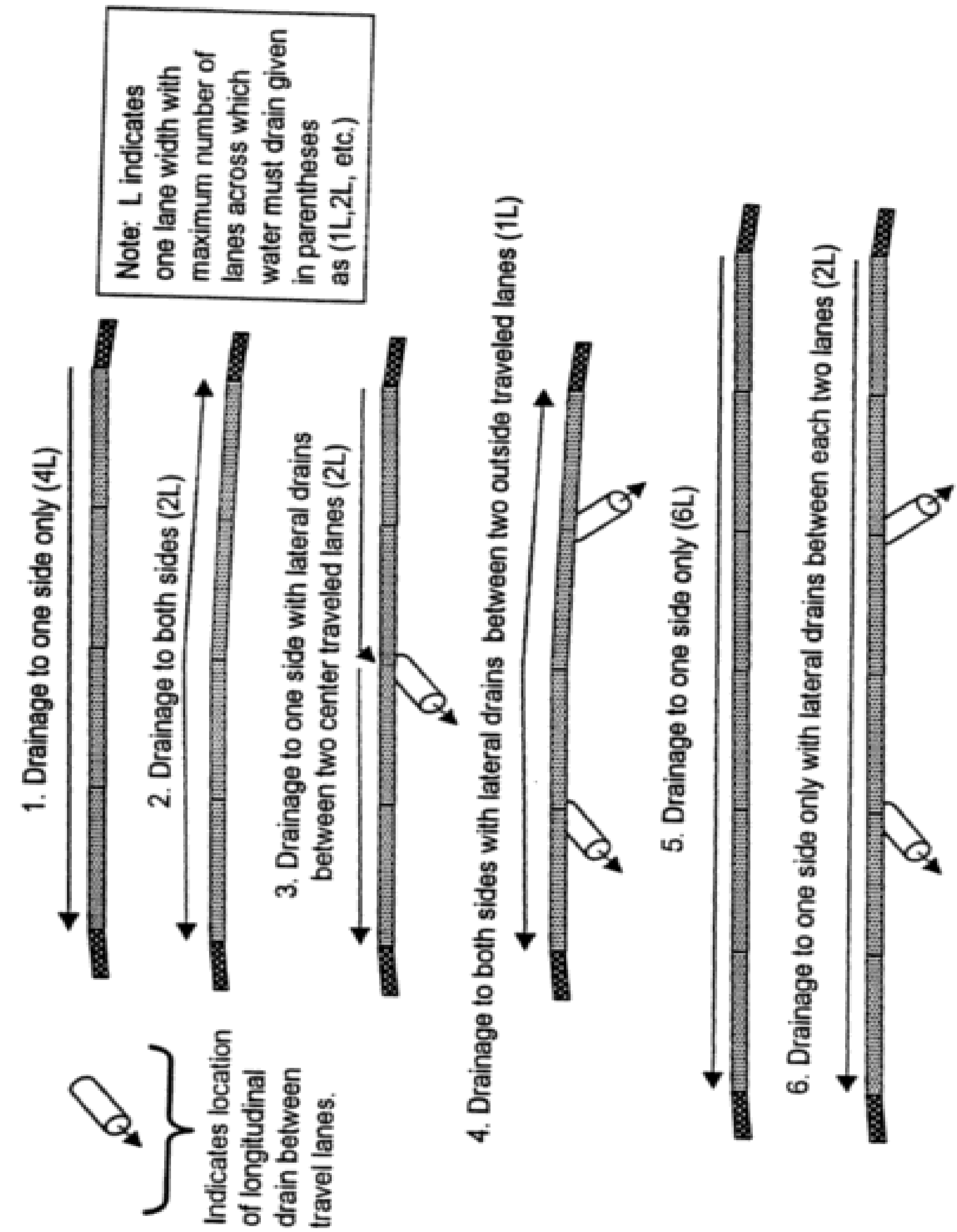

Figure 7. Lateral Drainage Configurations with and without Lateral Drains (Anderson et al., 1998).

Wada et al. 1997 demonstrated that construction of permeable pavements with infiltration pipes would be one of the most effective methods of storm runoff control for use in urban areas, particularly during the latter part of the rainfall. They failed to consider the clogging aspects of porous asphalt (PA) pavement in areas of slow traffic. The highway or street designer should keep in mind that drainage appurtenances create maintenance issues, and they must be maintained to function properly.

To supplement highway design and surface drainage specifications and guidelines provided by TxDOT, AASHTO offers several items including Highway Drainage Guidelines (Volumes 1 through 14), Model Drainage Manuel, and Guide to Standardized Highway Drainage Products. In addition, Pennsylvania State University (1998) developed Proposed Design Guidelines for Improving Pavement Surface Drainage, which is complemented by the interactive computer program, PAVDRN. However, PAVDRN has not been field-tested and validated and may need revisions.

Anderson et al. (1998) recommended that AASHTO review its current policy on the geometric design of highways and streets to consider establishing minimum cross-slope recommendations for highway pavements. Their findings showed that, as the longitudinal slope or grade increases, the cross-slope of a pavement section should also be increased to remove water more rapidly from the pavement. This effectively shortens the distance a droplet of water must travel to reach the nearest appurtenance of a pavement edge, a critical design parameter for drainage.

Macrotexture on Pavement Surfaces

It is common knowledge that permeable paving mixtures assist in rapidly draining water from a pavement surface. However, Henry and Dahir (1979) stated that surface macrotexture also facilitates drainage of water from the tire-pavement interface. Macrotexture, which is a function of aggregate gradation, provides passages for water to escape from the tire-pavement interface. They found that textures that improve skid resistance on wet surfaces also reduce S&S, glare, and hydroplaning, thereby increasing the safety of the pavement. High macrotexture or texture depth becomes more important as speed increases. Intuitively, it would appear that high texture would channel the water to the lower levels of the textured surface and thus reduce surface tension and cause the water to flow off the pavement more rapidly.

Water film thickness is the total thickness of the film of water on the pavement minus the water trapped in the macrotexture of the pavement surface. Therefore, water film thickness is reduced in direct proportion to the increase in macrotexture (total macrotexture volume, not macrotexture depth) (Anderson et al., 1998).

Macrotexture of asphalt surfaces (both dense and permeable) is controlled by aggregate gradation. Coarser aggregates yield coarser textures. In Europe, thin proprietary wearing courses of HMA designed to maximize surface texture [(e.g., Novachip [Estakhri and Button, 1995; Fort, 1994], Millom Hitex [Nicholls, 1998], Axoflex [Nicholls, 1997], UL-M [Parkinson, 1995], and Safepave [Parkinson, 1995)] are replacing porous asphalt where its performance has been deficient (Anderson et al., 1998).

In the U.S., the most common highly textured paving surface is the seal coat. Coarse-graded seal coats can improve safety during wet weather and probably serve satisfactorily on those TTC corridors dedicated to passenger cars; however, they can be quite noisy on high-speed thoroughfares.

Macrotexture is also important for portland cement concrete surfaces. The customary methods of producing macrotexture in concrete pavements are performed during construction by tining, brooming, burlap drag, and other methods. More recently, exposed-aggregate concrete, which is accomplished during construction, has shown good results in producing significant macrotexture. Exposed-aggregate concrete is discussed in the chapter on skid resistance, and several references are provided. Grooving or diamond grinding after the concrete hardens has also been used to enhance texture, particularly in areas considered hazardous. Exposed-aggregate concrete is the newest technology for texturing concrete pavements.

Porous Pavement Surfaces

Porous Asphalt Pavement. Since porous asphalt surface courses (also called open-graded friction course, open-graded asphalt concrete, drainage asphalt, permeable asphalt, or pervious macadam) are usually prepared using coarser aggregates and gradations with minimal sand-size particles, they typically provide substantial macrotexture. In addition, when properly designed and constructed, PA surfaces provide positive internal drainage of water downward from the pavement surface and laterally to the pavement shoulder. The pavement layer underlying PA must be impermeable to prevent infiltration of water into the lower layers, and the underlying layer must have a drainable grade. PA pavements cannot be placed as an inlay where lateral drainage across the shoulder is blocked.

Benefits of Porous Asphalt. PA pavements are the most effective products on the market for addressing S&S and thus improving driver visibility (Brown, 1973; Decoene, 1990; Sherard, 1973; Brosseaud et al., 1995; Brosseaud, 1997) and safety. Tappeiner (1993) indicated there were 20 percent fewer fatalities and injuries by motorists in Europe while travelling on PA during wet weather than on conventional pavements. Huddleston et al. (1991) reported similar findings in the U.S. Kam and Lynch (1993) commented that the Ontario Ministry of Transportation accepts PA pavements as the most suitable surface course mixtures for freeways and accident "black spots." Abe and Kishi (2002) predicted that PA pavement will be widely used in Japan.

PA pavements have also demonstrated excellent noise and vibration reduction as well as resistance to rutting and fatigue cracking (Ruiz et al., 1990; Berengier, et al., 1990). Researchers in France and Italy attributed good resistance to rutting and fatigue cracking under heavy truck traffic to the asphalt rubber, SBS, or other polymers in the binders in their PA mixtures (Sainton, 1990; Huet et al., 1990; and Perez-Jimenez and Gordillo, 1990). Other researchers favor modified binders to control draindown, improve low-temperature rheology, and minimize the effects of age hardening (Page, 1993; Colwill and Daines, 1987). Both mineral and organic (cellulose) fibers have been used successfully to minimize asphalt draindown (Cooley et al., 2000). It would appear that fibers would also act to reinforce the binder film and minimize the effects of age hardening.

Huddleston et al. (1991) stated that the first use of PA surfaces in the United States was in Oregon in the early 1930s. From this early work, OGFCs were developed (NCHRP, 1978), and much later, so-called permeable European mixtures along with acceptance test and criteria were produced in Europe. These European mixtures contained binders modified with fibers (Decoene, 1990), polymers, and/or tire rubber (Sainton, 1990); they were placed in relatively thick lifts (>1 inch), and contained approximately 20 percent air voids. These mixtures offer high wet skid resistance and contribute to rapid removal of water from the pavement surface. TxDOT has adopted this type of mixture and termed it permeable friction course. However, PA pavements have not been without their problems (Van der Zwan et al., 1990; Isenring et al., 1990; Heystraeten, 1991; Delanne et al., 1991).

In 2002, TxDOT used PFC to overlay continuously reinforced concrete pavement in the San Antonio District with overwhelming success (TxDOT, 2003). They reported 61 percent improvement in ride quality, 200 percent improvement in skid resistance, and a noise reduction of 14 decibels (a 3 to 6 decibel reduction is considered very good).

Limitations of Porous Asphalt. Although PA pavements are generally accepted as advantageous with respect to reducing S&S and other wet weather safety issues (Sherard, 1973; Colwill et al., 1993), their performance has not been excellent under all conditions (Camomilla et al., 1990). According to Anderson et al. (1998), several states have eliminated their use entirely. In contrast, they are used extensively on motorways in Europe, particularly France and The Netherlands. In fact, in the early 1990s, The Netherlands planned to surface all their motorways with PA by 2002. Note that Europe is in the same latitude as the northern U.S. to central Canada. Therefore, PA is being successfully used in climates much colder and wetter than those in Texas.

Some of the limitations of PA include the following.

- In much the same way that bridges are the first surfaces to ice over, air movement through porous OGFC and poor thermal conductivity from the ground (Greibe, 2002) make it susceptible to icing during wet, freezing weather more quickly than conventional paving surfaces. Icing can occur suddenly at the onset of light rainfall (Anderson et al., 1998). For the same reasons, OGFC is also slower to warm and thaw than conventional pavements, particularly when the pores are packed with ice.
- Loss of permeability in PA can result from clogging with roadway debris and deicing stone. About one-third of the permeability of PA can be lost due to plugging during the first year (Brosseaud et al., 1995). As a result, the French and Spanish concluded that a minimum of about 20 percent voids is required for PA to perform effectively (Lefebvre, 1993; Ruiz et al., 1990). Therefore, current designs in France require initial void contents of 27 to 30 percent. Clogging is exacerbated by slow traffic or where traffic is not intense (Van Heystraeten and Moraux, 1990). Ruiz et al. (1990) found that despite reduced drainage capacity, even those that had closed completely showed a dry appearance during light rains or immediately after heavy rainfall. Further, Nelson and Abbott (1990) reported that the fall in hydraulic

conductivity did not give rise to a concomitant fall in spray suppression properties of the surfaces.

- PA can ice over or develop "black ice" more quickly than conventional paving surfaces for the same reason that bridges will do so. It can occur suddenly at the onset of light rainfall (Anderson et al., 1998). PA is also slower to warm and thaw than conventional pavements (Camomilla et al., 1990).
- At lower speeds, skid resistance of PA is lower than that of conventional asphalt surfaces because there is less aggregate at the tire-pavement interface for the porous mixes (Anderson et al., 1998; Isenring et al., 1990).
- Deicing salts tend to infiltrate the surface voids thus reducing their effectiveness on the surface or requiring higher application rates than conventional surfaces. During a winter storm, almost three times the amount of salt is required to produce the same deicing effects (Decoene, 1990). However, this three-fold increase is not the case on an annual basis (Litzka, 2002). Ice removal may be more effective by using liquid chloride solutions (Camomilla et al., 1990) on OGFC. Tests in Austria with coarse dry road salt did not produce any longer-term effect on the surface (Litzka, 2002).
- Passage of a snowplow blade compresses snow into the pores of PA, and subsequent traffic brings to the surface part of the snow in the form of semi-liquid slush, which can easily refreeze. Immediate and rapid snow removal before it can penetrate to depth is beneficial (Camomilla et al., 1990).
- Raveling has been reported (Anderson et al., 1998); however, this may have been largely eliminated by TxDOT's PFC specifications or by selecting appropriate asphalt modifiers (Sainton, 1990) and/or admixtures (Decoene, 1990).
- Delamination from underlying layers has been reported. Anderson et al. (1998) hypothesized that freezing of water in the layer may proceed from the top to the bottom. The rigid top layer eliminates the outlet for the expanding water as it freezes, and sufficient force is created to delaminate the surface layer.
- Maintenance of PA is different than that for dense-graded mixtures, and ideal maintenance methods are still being developed (Rogge and Hunt, 1999). Isenring et al. (1990) and Van der Zwan, et al. (1990) indicate that initial cost and maintenance cost of PA is typically higher than conventional asphalt mixtures. However, Sainton (1990) says initial cost of PA pavements is less because of its lower density. Van der Zwan, et al. (1990) adds that the extra expenditures can be justified by the potential benefits on Netherlands pavements.
- Hand working of PA is very difficult. Therefore, it should not be placed where significant raking will be necessary (Kandhal, 2002).

- Current PA pavements are not yet satisfactory for urban situations because of special drainage requirements and clogging (Isenring et al., 1990).
- In PA, the binder is subjected to oxidative aging throughout the depth of the layer. Fortunately, however, the binder films are relatively thick and thus self-protecting. Modifiers are used to reduce the effects of binder hardening (Page, 1993; Colwill and Daines, 1987).
- At the end of its service life, PA should be milled off prior to replacement with new PA or any other HMA to avoid a permeable interlayer where water can reside.
- OGFC mixes should be protected from cooling during transportation to minimize cold lumps or crusting in the haul truck. Long haul distances will compound this problem. Oregon DOT limits haul distance to 35 miles, with 50 miles as the absolute upper limit (Kandhal, 2002).

These limitations are not listed herein to discourage the use of PFC mixes but merely to provide important information for use by engineers during their decision-making process.

NCHRP Project 9-41, "Cold Weather Performance of New Generation Open-Graded Friction Courses," should commence in early 2005. The objectives of this research are to:

(1) develop a synthesis report on the state of the practice in new generation OGFC design and performance, with a particular focus on winter maintenance issues;
(2) determine if and under what conditions new generation OGFCs will provide problems, and
(3) recommend what design and maintenance options are available to minimize such risk.

Clogging/Cleaning of PA Pavements. Research in Spain (Perez-Jimenez and Calzada-Perez, 1990) concluded "clearly and convincingly" that porous asphalt mixes provide excellent wearing surfaces for the following reasons: (1) improve road safety and comfort in wet conditions, (2) high macrotexture enhances tire-road adhesion at high speeds, (3) quietness, (4) adequate mechanical behavior. Moreover, their test sections generally maintained their initial qualities of permeability throughout their useful life. The natural process of filling by dirt and dust was counteracted by the forces of tire suction, which extracted and cleaned the dirt from the pores in the mix. For traffic to properly "clean" PA pavements, they must be placed on high-speed roadways.

Special truck-mounted high-pressure water spraying and vacuum systems have been developed (Abe and Kishi, 2002) and used to clean debris out of porous pavements and restore their drainage and noise-reducing capabilities. In Denmark, certain PA pavements in urban areas are cleaned twice per year using these systems (Bendtsen and Larsen, 2002).

Bendtsen and Larsen (2002) advocated design of porous pavements that do not clog and thus maintain permeability over their service life. Primarily for noise reduction in urban areas, they evaluated a two-layer PA apparently designed by Heerkins and Van Bochove (1998). The top layer has a small aggregate size (5 to 8 mm), and the bottom layer has a larger aggregate size (16 to 22 mm) (Figure 8). The concept is that the small holes at the surface prevent large particles from entering the void structure of the lower layer. Then the bottom layer, with large pores, allows rapid lateral flow of water with sufficient energy to wash away most accumulated dust. Bendtsen and Larsen (2002) reported some clogging with the 5-mm aggregate surface and subsequent difficulty in cleaning using high-pressure water.

Perez-Jimenez and Calzada-Perez (1990) measured in situ "permeability." According to Darcy' Law, permeability is measured only during perpendicular flow of a fluid through a media. In situ water flow through a porous pavement surface layer is normally not perpendicular but radiates mostly horizontally away from the so-called "permeameter." However, such testing provides valuable information regarding the speed at which the porous layer can transmit water from the surface. They presented the Cantabrian (or Cantabro) Abrasion Loss Test as a valid and advisable method for assessing resistance to disintegration of porous mixes. They found from field and laboratory tests that proper design of porous mixtures is a compromise between permeability and resistance to disintegration.

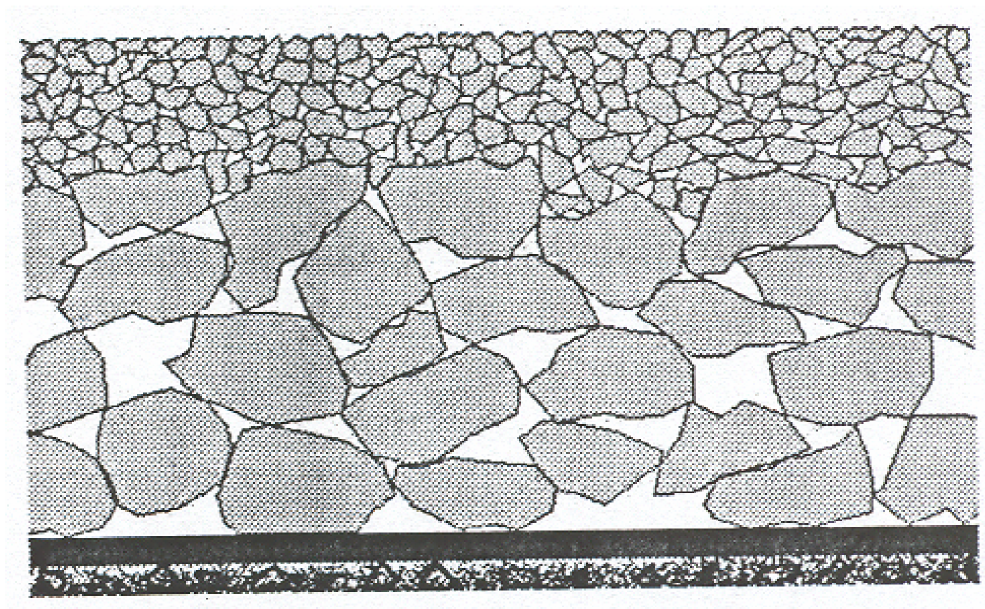

Figure 8. Two-Layer Porous Asphalt with Small Chips and Pores in Top Layer and Large Chips and Pores in the Bottom Layer (Bendsten and Larson, 2002).

Porous Concrete Pavements. Although most porous pavement surfaces in use are asphalt, portland cement concrete can also be used to produce porous pavement surfaces. They have proven effective in draining water from the surface and are subject to clogging (Christory, 1994). Porous concrete pavements will likely experience the same clogging problems as porous asphalt pavements and can likely be cleaned using similar processes.

Probability of Driving in the Rain

When moving from El Paso to Beaumont, Texas, the annual average rainfall rate increases almost an order of magnitude (Figure 9). Using this data and making some reasonable assumptions, Ivey et al. (1975) developed information to show the percentage of time that a vehicle driver will be exposed to rainfall in various cities in Texas (Table 3). Analysis of other statewide rainfall records by Hankins (1975) supported their approximation. When it is considered that the accident rate in wet weather can be as great as 10 times the accident rate in dry weather, it is further emphasized that, even though the actual driving time exposure is relatively small, the probability of being

Figure 9. Average Annual Rainfall Rates in the State of Texas.

unable to cope with a driving situation is much higher (Ivey et al., 1975). This type of information may be useful to determine where the more expensive and difficult-to-maintain porous pavement surfaces are justified.

Table 3. Rainfall Exposure in Various Major Cities in Texas.

Total Yearly Rainfall (inches)		Exposure to Rainfall	Proportion of Events
46	Houston	8%	1/12
36	Dallas	6%	1/11
57	Beaumont	10%	1/10
36	Ft. Worth	6%	1/17
33	Austin	6%	1/17
30	San Antonio	5%	1/20
8	El Paso	1.4%	1/71
19	Amarillo	3%	1/33
23	Abilene	4%	1/25
50	Texarkana	9%	1/11
32	Corpus Christi	6%	1/17
26	Brownsville	5%	1/20

Findings of International Conference on Winter Maintenance of PA Pavements

According to Litzka (2002), European engineers have expressed strongly diverging views on performance and maintenance of PA. Some have experienced heavy damage to PA, particularly during cold winters with heavy precipitation. In 1999, a workshop attended by experts from Austria, Switzerland, Germany, France, Italy, Netherlands, and Slovenia addressed the following PA issues based on past experience:

- letting, acceptance, execution of construction work, construction types;
- structural maintenance;
- winter maintenance, operational maintenance;
- development of acoustical properties;
- development of skid resistance; and
- change in drainage performance/spray plumes.

Findings concerning winter maintenance were:

- *Germany*: Winter service on porous asphalt is generally more expensive and slightly more difficult than on dense surfaces;
- *Italy*: Safety took precedence, and they changed from coarse mixes (20-mm maximum size) and a voids content of 20 – 25 percent to a smaller size (16-mm)

with about 15 percent voids, which led to a significant improvement in winter road conditions;

- *Netherlands*: Road salt consumption increased about 25 percent, speed limits are imposed, and roads may be closed temporarily;
- *Slovenia*: Salt consumption doubled. Packed snow removal is almost impossible with salt or by mechanical means;
- *Austria*: Emphasized anti-icing to preclude ice in the voids.

They reported a 10-15 percent increase in salt consumption, with best results achieved using wet application (salt/brine ratio of 2:1). Of significance, the *Swiss* and *French* participants did not make any specific comments on problems associated with winter maintenance. Litzka (2002) pointed out that, both in Austria and abroad, views on porous asphalt are by no means uniform.

Potential Solutions to Address Splash and Spray

No innovative solutions to reduce splash and spray were identified. The most effective readily available technology is porous pavement surfaces. Several varieties are available, and the logical choice will depend on the traffic type, intensity, and speed, and the climate (freeze-thaw cycles and annual precipitation).

The current Texas Transportation Code, Chapter 547.302 - Duty to Display Lights, states that:

> A vehicle shall display each required lighted lamp and illuminating device on the vehicle: (1) at nighttime; and (2) when light is insufficient or atmospheric conditions are unfavorable so that a person or vehicle on the highway is not clearly discernible at a distance of 1000 feet ahead.

Clearly, most people, including law enforcement officers, cannot accurately determine a distance of 1000 feet with the unaided eye. Therefore, the law can be neither heeded nor enforced. In their research report to TxDOT, TTI offered the following recommendation to increase safety during rainfall and provide an understandable and enforceable statute (Ivey et al., 1975):

> Although this would seem to cover much of a typical rainfall period, the specification of 1000 feet visibility is not easily understood and is rarely if

> ever enforced. An alternative would be to require that a vehicle display lighted headlamps whenever the windshield wipers are in use due to rainfall.

The author believes that the Texas State Legislature should reconsider this easily understood and enforceable recommendation. In fact, many drivers already observe this recommendation because of common sense. Incorporation of this wording into the Texas Transportation Code would not necessarily increase sight distance when driving through splash and spray, but it would improve conspicuousness of vehicles driving in splash and spray and possibly warn other vehicles of their presence, particularly during periods of rainfall in daylight hours.

Use PFC pavement surfaces. Maximize void content and more importantly void size. Larger voids drain more rapidly and are more easily unclogged by traffic or other manual cleaning methods (Perez-Jimenez and Gordillo, 1990). The effectiveness of PFCs can be enhanced if drains are installed internally within the pavement layers. Currently, these combined pavement drainage techniques appear to be the best means to minimize splash and spray.

Research Needs Related to Splash and Spray

Justification for installing porous pavements in various portions of Texas needs to be investigated. For example, if noise is not an issue, the additional cost of installing and maintaining porous pavements in areas with annual average rainfall rates less than, say, 20 inches per year may not be justified to address S&S only.

Porous paving surfaces need to be evaluated to determine performance and comparative life-cycle cost and search for innovative ideas to reduce cost and minimize clogging. The two-layer porous asphalt paving systems appear promising. Porous concrete pavements constitute fairly new technology and should be examined from the standpoints of design, constructability, performance, and maintenance. These and other concepts need to be evaluated and further developed in a well-designed experimental program to address the particular needs of the TTC.

In wet weather, highly textured pavements are known to provide improved skid resistance and lower glare at night than lower-textured surfaces. The effects of high texture are not so clear with regard to splash and spray and should be studied. Highly textured pavements are noisy, particularly at high speeds. However, in remote areas such as western Texas where the population and annual rainfall rates are low, high texture may be the most logical solution to address the issues related to wet pavements.

PAVEMENT RIDE QUALITY

Introduction

A recent National Quality Initiative survey of drivers indicated that pavement smoothness is the most influential element in standard measures of pavement quality (http://www.fhwa.dot.gov/construction/fs98002.htm). This is true whether measured objectively by high-tech instruments like pavement profilers or subjectively by vehicle drivers (Kuennen, 2003). Harrison and Bertrand (1991) found that longitudinal roughness contributes to undesirable driver discomfort. Smooth roads provide comfort for the driving public, minimize wear and tear on vehicle components, increase pavement life, and, last but certainly not least, maximize driver safety. Recognizing these facts, most state DOTs, worldwide, specify a certain level of pavement smoothness and require verification of ride quality by measurements using one or more of several available methods. Currently for TxDOT, deviations from acceptable smoothness levels result in either a bonus to the contractor for high quality work that exceed standards, or a penalty for sub-standard work.

The importance of pavement smoothness increases with vehicle speed. For the TTC with design speeds approaching 100 mph, pavement smoothness will be extremely important. Therefore, rigorous smoothness specifications will be necessary, and the latest technology will be needed to ensure they are attained. Further, long-term smoothness will need to be considered during pavement design, particularly for pavements constructed on subgrade soils with high plasticity indices. Smoothness of the truck-only lanes will help maintain longer service lives by reducing dynamic loads on the pavements. The purpose of this section of the synthesis is to identify and elucidate the latest available pertinent technology.

Since the TTC truck lanes will be constructed first, and since the current plan is to construct them of portland cement concrete, special attention will be given to concrete pavements in this section.

Measuring Pavement Smoothness

Several types of devices are now in use to quantify pavement smoothness. A list of typical devices includes (Kuennen, 2003 and Jones and Omundson, 2004):

- *Profilographs.* With the advent of non-contact, lightweight profilers, the profilograph (e.g., 25-foot California profilograph) may become most suited to retest short defective pavement sections for verifying correction and for bridge deck testing, as those jobs require only a short profile distance.
- *Ride Meters.* This is a response-type road roughness measuring system. The best-known example is the Mays Ride Meter, utilizing a rotary transducer, pavement condition recorder, and distance-measuring instrument.
- *Inertial Profilers.* These newer devices can measure and record network road surface profiles at speeds between 10 and 70 miles per hour. Most high-speed and lightweight non-contact profilers will fall under this general category.
- *High-Speed Non-Contact Laser Profilers.* These are the standard testing equipment for network level pavement management ride quality testing.
- *Lightweight Non-Contact Profilers.* These may be considered the next generation devices for construction quality control and quality acceptance purposes. These feature state-of-the-art measuring equipment mounted on an all-terrain vehicle. A non-contact sensor collects data as the profiler travels the pavement surface. The raw data are stored in an on-board computer for processing. Profile data can be analyzed under various roughness indices, including the International Roughness Index (IRI), Profile Index (PI), and Ride Number (RN), and the results can be viewed on-screen or output to a printer.

Influence of Smoothness on Pavement Performance

Loads imposed on pavements by traveling vehicles are a combination of the static weight of the vehicle and induced dynamic forces. These dynamic forces influence the life expectancy of pavements by speeding up the deterioration process. Unevenness or roughness of road surface is the primary source of dynamic motion in vehicles. Therefore, one must address the smoothness criteria for pavements not only from the ride point of view by using ride indices such as IRI or the Present Serviceability Index (PSI) but also from the induced dynamic load point of view by using an appropriate pavement damage index.

Dynamic load simulations performed at varying vehicle speeds for pavements with varying PSI values indicated that, as roughness increases (i.e., as PSI decreases), dynamic loads on a pavement increase (Figure 10) (Ma and Caprez, 1995). Hence, it is essential to consider predicted dynamic loads when evaluating the smoothness of a pavement. Fernando (1998) proposed a pavement damage index, Δ, to evaluate acceptability of inertial overlay smoothness based on predicted pavement life. He related the variability in applied surface loads to pavement performance. The dynamic load variability was evaluated by simulating the response of the standard 80 kN single axle to the measured profile using a two-axle planar model. The pavement damage index was developed to estimate the predicted change in overlay service life due to departures from the target profile established in the design stage and the as-built profile. A similar damage index that can estimate the predicted change in service life of new rigid and flexible pavements should be developed and used along with ride indices (IRI, PSI, RN, and others) to evaluate smoothness in pavements. Implementation of the proposed index in a smoothness specification will require the use of surface profilers and the simulation of vehicle dynamic loads from measured profiles (Fernando, 2002).

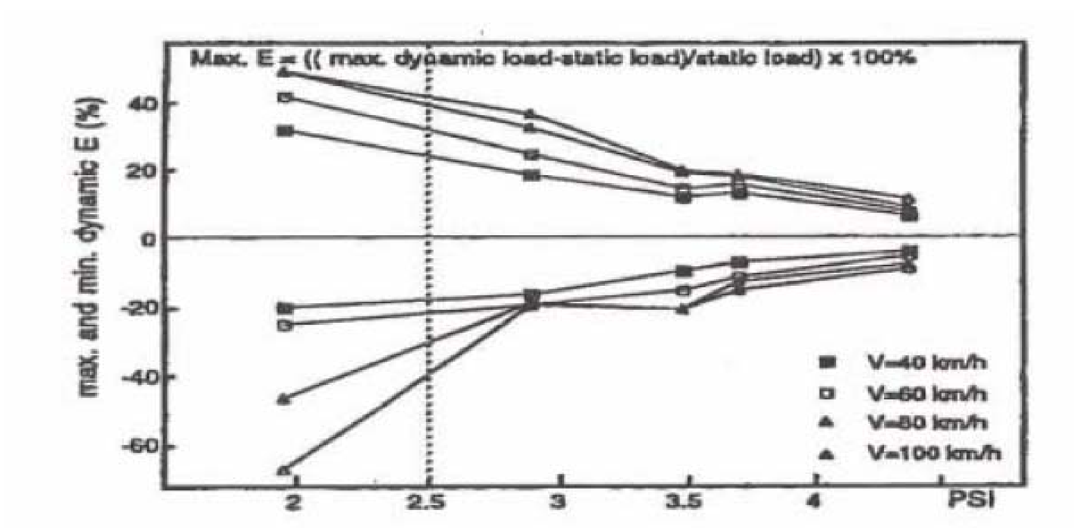

Figure 10. Variation of Dynamic Loads with Roughness Statistic (PSI) (after Ma and Caprez, 1995).

Chatti and Lee (2002) developed a dynamic load index (DLI) to identify pavement profiles that are likely to generate high dynamic truck-axle loads. Two frequency ranges in the analysis represent truck body bounce and axle bounce. DLI can differentiate between profiles that generate high dynamic loads and those having the same ride quality index but generate low dynamic loads. They claim that use of DLI negates the need for running a truck simulation program to determine if a particular section of pavement needs smoothing.

In a study for the Italian Research and University Ministry, La Torre et al. (2002) developed a roughness index to represent urban streets and identify acceptability thresholds. They had to use special considerations since standard IRI measurements and computations are not suitable for short sections of slow-speed urban streets.

The impact of dynamic loads on pavement smoothness is tremendous and steadily increasing. From 1991 to 2001, travel by large trucks in the U.S. increased by 46 percent, and from 2003 to 2020, another 42 percent increase is expected (TRIP, 2003). (The Road Information Program (TRIP) is a nonprofit organization that researches, evaluates, and distributes economic and technical data on highway transportation issues.)

The National Workshop on Pavement Smoothness

A workshop on pavement smoothness was held in August 2001 in Irvine, California, as part of NCHRP Project 20-51(01) (Perera and Kohn, 2002) (Report is available at http://trb.org/publications/nchrp/nchrp_webdoc_42.pdf.) Participants included individuals from state highway agencies, FHWA, asphalt concrete and portland cement concrete paving industries, academia, consulting firms, and research organizations. Through their discussions and a consensus-building process, workshop participants identified and prioritized the primary issues related to pavement smoothness that require concerted efforts for advancement. The top nine issues (in order of priority) were:

- accuracy and repeatability of equipment,
- reproducibility of equipment,
- use of profile data for corrective actions,
- knowledge and understanding of equipment and measurements,
- relating smoothness to cost and performance,
- identifying an appropriate index for smoothness,
- standard guide specification,
- future use of profile data, and
- use of roughness index for monitoring pavement performance during service life.

Workshop participants then recommended strategies to address each of the nine issues. These strategies require an extensive effort that involves research, training, specialized development, and demonstration activities to improve use of profile/smoothness information. Workshop participants also identified groups within the private and public sectors that could play an active role in implementing these strategies. The information provided by Perera and Kohn (2002) should serve as an up-to-date guide to those concerned with pavement smoothness.

Other Recent Ride Quality Research Findings

Rawool et al. (2002) indicated that there are three basic types of profiling devices. The three types are used for high-speed (greater than 20 mph), low-speed (10-20 mph) and very low-speed (0 to 5 mph) measurements. The measurement speeds of profilers dictate two distinctively different methods for performing measurements. High-speed and low-speed devices use an accelerometer-laser combination and a distance encoder for profile measurements. Each wheel path requires a separate laser and accelerometer. Systems using this method are known as inertial reference profiling devices. The very low-speed methods include measurement of accumulated slopes and/or elevation changes.

The very low speed devices include, at the slowest end, rod and level measurements, Dip Stick, Walking Profiler, and other similar methods. The Dip Stick, Walking Profiler, and, more recently, the new Ames wet profiler use a method of accumulated slope measurements along the pavement. Using this method, the measurement process can stop completely and then continue. Even with these methods, however, errors are introduced in determining the slope and often require some filtering, and filters can introduce other undesirable effects.

Rawool et al. (2002) listed several factors related to a profile meter that affect quality of the data collected: calibration and operation of the profiler, environment, and others. Malfunctioning of profiler components, such as the height sensor, distance encoder, or accelerometer, affects the profile data. Environmental factors that affect the measurement of pavement profile include surface contaminants and surface moisture on the pavement during data collection. Factors related to operation of the profiler include operating speed, speed changes during profiling, lead-in distance required prior to the section, lateral positioning within a section, and correct data information at the start of the section. Larsen (1999) reported that lateral positioning is the single greatest factor affecting repeatability. The FHWA report on long-term pavement performance data variability (Evans and Eltahan, 2000) identified unedited, equipment-related saturation spikes, partial and complete lost lock (inadequate light for optical sensors), and mis-calibrated distance measuring instrument as among the major factors that cause data variability. Rawool et al. (2002) explain these problems in detail.

Jones and Omundson (2004), of Iowa DOT, concluded that lightweight profilers have many advantages over the California 25-foot profilograph. Despite their advantages, there is resistance from the contracting industry to replacing the profilograph for construction ride testing. They documented the comparative advantages of an Ames Engineering Lightweight Inertial Surface Analyzer (LISA) single laser unit for construction smoothness quality verification and quality acceptance objects. They concluded:

- For HMA surfaces, LISA correlated well with the contractors' profilographs.
- LISA results are significantly affected by longitudinal tining on PCC pavements. (Karamihas [2004] reported similar findings.) Without improvements to the hardware and software, LISA as well as the International Cybernetics Corporation (ICC) high-speed profiler will not give accurate results on longitudinally tined PCC surfaces. A laser system upgrade is needed.
- A significant timesavings was realized by using LISA. Larger projects will yield greater timesavings. The portability of LISA allowed Iowa DOT to test a number of locations within a project and to test more than the minimum 10 percent, when the situation warranted.
    - Increasing visibility and reducing time in the construction zone improved safety.
    - Much less physical ability was needed to use LISA. One person with limited lifting capabilities could set up and operate the unit.
    - With the current Iowa DOT specification, LISA cannot totally replace the profilograph. Bridges and short segments with no adjoining pavement would still require a profilograph.

El-Korchi et al. (2002) conducted a study to identify suitable profiling devices with adequate precision and bias (based on ASTM E 950-94) for implementing construction quality assurance specifications. Sixteen profiling devices, including high-speed, lightweight, and walking profiling devices, performed 10 repeat runs on each of eight sites. Repeatability analyses using IRI showed that about 75 percent of all tests had an average standard deviation below 3 inches/mile. The high-speed devices produced better results than the lightweight profilers with almost 90 percent of these tests.

As part of the development efforts on profile-based smoothness specifications, Fernando and Leong (1997) conducted an evaluation of various profilers for TxDOT that included high-speed and slow-speed inertial profilers, as well as devices that measure unfiltered profiles. This is the first reported evaluation of surface profilers that included assessments of profile accuracy using rod and level data collected on the test sections surveyed, in addition to evaluations of profile repeatability among the different profilers tested. The findings were later used to develop a specification for evaluating inertial profilers that is now implemented in TxDOT Test Method Tex-1001S.

Mondal et al. (2000) conducted a field study of lightweight non-contact profilers in Indiana. They concluded that the data clearly showed that PI with a 0.0 blanking band is a better index for assessing pavement smoothness than PI with a 0.2 inch blanking band. However, the analysis revealed poor reproducibility or between-vendor consistency. This explained the poor IRI and PI reproducibility. Their precision analysis demonstrated that current lightweight profiler technology needs further refining to develop smoothness specifications that rely upon their use.

Karamihas (2004) discussed repeatability and reproducibility of simulated PI values from 11 common profiling devices on four pavement sections. His results showed that existing profilers do not agree on PI values sufficiently when a zero blanking band is used.

Swan and Karamihas (2003) found that a major drawback to using a ride quality index (RQI), as cited by the construction industry, is the lack of a method for pinpointing bad spots in the pavement that should be corrected by a diamond grinder. Their paper presents a method for locating isolated rough spots on new pavement and a basis for prioritizing the use of a grinder to improve new pavement smoothness using inertial profiler output. Fernando and Bertrand (2002) also illustrated a method of using profile data to detect localized roughness based on deviations from a moving average profile and projected improvements in surface smoothness from corrections made on rough areas. TxDOT has implemented a variation of this method in its new standard smoothness specification based on inertial profile measurements (Item 585).

Portland Cement Concrete Pavements (PCCP)

Measurement of Smoothness. According to Rawool et al. (2002), the smoothness of PCCP depends on the base type, vertical and horizontal alignments, grades, pavement type, paving equipment, and the concrete mix. To achieve smoothness, consistency is required in concrete delivery, concrete slump and quality, paver movement, mix vibration, a consistent head in front of the paver, and a very tight and accurately set stringline. If roughness of a cured PCCP is in excess of the specified limit, expensive remedial measures, such as surface grinding, are required. If this roughness can be identified before concrete reaches its initial set, remedial action can be taken by refinishing the entire surface or by localized refinishing.

A number of different types of equipment are used in construction of PCCP. However, a slipform paver is typically used to place rural highway pavements such as TTC. Slipform pavers are self propelled and designed to perform placing, consolidation, and finishing of PCCP, true to grade, tolerances, and cross section.

TxDOT is conducting research to determine if early detection of inadequate ride or smoothness in PCCP can be determined and, if so, identify the appropriate correction procedures needed before the concrete has hardened. As part of this study, the lead researchers visited several concrete pavement construction sites and found that none of the contractors were using a device for early bump detection. One contractor suggested that, since specifications vary between states, it is difficult for equipment manufacturers to design equipment that meets the criteria for all states. Regarding placement of sensors for early bump detection, another contractor indicated that the bump meter should be placed behind the paver and before the finishers, so that they may know when and where to take remedial action to correct defects. Another contractor stated that the sensors should be placed behind the finishers to check their work. Researchers emphasized that it may be difficult to mount the equipment on the paver since the vibrations of the motor may affect measurements. A dedicated unit behind the paver carrying the sensors for early bump detection may be more suited.

Rawool et al. (2002) surveyed several equipment manufacturers and found two companies that were developing devices to detect defects during concrete placement. One company (Gomaco) claimed it was developing a piece of equipment, called a wet profilograph, for this purpose. Although the researchers attempted to gather more details regarding the product, the company could provide neither information nor a demonstration of the device.

Ames Engineering in Iowa has developed a wet profiler they call the SmoothPave RTP® (Real Time Profiler) (http://www.amesengineering.com/ameswet.htm). The device is a laser-based profiler that can be mounted directly on the rear of a paver or laydown machine. RTP is capable of measuring and displaying the smoothness of the wet road surface as you lay it. The system will display IRI, PI, RN, and RQI values, as well as showing you the filtered profile and California profilograph simulated profile. Multiple units can be networked together in a single system, to monitor more than one wheel path. The collected data are displayed on a laptop mounted on the paver. Ames collected data that show reasonable agreement between the RTP and its Model 6000 lightweight inertial profiler. Software included with the equipment plots the measured profile in real time. Additionally, a profilograph simulation may be performed on the measured profile to produce a profilogram showing the defective locations. The estimated price of $50,000 provides contractors with a real-time profiler to measure one wheel path during paving.

According to Kuennen (2003), Kansas DOT and FHWA recommend the following to improve pavement smoothness of PCCPs:

- Have precise stringlines. Stringlines have the greatest effect on pavement smoothness. Place them carefully; keep them safe, and use aircraft cable instead of rope; it can be tensioned to eliminate sag without breaking. Conventional supports are placed 50 feet apart, but Kansas contractors place them 25 feet apart, which increases labor and material costs.
- Build from the ground, up. Without a solid, stable, smooth foundation, it's not possible to get a smooth driving surface.
- Watch paving speed and delivery rate. The paving train should move at a consistent speed and without stops. Constant batch plant production as well as adequate and unfettered delivery vehicles is essential.

- Control concrete head. Monitor the size of the head of concrete at the paver; it should be neither too high nor too low. The paver should finish the surface, not act as a bulldozer. Hydraulic forces can be imposed in the concrete head that can cause the finished concrete to surge and swell, creating permanent defects. A spreader/placer in front of the paver can maximize production while optimizing smoothness.
- Strive for mix consistency. The design should be proportioned for correct consolidation without excessive vibration, which can cause segregation and vibrator trails with accompanying rougher surface and lower strength concrete. Test samples often to track slump and air content.
- Use minimal hand finishing. If quality controls and pavements are used, hand finishing should be needed only for surface sealing, edging, and checking with straightedges. Use restraint. Know the correct texture or tining to reduce pavement noise (or whine) while keeping surfaces safe for drivers.
- Use good equipment. Clean equipment, in top working order, is necessary. Equipment is an investment, the benefits of which are realized in the field.
- Motivate your workforce. The workforce is the contractor's most important resource. Unique steps can be taken to motivate employees and create a sense of ownership and consistent self-improvement, including education in smoothness specs, pride programs, and distribution of part of earned smoothness incentives back to employees as an end-of-year bonus.
- Create a smooth base. A smooth base is critical to smooth PCCP. Bases will benefit from use of a trimmer ahead of the placer/spreader and slipform paver.

Installation of a manual stringline costs time and money in labor and material costs, especially if supports are spaced more closely for greater accuracy. Stringline also limits access to the area in front of the slipform paver. Stringless paving technology is available from Gomaco and Leica Geosystems (http://www.gomaco.com/Resources/leica.html). Cable et al. (2004) found on a construction project that, due to the speed of paving and rapid changes in terrain, laser technology was inappropriate. However, total control of the guidance and elevation controls on the slip-form paver were moved successfully from stringline to global positioning systems. The results indicated that GPS control is feasible and approaching the desired goals of guidance and profile control with the use of three dimensional design models. The Leica system is said to provide control within 3 mm of plan elevations (Kuennen, 2003). Further enhancements are needed in the physical features of the slipform paver oil system controls and in the computer program for controlling elevation.

Causes of Roughness in PCCP. A report prepared by Perera and Kohn (2001) for the National Cooperative Highway Research Program relates factors such as pavement structure, rehabilitation techniques, climatic conditions, traffic levels, layer materials and properties, and pavement distress to changes in pavement smoothness. Rawool et al. (2002) stated that PCCP smoothness depends on the base type, vertical and horizontal alignment, grades, pavement type, and concrete mix. Hossain et al. (2003) added that curing the compound application can significantly influence the as-constructed smoothness and subsequent loss of smoothness of PCCP.

When selecting a concrete mixture design, ensure that the aggregate gradation is not too harsh and unworkable. Harsh mixtures increase load on the paver and create extra work for the finishing crew, which may also adversely affect the smoothness (Banasiak, 1996). A steady supply of concrete should be maintained to properly run the paver. Stopping of the paver causes dips and bumps on the surface. In case of stoppages, the area should be recorded for later correction of defects. Dalimier and Torrent (2001) observed an inverse relationship between smoothness and the haul distance from the batch plant. He noted that, as the project progresses, the later sections exhibited higher smoothness than the earlier ones. This observation probably reflects the gain in know-how during the construction period, and an improvement in logistics to suit the particular project. LaCroix and Schwartz (1975) found that longer projects had better smoothness.

Smith et al. (1997) analyzed the percent change in pavement life as a function of the percent change in initial smoothness. A 25 percent increase in initial smoothness equated to a 9 percent increase in life. Target profile indices of 7 inches/mile (0.2 in. blanking band) for PCCP were considered in this study. A 50 percent increase in smoothness was found to increase life by about 15 percent.

Perera and Kohn (2001) reported that jointed plain concrete (JPC) pavements exhibited higher values of International Roughness Index in areas with higher precipitation, higher freezing index, and higher content of fines in the sub-grade. In the non-freeze regions, lower IRI values were noted in pavements located in areas having daily temperatures in excess of 32°C and in pavements having lower elastic modulus values.

Non-doweled pavements increased in roughness at a higher rate than doweled pavements. Jointed reinforced concrete pavements (JRCP) exhibited higher values of IRI in areas with higher precipitation, higher moisture content in subgrade, thicker slabs, longer joint spacing, lower water cement ratios, and higher PCCP modulus values. JRCP constructed on coarse-grained soils are found smoother as compared to those on fine-grained soils, but no significant difference was found for pavements constructed on granular and stabilized bases. Thicker slabs exhibited higher IRI values as compared to thinner slabs. Continuously reinforced concrete pavements (CRCP) exhibited lower IRI values with a higher percentage of longitudinal steel and higher water cement ratio and higher IRI values with higher PCCP modulus. In non-freezing areas, higher values of IRI were noted in areas that had a higher number of days above 32°C. They found that 63 percent of pavements rated poor were constructed over fine-grained subgrade; whereas, 37 percent of the pavements were rated poor that were constructed on coarse-grained subgrade.

Rawool et al. (2002) concluded that the contribution of curling to measured roughness is significant. Curling induces stress since the pavement is restrained by its weight, as well as the reaction from the subgrade, and causes cracking in the pavement. The curing technique could affect the as-built curling and, in turn, the smoothness of a newly placed PCCP. Temperature and moisture conditions at the time of paving and immediately following construction affect curling and warping in PCC pavements. Based on field data collected from Phoenix, Arizona (where the section was paved at night), and Mankato, Minnesota (paved during the day), Rao et al. (2001) observed that daytime paving induced negative gradients that further increased as the pavement underwent drying shrinkage and creep.

According to Karamihas et al. (2001), roughness of a PCC pavement changes with time during the day depending on solar radiation and temperature. Changes in IRI of up to 0.40 m/km were observed.

Sources of Current Ride Quality Information Online

According to the FHWA Pavement Smoothness Initiative (http://www.nhi.fhwa.dot.gov/tccc/aashto_soc_2001/pavement_smoothness.doc), the following agencies are currently or have recently revised their smoothness specifications:

South Carolina, New Jersey, Maryland, South Dakota, North Dakota, Virginia, Pennsylvania, Texas, Indiana, Arkansas, West Virginia, Alaska, and the Port Authorities of New York and New Jersey. These may have information useful to TxDOT.

The FHWA website at http://www.fhwa.dot.gov/pavement/rough.htm provides "A Synopsis on the Current Equipment Used for Measuring Pavement Smoothness." According to this website, FHWA has set a performance goal to significantly improve the quality of measured pavement smoothness of the National Highway System by 2008.

On-Going Ride Quality Studies

Perera and Kohn (2001) analyzed the data available in the LTPP Information Management System (IMS) database classified as "Level E" for four Special Pavement Studies (SPS) experiments and seven GPS experiments. This analysis considered the time-sequence nature of the data at the test sections and used the IRI as the measure of pavement smoothness. Through this analysis, the factors related to pavement structure and features, rehabilitation techniques, climatic conditions, traffic levels, layer materials and properties, and pavement distress variables that contribute to changes in pavement smoothness were identified for each type of pavement structure. Because limited data were available for many of the SPS experiments, the findings of this research should be regarded as preliminary. Additional data have been collected since the conduct of this research, and more data will be collected in the coming years; thus, a much larger database should be available in a few years. According to Perera and Kohn (2001), a similar research effort would be warranted at some time in the future. Such an effort would refine the findings of this research and contribute to an improved understanding of the factors affecting pavement smoothness and their relative effects.

Two on-going projects sponsored by the Texas Department of Transportation are developing tools that engineers and contractors can use to build pavements with good ride quality. Both projects are joint studies between the University of Texas at Arlington and the Texas Transportation Institute. In one project, researchers are developing a device called the sliding profiler for detecting defects on concrete pavements while the concrete is being placed. This device is intended for use behind the autofloat of a concrete paving train. The objective is to detect defects so that finishers can perform the necessary corrections while the concrete is still plastic. In this way, the need for grinding is significantly minimized, if not eliminated. A prototype device has been developed for testing on actual concrete paving projects.

In the other study, a scanning laser is being integrated with an inertial profile system to develop a device that can provide a three-dimensional profile of the existing surface, which engineers can use to evaluate potential benefits of different overlay and milling strategies. A potential application is the location and measurement of areas on paving projects that require grinding and filling prior to overlaying. Another application is the evaluation of overlay thickness requirements to reduce the existing surface roughness. The project is developing software to use data from the 3-D profiler for these applications. The main goal is to develop a tool that engineers can use to plan an overlay project and provide the appropriate information to the contractor to achieve the desired smoothness.

Potential Solutions Related to Ride Quality

Based on the findings of this study, it appears that there is no emerging technology in smoothness specifications, construction techniques, or ride quality measurement methods that can be used to improve construction of smooth pavements over that currently in use. TxDOT and its university research partners in this area of study continuously stay current on relevant issues.

FHWA (2002) concluded that, "All other things being equal, the smoother a pavement is built, the smoother it will stay over time. The smoother it stays over time, the longer it will serve the traveling public, thereby benefiting the public in terms of investment and vehicular wear costs, as well as comfort and safety." TRIP (2003) added that once a smooth, new pavement has been built, some agencies are putting greater emphasis on early preventative maintenance on these pavements to preserve smoothness, extend the lifespan of roadway surfaces, and delay the need for more significant pavement rehabilitation. For preservation strategies to be effective, they must be applied while the pavement surface is still in good condition with no structural damage.

Research Needs Related to Ride Quality

TRIP (2003) concluded that new materials and techniques offer the opportunity of building and reconstructing roads and highways that provide a smoother ride to the public and remain smooth for longer periods, thus delaying the need for road repairs. They recommended additional research on improved materials and techniques to assist transportation agencies in providing the public with smoother roads and highways.

MISCELLANEOUS PAVEMENT-RELATED ISSUES

Web-Based Training Programs

Distance learning involves delivering instruction to locations away from a classroom by using video, audio, computer, multimedia communications, or some combination of these with other traditional delivery methods. An increasing number of distance learning courses are available on the worldwide web. These can typically be located by using key words with the web browser. Some are free, but most of the substantive courses are only accessible for a fee. The National Highway Institute (NHI) has developed a wide variety of courses including pavements-related lessons or modules. The NHI course catalogue can be accessed at http://www.nhi.fhwa.dot.gov/coursec.asp. Their registration form offers five options: the Full Semester Course, Certificate Programs, Instructor-led Web-based Courses, Individual Courses Selections, and Individual Courses in Spanish.

The American Society for Civil Engineers (ASCE) offers several distance-learning programs (some of which are videos or CD-ROMs, which may be purchased). The ASCE site for transportation courses is located at http://www.asce.org/conted/distancelearning/transportation.cfm. The Local Technical Assistance Program (LTAP) (http://www.ltapt2.org/handbook/train-delivery.htm) is beginning to develop or make available distance learning programs. In addition, several universities offer transportation or even pavements-related distance learning courses; the University of Washington is leading a pooled-fund effort in the pavements area.

The Construction Industry Institute offers several non-pavements-related courses (http://construction-institute.org/services/catalog/cat_home.cfm) that should be applicable to a major construction project such as the TTC. Incidentally, the Consortium for ITS Training and Education (CITE) provides several potentially applicable courses at http://www.citeconsortium.org/curriculum.html.

Several private companies also offer web-based infrastructure or transportation training for a fee. Examples of these sites include Regulations Training, Inc. (http://www.hazardousmaterials.com/), i2, Inc. (http://education.i2.com/WBTOfferings.asp), Duratek (http://www.duratekinc.com/Services/training.asp), and Nichols Consulting Engineers (http://www.ncenet.com/trainprojects.html).

Intelligent Compaction

Intelligent compaction is a relatively new but fairly mature technology. In fact, Heinz and Sandstrom (2000) stated that continuous compaction control (CCC) has been accepted in many countries and even implemented in some national compaction standards. CCC is recognized as the optimum tool for the roller operator to efficiently achieve homogeneous compaction in a minimum time and reduce life cycle costs. Weak spots can be located and corrected. Modern compaction requirements cannot be met by a constant numbers of passes, constant roller parameters, and spot test methods.

According to Geodynamik (http://www.geodynamik.com/english/se17.htm), the basic concept involves recording the compaction history of small area and the reduction of the history into one value for each area. The size of the area can vary, but is normally of the order of 1 m^2. The history is documented by the time, mix temperature, rolling speed, and layer thickness when the mix is leaving the paver. Each separate drum pass is evaluated in terms of the incremental effective compaction it produces. The device calculates magnitude of the incremental compaction from known or measured parameters for the particular paving operation. Results are shown to the paver and roller operators in real time on computer screens and can be printed for documentation.

TRB held a session in January 2004 titled Intelligent Compaction Systems. This current information should be available in a TRB journal in the fall of 2004.

Oklahoma University is conduction a three-year study of intelligent compaction that is due for completion in August 2006. The objective is to develop an intelligent asphalt compaction analyzer for real-time monitoring of the compaction level in the field, which includes an intelligent asphalt compaction module (IACM) that can be integrated with a vibratory compactor, and intelligent compaction process guidelines. IACM will primarily consist of sensors (e.g., accelerometers, temperature, pressure, displacement), an onboard computer that will process the signals from the sensors, a customized software and hardware package with pattern recognition and classification capability, and accessories including display panels, compaction level indicator and lights, and mounting brackets (http://hotnsour.ou.edu/commuri/Intelligent_Compaction.html).

TxDOT should consider using intelligent compaction or CCC during construction of asphalt pavements for the TTC.

Ground-Penetrating Radar and Infrared Imaging for Quality Assurance

Segregation and inadequate compaction, particularly near longitudinal joints, are major detriments to hot mix asphalt pavement service life and maintenance costs (Stroup-Gardiner and Brown, 2000). The higher permeability of these areas can allow moisture and air to enter and cause asphalt stripping and oxidation, respectively, and/or allow water to enter the base layer and cause major structural damage. These potential problems should be minimized during construction of the TTC. Further, verifying continuous application of the specified mat thickness is important to TxDOT. Scullion and Chen (1999) have demonstrated that ground-penetrating radar is capable of real-time data acquisition and processing to identify low-density areas (due to segregation or poor compaction) and accurately measure mat thickness.

Sebesta and Scullion (2002) demonstrated the ability of GPR in conjunction with infrared (IR) imaging to evaluate the uniformity (related to segregation and density) of newly placed HMA pavements. An advantage of these techniques over nuclear gauge testing is that they provide coverage of 100 percent of the pavement surface. They proposed GPR specifications for certain types of HMA mixtures (dense graded, SMA, and CMHB) and indicated that both GPR and IR could be effective tools for quality control and quality assurance testing. Their findings were consistent with those of Read (1996), who proved the IR camera to be highly accurate for measuring surface temperature of an HMA pavement mat and able to dramatically reveal variations in surface temperatures.

Al-Qadi et al. (2003) also demonstrated successful application of GPR as a QC/QA tool to measure layer thickness. Accuracy of GPR system results were checked by comparing thicknesses measured directly from cores taken from the different HMA lifts. This comparison revealed a mean thickness error of 2.9 percent for HMA layers ranging in thickness from 4 to 10 inches. This GPR error is similar to that obtained from direct measurement of core thickness.

Research is needed to optimize the GPR data acquisition and processing methodologies; validate measurements of layer thickness, density, permeability, and asphalt content; develop field operator guidelines; and prepare functional specifications. Sebesta and Scullion (2002) proposed an implementation scheme for the IR technology. Additional work is needed, however, to support implementation of both GPR and IR. The GPR and IR processes need to be integrated and automated to facilitate their application for QC/QA testing on the TTC.

FINDINGS AND RECOMMENDATIONS

Findings

Potential solutions and recommended research for each subject area addressed in this synthesis are presented near the end of each section.

Recommendations for Future Syntheses Related to the TTC

The main objective of this synthesis study was to determine if new or emerging technology related to specific areas of pavement technology could be identified for potential implementation during design and construction of the TTC. This objective was accomplished, and the findings and recommendations for further study are presented in each section of the synthesis. This is the first synthesis study to address issues related to the TTC. A secondary objective of this project was to determine if additional synthesis studies in other areas of transportation related to the TTC should be conducted and how the process might be improved.

If this type of synthesis study is performed for other functional areas related to the TTC, the authors believe future studies should be more focused on a specific, maybe critical, issue(s), and the researcher should be instructed to present only those findings that are really new and innovative and potentially implementable. One element of the study should pursue non-transportation-related technology. That is, the study should attempt to find potentially usable technology in disciplines other than transportation and determine if it is feasible to adapt the technology to TTC design, construction, and/or operations. The researcher conducting future TTC synthesis studies should recommend an experimental plan to adapt any new method or process to transportation. Examples of potential sources of state-of–the-art relevant information might include National Aeronautics and Space Administration (NASA), National Science Foundation, FHWA Turner-Fairbanks Highway Research Center, Army Cold Regions Research and Engineering Laboratory (CRREL), Materials Research Society, Los Alamos National Laboratory, and many scientific journals. Successful completion of a study of this nature would likely require an expert team to guide the research supervisor.

After conducting this synthesis study on pavements, the authors are convinced that researchers in a given discipline are generally aware of the latest technology for their specific discipline. They periodically attend international research forums devoted to their area of study, and it is in their best interest to stay abreast of the latest findings. For a very focused item in their broad area of study, the researcher will generally be acquainted with the agency(s) or person(s) who has the particular expertise. Therefore, the latest technology is essentially readily available, and the researcher knows where to obtain details of the process or procedure. To obtain specific information in a given subject area, TxDOT or Texas Turnpike Authority personnel can contact the university researcher(s) with a specific question. The researcher can probably very quickly obtain, or help the TxDOT engineer, obtain the desired information.

Typically, a researcher feels an obligation to produce a written synthesis on the assigned subject matter to demonstrate that he/she has studied and digested many sources of pertinent information. The standard technique is to examine the latest research findings in the selected areas of study and report this to the funding agency along with the references in a written synthesis. This was the approach used in producing this synthesis. Admittedly, much of this synthesis has summarized known information. Based on reviews from the first draft synthesis, it appears that many reviewers are reluctant to read a detailed synthesis of existing information but desires to see only the new, innovative findings.

Therefore, in subsequent TTC synthesis studies, the authors recommend the researcher be given the latitude to report only those findings related to new and innovative methods or processes or those that can potentially be adapted from disciplines other than transportation. If new technologies are recommended, the researcher should devote significant time to outlining a research plan to adapt the new technology to safety, policy/planning, materials testing/analysis, specifications, design, construction, operations, or management related to the TTC. If the researcher is not expert in the discovered technology, he/she will likely need help from experts to develop a viable research program to adapt the new technology to the TTC.

Summary of Research Needs Related to the TTC

Recommended research to support the specific pavements-related areas of the TTC addressed in this synthesis are provided at the end of each section. Some of the research needs have been selected and are briefly highlighted below. Additional details can be found at the end of each section.

Truck-Only Lanes. The main challenge is in implementing current analysis procedures into a comprehensive methodology for designing and building dedicated heavy truck lanes to ensure that pavements are built as per design. In this regard, the following research and development needs are identified:

- Quality control and assurance to include state-of-the-art nondestructive testing,
- Investigate laboratory and nondestructive field test procedures as reliable predictors of pavement performance,
- Continue research on new materials specifications,
- Develop new construction methods to include guidelines to assist inspectors and contractors in successfully building pavements under new material specifications.
- Accelerated pavement testing to evaluate the performance of pavements utilizing new materials, verify potential pavement designs, and verify and calibrate models for design heavy truck routes.

Light Vehicle Pavements. Research is needed to develop a completely new overall design strategy for pavements devoted solely to passenger vehicles. Researchers need to adopt a new philosophy during the development of structural design procedures, mixture design procedures, materials selection guidelines, materials test methods and criteria, and construction specifications to optimize performance and cost effectiveness for light-traffic pavements.

Skid Resistance. Laser-based systems accurately measure pavement surface texture and relate the findings to skid resistance. These relatively new technologies offer significant promise for estimating skid resistance at atypical high speeds. To apply TxDOT's current laser-based system to high-speed corridors, additional research (skid vs. texture) will be required to recalibrate the algorithm for higher speeds.

For high-speed corridors, highly textured pavement surface mixtures (e.g., PFC, SMA, CMHB, and exposed aggregate concrete) and/or new aggregate specifications requiring increased texture and polishing resistance values may be required to ensure adequate wet skid resistance. Research should examine the suitability of certain new pavement surfaces, adequacy of current test methods for measuring skid resistance, physical properties of coarse aggregates, and related aggregate specifications.

Skid resistance of asphalt pavement is often at its lowest after initial placement, due to the heavy asphalt coating on the exposed aggregate particles. To maximize skid resistance of SMA pavement surfaces, the Germans use a process called gritting (Texans would call it sanding). Gritting is the application of a uniform coating of coarse sand over freshly placed SMA in advance of finish rolling. Gritting not only enhances skid resistance but also reduces surface permeability and, depending on the color of the sand, can even make the surface white, thus improving night visibility. This promising process deserves further study to optimize its benefits and develop field guidelines.

Traffic Characterization. A research project is needed to determine the effects of heavy, high-speed trucks on traffic characterization devices used on the TTC. It may be possible to perform the research (or a portion thereof) as a laboratory study using fatigue-type loads on certain WIMs. Environmental testing of a variety of sensors and sensor materials should be performed to determine the most suitable materials for a variety of climates. A more realistic field study of heavy, high-speed trucks on WIMs will be very expensive and time consuming. Since this is a national, even an international issue, it may be possible and will certainly be efficient to conduct this research as a national (NCHRP) or a pooled-fund study.

Research may include improving the second-generation fiber grating strain sensors and organizing it to analyze capabilities for WIM by studying same-vehicle repeatability, vehicle calibration, and axle response/stability. Further studies should include optimal installation depth, speed-related effects, position-dependent effects, and materials and procedures for installation.

There is research potential related to commercial vehicle weight and other enforcement along the TTC. Access points will probably be spaced much farther apart than existing rural interstate highways. WIM will undoubtedly continue to serve as a screening mechanism to identify overweight vehicles, but there will still need to be a means of verifying axle and gross weights using static scales. Research should determine the optimum uses of WIM and static scales along with related technologies that could be used in scale bypass today such as AVI tags. Investigation of other high-tech means of expediting safety inspections or related aspects of enforcement might also be included.

TxDOT might consider including the Kistler Lineas piezo-quartz sensors in high-speed tests, either in a laboratory setting or in a controlled environment where trucks could exceed “normal” speeds.

Smart Pavements. Research is needed to conduct field evaluations of the most promising “smart” materials, devices, and systems with particular focus on unique elements of the TTC. Full-scale implementation of these devices could decrease the cost of pavement and bridge condition surveys and resultant maintenance, reduce traffic delays, and improve safety. Smart systems will have particular value in remote areas where urgent conditions can be rapidly detected and transmitted to a central control group.

Application of MEMS has not reached its full potential in civil infrastructures. Laboratory investigation on the behavior of embedded MEMS in asphalt materials under dynamic loading needs to be studied. Field and laboratory research is needed to establish both repeatability and long-term behavior of MEMS embedded in various types of pavements in different working and environmental conditions.

Clearly, technology is available to automatically detect overloaded trucks, trigger mechanisms to capture their license plate number, and transmit the data to enforcement officials (a process similar to that for identifying drivers who avoid tolls by going through the annual permit booth). Overloaded trucks are particularly destructive during spring when subgrade layers are wettest and where they may be thawing. The operational capabilities and legal issues related to this type of system need to be studied.

Pavement Response to Loads and Performance Prediction. This synthesis immediately followed a multi-million dollar concerted NCHRP research effort in this area of study, with some studies still in progress. Therefore, much current information related to pavement responses to loads and environmental conditioning and prediction of pavement performance is readily available to TxDOT. During preparation of this synthesis, no other relevant emerging technology was identified. Since pavement response to loads and performance prediction are national and even international issues and topics that need further work, research supported by national or international funds may be in order as appropriate projects can be identified.

While examining the perpetual pavement concept, TxDOT has experienced some problems related to permeability of certain pavement layers. The anticipated long life of such pavements is threatened by poor construction quality. Therefore, design and construction guidelines and specifications are needed to aid the pavement design engineer in optimizing the structural design for particular combinations of traffic, climate, and subgrade to ensure the long design life.

TxDOT experience indicates that some CRC pavements develop a distress that is difficult to repair and that manifests itself in the form of widened longitudinal joints in the vicinity of the transverse construction joints after a period of 10 to 15 years. This widening results from the pavement system laterally displacing under stresses due to cyclic temperature changes in the longitudinal axis of the pavement, forcing the longitudinal joint to severely expand. One approach to eliminate this is to eliminate the need for longitudinal control joints during the construction process by placing post-tensioned cabling transversely in the pavement and tensioning the cable prior to the formation of cracking stress. This action would also significantly reduce the required pavement thickness for design and possibly eliminate short cracking intervals in the crack pattern. For the truck lanes of the TTC, research should examine the concept of post-tensioned CRC pavement design. This process could provide practical construction of thinner concrete pavement with no concern about longitudinal joint separation and minimal concern about load transfer at the transverse cracks.

Splash and Spray. Justification for installing PFC pavements in various portions of Texas needs to be investigated. For example, if noise is not an issue, the additional cost of installing and maintaining PFC in areas with annual average rainfall rates less than, say, 20 inches per year may not be justified only to address S&S and wet friction.

Porous paving surfaces need to be evaluated to determine performance and comparative life-cycle cost and search for innovative ideas to reduce cost and minimize clogging. The two-layer porous asphalt paving systems appear promising. Porous concrete pavements constitute fairly new technology and should be examined from the standpoints of design, constructability, performance, and maintenance. Evaluation and development should address the particular needs of the TTC.

In wet weather, highly textured pavements are known to provide improved skid resistance and lower glare at night compared to lower textured surfaces. The effects of high texture are not so clear with regard to splash and spray and should be studied. Highly textured pavements are noisy, particularly at high speeds. However, in remote areas such as western Texas where the population and annual rainfall rates are low, high texture may be the most logical solution to address the issues related to wet pavements.

Current Texas Transportation Code states:

> A vehicle shall display each required lighted lamp and illuminating device on the vehicle: (1) at nighttime; and (2) when light is insufficient or atmospheric conditions are unfavorable so that a person or vehicle on the highway is not clearly discernible at a distance of 1000 feet ahead.

Clearly, drivers and law enforcement officers, cannot accurately determine a distance of 1000 feet with the unaided eye. Therefore, the law can be neither heeded nor enforced. Researchers recommend following revision to the Code to increase safety during rainfall and provide an understandable and enforceable statute.

> …a vehicle display lighted headlamps whenever the windshield wipers are in use due to rainfall.

The Texas State Legislature should reconsider this easily understood and enforceable recommendation. In fact, many drivers already observe this recommendation because of common sense. Incorporation of this wording into the Code would not necessarily increase sight distance when driving through splash and spray, but it would improve conspicuousness of vehicles driving in splash and spray and warn other vehicles of their presence, particularly during periods of rainfall in daylight hours.

Ride Quality. TxDOT is leading the state of the art in specifying and measuring pavement smoothness and has an ongoing research program. Nevertheless, a national group has recommended additional research on improved materials and techniques to assist transportation agencies in providing the public with smoother roads and highways. This appears particularly appropriate for the TTC which may permit speeds greater than any other thoroughfares in the U.S.

Web-Based Training. An increasing number of distance learning courses are available on the worldwide web. These can typically be located by using key words with the web browser. Some are free but most of the substantive courses are only accessible for a fee. A research agency could maintain a catalogue of current information for TxDOT on available courses and their costs. These could be used to efficiently train individuals by having immediate access and avoiding travel costs.

REFERENCES

AAPA, "A Guide to Asphalt for Lightly Trafficked Streets," Advisory Note 5, (http://www.aapa.asn.au/docs/no5.pdf), Australian Asphalt Pavement Association, Kew, Victoria, Australia, 1990.

AAPA, "Guide to the Design, Construction, and Specification of Light-Duty Hot Mix Asphalt Pavements," Implementation Guide No. 5, Australian Asphalt Pavement Association, Kew, Victoria, Australia, 2002.

AASHTO, "Guide for Design of Pavement Structures," American Association of State Highway and Transportation Engineers, Washington, D.C., 1993.

AASHTO, "Guidelines for Skid Resistant Pavement Design," American Association of State Highway and Transportation Officials, Washington, D.C., 1976.

AASHTO, *Policy on Geometric Design of Highways and Streets*, American Association of Highway and Transportation Officials, Washington, D.C., 2001.

Abe, T., and Y. Kishi, "Development of Low-Noise Pavement Function-Recovery Machine," Vol. 2, *Proceedings*, 9th International Conference on Asphalt Pavements, Copenhagen, Denmark, August 2002, pp. 4: 1-4.

Accident Sites. *The Tire Pavement Interface, ASTM STP929*, American Society for Testing and Materials, Philadelphia, Pennsylvania., 1986, pp. 47-60.

ACI, "Guide for Design and Construction of Concrete Parking Lots," American Concrete Institute, Detroit, Michigan, 1990.

ACI, "Guide for Design of Jointed Concrete Pavements for Streets and Local Roads," ACI 325.12R-02, American Concrete Institute, Farmington Hills, Michigan, 2002.

Adu-Osei, A., "Characterization of Unbound Granular Layers in Flexible Pavements." *Ph.D. Dissertation*, Texas A&M University, College Station, Texas, 2000.

Alavi, S.H., J.A. Mactutis, S.D. Gibson, A.T. Papagiannakis, and D. Reynaud, "Performance Evaluation of Piezoelectric Weigh-in-Motion Sensors under Controlled Field-Loading Conditions," *Transportation Research Record 1769*, Transportation Research Board, Washington, D.C., 2001, pp. 95-102.

Al-Qadi, I.L., personal communication and unpublished interim report, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, March 2004.

Al-Qadi, I.L., S. Lahouar, and A. Loulizi, "Successful Application of Ground Penetrating Radar for Quality Assurance-Quality Control of New Pavements," Journal of the Transportation Research Board No. 1861, Transportation Research Board, National Research Council, Washington, D.C., 2003.

Amato, I., "Nanotechnology: Shaping the World Atom by Atom," National Science and Technology Council, Committee on Technology, Washington, D.C., 1999.

Anderson, D.A., R.S. Huebner, J.R. Reed, J.C. Warner, and J.J. Henry, "Improved Surface Drainage of Pavements," *NCHRP Web Document 16* (Project 1-29), National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., 1998.

Anderson, R.M., D. Walker, J.A. Scherocman, and L.E. Epley, "Kentucky's Experience with Large Size Aggregate in Bituminous Hot Mix," *Journal of the Association of Asphalt Paving Technologists*, Vol. 60, Seattle, Washington, 1991, pp. 1-18.

András G., "Use of WIM Data for Pavement Structural Design," *Proceedings, Pavement Performance Data Analysis Forum*, sponsored by the TRB Data Analysis Working Group, Budapest, Hungary, September 2000.

Ansari, R., "Theory and Applications of Integrated Fiber Optic Sensors in Structures," *Intelligent Civil Engineering Materials and Structures*, American Society of Civil Engineers, 1997, pp. 2-28.

ASTM, "Road and Paving Materials; Vehicle-Pavement Systems," Volume 04.03, American Society for Testing and Materials, ASTM International, Conshohocken, Pennsylvania, 2002.

Attoh-Okine, N.O., and S. Menash, "MEMS Application in Pavement Condition Monitoring - Challenges," Proceedings, 19th International Symposium on Automation and Robotics in Construction, National Institute of Standards and Technology, Gaithersburg, Maryland, September 2002, pp. 387-392.

Austroads, "A Guide to the Design of New Pavements for Light Traffic," APRG Report No. 21, Austroads Pavement Reference Group, Vermont South, Victoria, Australia, 1998.

Austroads, "Pavement Design – A Guide to the Structural Design of Road Pavements," Haymarket, New South Wales, Australia, 2001.

BAA, "Aircraft Pavements: Pavement Design Guide for Heavy Aircraft Loading," BAA PLC, Group Technical Services, West Sussex, United Kingdom, 1993.

Bagui, S.K., "Design of Flexible Pavement for Low-Volume Road and Residential Street," Proceedings, Indian Roads Congress, New Delhi, India, 2002, pp. 61-66.

Baker, H.B., and M.R. Buth, "Load Response Instrumentation Installation and Testing Procedures: Minnesota Road Research Project," *Proceedings, 4th International Conference on Bearing Capacity of Roads and Airfields*, Minnesota Department of Transportation, Minneapolis, Minnesota, August 1994, pp. 1371-1383.

Balmer, G.G., and B.M Gallaway, "Pavement Design and Controls for Minimizing Automotive Hydroplaning and Increasing Traction," *Frictional Interaction of Tire and*

Pavement, ASTM STP 793, American Society for Testing and Materials, 1983, pp. 167–190.

Banasiak, D. "Smooth as a Baby's…," *Roads and Bridges Magazine*, April 1996, pp. 36-37.

Bendtsen, H., and L.E. Larsen, "Two-Layer Porous Pavements and Noise Reductions in Denmark," Vol. 2, *Proceedings*, 9th International Conference on Asphalt Pavements, Copenhagen, Denmark, August 2002, pp. 4: 1-3.

Benekohal, R.F., and M. Girianna, "Technologies Used for Truck Classification and Methodologies for Estimating Truck VMT," Transportation Research Board Annual Meeting CD-ROM, Washington, D.C., January 2003.

Benz, R.J., D.W. Fenno, and M.E. Goolsby, "ITS Environmental Sensors: The Houston Experience," Report Number FHWA/TX-02/3986-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2002.

Berengier, M., J.F. Hamet, and P. Bar, "Acoustical Properties of Porous Asphalts: Theoretical and Environmental Aspects," *Transportation Research Record 1265*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1990, pp. 9-24.

Bertrand, C.B., Jr., Personal communication via telephone on November 17, 2003.

Bertrand, C.B., Jr., Personal communication via telephone on January 27, 2005.

Bhasin, A., J.W. Button, and A. Chowdhury, "Evaluation of Simple Performance Tests on HMA Mixtures from the South Central United States," Research Report FHWA/TX-03/558-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2003.

Bishop, R., "Intelligent Vehicles-A New World Coming," Presentation at the Casualty Actuarial Society, Arlington, Virginia, May 2000.

Blomquist, D., and J. Carson, "Utilizing Road Weather Information System (RWIS) Data to Improve Response to Adverse Weather Conditions," *Proceedings, Conference on Traffic Safety on Three Continents*, Moscow, Russia, September 2001, pp. 65-77.

Bonaquist, R.F., D.W. Christensen, and W. Stump, III, "Simple Performance Tester for Superpave Mix Design: First-Article Development and Evaluation," NCHRP Report 513, National Cooperative Highway Research Program, National Academy of Sciences, Washington, D.C., 2003.

Brosseaud, Y., "Evaluation of the Experimental Site of Porous Asphalt on Motorway A63 after Eight Years of Traffic," Presented at European Conference on Porous Asphalt, Madrid Spain, 1997.

Brosseaud, Y., J.C. Poirier, and J.P. Roche, "Draining Asphalts – Conclusions Drawn from the Performance Assessment of the Two Experimental Road Sites," *Proceedings*, XXth World Road Congress, Permanent International Association of Road Congresses (PIARC), Montreal, Canada, 1995.

Brown, E.R., P.S. Kandhal, and J. Zhang, "Performance Testing for Hot Mix Asphalt," NCAT Report No. 2001-05, National Center for Asphalt Technology, Auburn University, Alabama, 2001.

Brown, J.R., "Pervious Bitumen–Macadam Surfacings Laid to Reduce Splash and Spray at Stonebridge, Warwickshire," Transportation Road Research Laboratory Report No. LR 563, 1973.

Buiter, R, W.M.H. Cortenraad, A.C. van-Eck, and H. van-Rij, "Effects of Transverse Distribution of Heavy Vehicles on Thickness Design of Full-Depth Asphalt Pavements," *Transportation Research Record 1227*, Transportation Research Board, Washington, D.C., 1989, pp. 66-74.

Button, J.W., W.W. Crockford, E.G. Fernando, H.L Von Quintus, J.A. Scherocman, J.T. Harvey, and B. Coree, "Design and Evaluation of Large-Stone Asphalt Mixtures," *NCHRP Report 386*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 1997.

Cable, J.K., C. Bauer, E. Jaselskis, and L. Li, "Stringless Portland Cement Concrete Paving," Report CTRE Project 02-128, Center for Portland Cement Concrete Pavement Technology, Iowa State University, Ames, Iowa, February 2004.

Cackler, E.T., "Detailed Planning for Research on Accelerating the Renewal of America's Highways," F-SHRP Web Document 1, Study 1 – Renewal, Future Strategic Highway Research Program, Transportation Research Board, Washington, D.C., 2003.

Camomilla, G., M. Malgarini, and S. Gervasio, "Sound Absorption and Winter Performance of Porous Asphalt Pavement," *Transportation Research Record 1265*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1990, pp. 1-8.

Cenek, P.D., N.J. Jamieson, and J.I. Towler, "The Influence of Texture Depth on Skidding Resistance," presented at The New Zealand Land Transport Symposium 2000, "Engineering for Road Safety," Rotorua, New Zealand, October 2000.

Ceylan, H., E. Tutumluer, E.J. Barenberg, "Artificial Neural Networks for Analyzing Concrete Airfield Pavements Serving the Boeing B-777 Aircraft," *Transportation Research Record 1684*, Transportation Research Board, Washington, D.C., 1999, pp. 110-117.

Chatti, K., and D. Lee, "Development of New Profile-Based Truck Dynamic Load Index," *Journal of the Transportation Research Board No. 1806*, The National Academies, Washington, D.C., 2002.

Chong, K.P., and E.J. Garboczi, "Smart and Designer Structural Material Systems," *Progress in Structural Engineering and Materials*, Vol. 4, 2002, pp. 417-430.

Chong, K.P., N.J. Carino, and G. Washer, "Health Monitoring of Civil Structures," *Electronic Journal of Smart Materials and Structures* (http://www.iop.org/EJ/journal/SMS), Vol. 12, June 2003, pp. 483-493.

Christory, M.J-P., "Urban and Peri-Urban Porous Pavements," *Proceedings, 7th International Symposium on Concrete Roads*, The European Cement Association, Vienna, Austria, October 1994.

Chung, H.C., R. Girardello, T. Soeller, and M. Shinozuka, "Automated Management of Pavement Inspection System (AMPIS)," *Proceedings, International Society for Optical Engineering*, Vol. 5057, San Diego, California, March 2003, pp. 634-644.

Collop, A.C., B. Al Hakim, and N.H. Thom, "Effects of Weigh-in-Motion Errors on Pavement Thickness Design," *Proceedings, Institution of Mechanical Engineers*, Part D, Journal of Automobile Engineering, Vol. 216, No. 2, 2002, pp. 141-151.

Colwill, D.M., and M.E. Daines, "Development of Spray-Reducing Macadam Road Surfacings in the United Kingdom, 1987-1967," *Transportation Research Record 1115*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1987, pp. 196-202.

Colwill, D.M., G.J. Bowskill, J.C. Nicholls, and M.E. Daines, "Porous Asphalt Trials in the United Kingdom," *Transportation Research Record 1427*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1993, pp. 13-21.

Cooley, L.A., E.R. Brown, and D.E. Watson, "Evaluation of Open-Graded Friction Course Mixtures Containing Cellulose Fibers," *Transportation Research Record 1723*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 2000, pp. 19-25.

Corps of Engineers, "Pavement Design for Roads, Streets, Walks, and Open Storage Areas," *TM 5-822-5*, (http://www.usace.army.mil/inet/usace-docs/armytm/tm5-822-5/) Department of Army, Corps of Engineers, Washington, D.C., 1992.

Corte, J.F., and J.P. Serfass, "The French Approach to Asphalt Mixture Design: A Performance-Related System of Specifications," *Journal of the Association of Asphalt Paving Technologists*, Vol. 69, Reno, Nevada, 2000.

Cosentino, P.J., and B.G. Grossman, "Development and Implementation of a Fiber Optic Vehicle Detection and Counter System," Report No. FL/DOT/RMC/06650-0726, Florida Institute of Technology, Melbourne, Florida, 1996.

Cosentino, P.J., W. von Eckroth, and B.G. "Grossman, Analysis of Fiber Optic Traffic Sensors in Flexible Pavements," *Journal of Transportation Engineering*, Vol. 129, No. 5, American Society of Civil Engineers, September/October 2003, pp. 549-557.

CPCA, "Thickness Design for Concrete Highway and Street Pavements," EB209.03P, Canadian Portland Cement Association, Ottawa, Ontario, Canada, 1984.

Crawford, D., "A WISA Way to Drive: Intelligent Speed Adaptation Can Have a Positive Role in Automatically Implementing Weather Warnings," *ITS International*, Vol. 6, No. 2, March/April 2000, pp. 52-53.

Croney, D., and Croney, P., *The Design and Performance of Road Pavements*, McGraw-Hill Book Company, Inc, New York, New York, 1991.

Dalimier, M., and R. Torrent, "Improvement of IRI Values of Concrete Pavements Constructed in Argentina with Slip-Form Pavers," 7th International Conference on Concrete Pavements, Orlando, Florida, 2001, pp. 407-420.

De Bondt, A.H., "Innovative Airfield Pavement Design," Minicad Systems Pty. Ltd., http://www.mincad.com.au/APSDSPaperdeBondt/APSDSPaperdeBondt.htm), Victoria, Australia, 2002.

De Lurdes Antunes, M., and L. Francken, "Development of a Bituminous Pavement Design Method for Europe: COST 333 Action and AMADEUS Project, *Proceedings, 2nd European Road Research Conference*, Directorate-General VII Transport, European Commission, Brussels, Belgium, June 1999.

Decoene, Y. "Contribution of Cellulose Fibers to the Performance of Porous Asphalts," *Transportation Research Record 1265*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1990, pp. 82-86.

Delanne, Y., V. Goyon, and J.P. Poirier, "Experimental Sites for Testing Thin Layer Drainage Asphalt Performances: First Results," *Proceedings*, *XIXth World Road Congress*, PIARC Technical Committees on Flexible Roads and Surface Characteristics, Marrakech, Morocco, September 1991, pp. 278-281.

Diringer, K.T., and R.T. Barros, "Predicting the Skid Resistance of Bituminous Pavements through Accelerated Laboratory Testing of Aggregates," *Surface Characteristics of Roadways: International Research Technologies, ASTM STP 1031*, American Society of Testing and Materials, Philadelphia, Pennsylvania. 1990, pp. 61-76.

Dore, G., and G. Dupling "Monitoring Pavement Response during Spring Thaw Using Fiber-Optic Sensors," *Proceedings, 6th International Conference on the Bearing Capacity of Roads and Airfields*, Vol. 1, Lisbon, Portugal, June 2002, pp. 15-24.

Dry, C.M., "Improvement in Reinforcing Bond Strength in Reinforced Concrete with Self-Repairing Chemical Adhesives," Proceedings, International Society for Optical Engineering, Vol. 3043, San Diego, California, 1997, pp. 44-50.

Dry, C.M., "Smart Bridge and Building Materials in which Cyclic Motion is Controlled by Internally Released Adhesives," *Proceedings, International Society for Optical Engineering,* Vol. 2719, San Diego, California, 1996, pp. 247-254.

Eason, J.R., and J.F. Shook, "Design of Hot Mix Asphalt Pavements for Commercial, Industrial, and Residential Applications," IS-109, National Asphalt Pavement Association, Lanham, Maryland, 1991.

El-Korchi, T., J. Bacon, M. Turo, and M. Emecian, "Ride Quality Assessment with Pavement Profiling Devices," *Journal of the Transportation Research Board No. 1806*, The National Academies, Washington, D.C., 2002.

Elseifi, M.A., I.L. Al-Qadi, A. Loulizi, and J. Wilkes, "Performance of Geocomposite Membrane as Pavement Moisture Barrier," *Transportation Research Record 1772*, Transportation Research Board, Washington, D.C., 2001, pp. 168-173.

Epps Martin, A., personal communication with the research supervisor of TxDOT Research Project 4468, "Evaluate Fatigue Resistance of Rut-Resistant Mixes," July 2004.

ERES Consultants, Inc., "Development of 2002 Guide for Design of New and Rehabilitated Pavement Structures – Stage A Report," NCHRP Project 1-37A Interim Report, 1999.

Estakhri, C.K., and J.W. Button, "Performance Evaluation of Novachip Ultrathin Friction Course," Report No. FHWA/TX-96/553-2F, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1995.

Evans, L.D., and A. Eltahan, "LTPP Profile Variability," Report No. FHWA-RD-00-113, Office of Infrastructure Research and Development, Federal Highway Administration, Virginia, 2000.

Federal Highway Administration, "Nationwide Personal Transportation Survey Databook." Report No. FHWA-PL-94-010, Federal Highway Administration, Washington, D.C., 1990.

Fernando, E.G., "Development of Ride Quality Specifications Criteria for ACP Overlays," Research Report 1378-S, Texas Transportation Institute, Texas A&M University, College Station, Texas, July 1998.

Fernando, E.G., "Index for Evaluation Initial Overlay Smoothness with Measured Profiles," *Journal of the Transportation Research Board No. 1806*, The National Academies, Washington, D.C., 2002.

Fernando, E.G., and C. Bertrand, "Application of Profile Data to Detect Localized Roughness," *Journal of the Transportation Research Board No. 1813*, Transportation Research Board, Washington, D.C., 2002.

Fernando, E.G., and S.C. Leong, "Profile Equipment Evaluation," Research Report 1378-2, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1997.

Ferne, B., and M. Nunn, "The European Approach to Long Lasting Asphalt Pavements," *Proceedings, International Symposium on Design and Construction of Long-Lasting Asphalt Pavements*," Auburn University, Auburn, Alabama, June 2004.

FHWA, "Field Test of Monitoring of Urban Vehicle Operations Using Non-Intrusive Technologies," Report No. FHWA-PL-97-018, Federal Highway Administration, 1997.

FHWA, "Pilot Projects Kick Off Traffic Data Pooled-Fund Study," *Focus Magazine*, Federal Highway Administration, Turner-Fairbanks Highway Research Center, McLean, Virginia, March 2002.

FHWA, "Wanted: A Smoother Ride," *Focus*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., July 2002, p. 5.

Foley, G., "Review of Residential Street Design and Construction Standards," Research Report ARR 337, Australian Road Research Board Transport Research Ltd., Vermont South, Victoria, Australia, 2000.

Fontaine, M.D., "Guidelines for Application of Portable Work Zone Intelligent Transportation Systems," Transportation Research Record 1824, Transportation Research Board, Washington, D.C., 2003, pp. 15-22.

Fort, J.P., "Performance Assessment of Ultra-Thin Friction Courses," *Proceedings*, *Conference on Strategic Highway Research Program and Traffic Safety on Two Continents*, Swedish Road and Transport Research Institute, Linkoping, Sweden, 1994.

Franklin, R.E., D.P. Jones, and J. Mercer, "Surface Characteristics of a Recently Constructed Concrete Motorway in the UK," Session 8, *Proceedings*, *7th International Symposium on Concrete Roads*, Vienna, Austria, October 1994, pp. 91-96.

Fuch, M., "Skid Resistance of Exposed Aggregate Concrete," Session 8, *Proceedings*, *7th International Symposium on Concrete Roads*, Vienna, Austria, October 1994, pp. 161-166.

Fuhr, P.L., and D.R. Huston, "Corrosion Detection in Reinforced Concrete Roadways and Bridges via Embedded Fiber Optic Sensors," *Electronic Journal of Smart Materials and Structures* (http://www.iop.org/EJ/journal/SMS), Vol. 7, April 1998, pp. 217-228.

Fuhr, P.L., D.R. Huston, P.J. Kajenski, and T.P. Ambrose, "Performance and Health Monitoring of the Stafford Medical Building Using Embedded Sensors," *Electronic Journal of Smart Materials and Structures* (http://www.iop.org/EJ/journal/SMS), Vol. 1, March 1992, pp. 63-68.

Gallaway, B.M., D. L. Ivey, H. E. Ross, W. B. Ledbetter, D. L. Woods, and R. E. Schiller, "Tentative Pavement and Geometric Design Criteria for Minimizing Hydroplaning," Report No. FHWA-RD-75-11, Federal Highway Administration, Washington, D.C., 1975.

Gallaway, B.M., R.E. Schiller, D.L. Ivey, W.B. Ledbetter, H.E. Ross, D.L. Woods, and F. White, "Pavement and Geometric Design Criteria for Minimizing Hydroplaning," Report No. FHWA-RD-79-31, Federal Highway Administration, Washington, D.C., 1979.

Gargett, T., "The Introduction of a Skidding-Resistance Policy in Great Britain," *Surface Characteristics of Roadways: International Research Technologies, ASTM STP 1031*, American Society of Testing and Materials, Philadelphia, Pennsylvania. 1990, pp. 30-38.

Gazetas, A.M., "Stresses and Displacements in Cross-Anisotropic Soils," *Journal of Geotechnical Engineering*, Vol. 108, No. 4, 1982, pp. 532-553.

Gent, S., "Iowa DOT Uses Smart Work Zone to Increase Safety," American Public Works Association, Kansas City, Missouri, 1998.

Gent, S., "Rural Smart Work Zone: A Warning System for Motorists during Interstate Reconstruction Projects," Iowa Department of Transportation, Ames, Iowa, 1998.

Gonzalez, A., A.T. Papagiannakis, and E.J. O'Brien, "Evaluation of an Artificial Neural Network Technique Applied to Multiple-Sensor Weigh-in-Motion Systems," *Proceedings, 82nd Annual Meeting of the Transportation Research Board* (CD-ROM), Washington, D.C., 2003.

Goodwin, L.C., and Pisano, P., "Best Practices for Road Weather Management: Version 2," Federal Highway Administration, Washington, D.C., 2003.

Gorte, C.B., K. Pedersen, and C.C. McDonnell, "The MVMA Investigation into the Complexities of Heavy Truck Splash and Spray Problem," *Proceedings*, *10th International Technical Conference on Experimental Safety Vehicles*, (published by National Highway Traffic Safety Administration), Oxford, United Kingdom, 1986, pp. 848-863.

Gothie, M., T. Parry, and P. Roe, "The Relative Influence of the Parameters Affecting Road Surface Friction," 2nd International Colloquium on Vehicle-Tyre-Road Interaction, Florence, Italy, 2001.

Greibe, A.P., "Porous Asphalt and Traffic Study," *Proceedings, Ninth International Conference on Asphalt Pavements*, International Society for Asphalt Pavements, Copenhagen, Denmark, 2002, pp. 4:3-2.

Hallenbeck, M., and H. Weinblatt, "Equipment for Collecting Traffic Load Data," *NCHRP Report 509*, National Cooperative Highway Research Board, Transportation Research Board, Washington, D.C., 2004.

Hankins, K.C., "Use of Rainfall Characteristics in Developing Methods for Reducing Wet Weather Accidents in Texas," Report No. 135-4, Texas Highway Department, 1975.

Harrison, R., and C. Bertrand, "The Development of Smoothness Specifications for Rigid and Flexible Pavements in Texas," Research Report 1167-1, Center for Transportation Research, The University of Texas at Austin, 1991.

Harwood, D.W., D.J. Torbic, K.R. Richard, W.D. Glauz, and L. Elefteriadou, "Review of Truck Characteristics as Factors in Roadway Design," *NCHRP Report 505*, National

Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 2003.

Hayes, G.G., D.L. Ivey, and B.M. Gallaway, "Hydroplaning, Hydrodynamic Drag, and Vehicle Stability," *Frictional Interaction of Tire and Pavement, ASTM STP 793*, American Society for Testing and Materials, 1983, pp. 151–166.

He, Z., G. Kennepohl, Y. Cai, and R. Haas, "Development of Performance Models for Ontario's New Mechanistic-Empirical Pavement Design Method," *Proceedings, 8th International Conference on Asphalt Pavements*," Seattle, Washington, August 1997.

Heerkens, J.C.P., and G.G. Van Bochove, "Twinlay, A New Concept of Drainage Asphalt Concrete," *Proceedings*, *EuroNoise*, Infratech Pavement Consultants and Heijmans Road Construction Company, The Netherlands, 1998.

Hegmon, R.R., T.D. Gillespie, and W.E. Meyer, "Measurement Principles Applied to Skid Testing," *Skid Resistance of Highway Pavements, ASTM STP 530*, American Society for Testing and Materials, 1973, pp. 78-90.

Heinz, F.T. and A. Sandstrom, "Continuous Compaction Control, CCC," European Workshop Compaction of Soils and Granular Materials, Paris, May 2000, pp. 237-246.

Henry, J.J., "Evaluation of Pavement Friction Characteristics," *NCHRP Synthesis 291*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 2000.

Henry, J.J., "Tire Wet-Pavement Traction Measurement: A State-of-the-Art Review," *The Tire Pavement Interface, ASTM STP 929*, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1986, pp. 3-25.

Henry, J.J., and S.H. Dahir, "Effects of Textures and the Aggregates that Produce Them on the Performance of Bituminous Surfaces," *Transportation Research Record 712*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1979, pp. 44-50.

Heystraeten, G.V., "The Winter Behaviour of Porous Asphalt in Belgium," *Proceedings*, *XIXth World Road Congress*, PIARC Technical Committees on Flexible Roads and Surface Characteristics, Marrakech, Morocco, September 1991, pp. 289-291.

Hicks, R.G., P. Curren, and J.R. Lundy, "Asphalt Paving Design Guide," Asphalt Pavement Association of Oregon, Salem, Oregon, 1998.

Highway Research Board, "Skid Resistance," *NCHRP Synthesis 14*, National Cooperative Highway Research Program, Highway Research Board, National Academy of Sciences, Washington, D.C., 1972.

Hoerner, T.E., K.D. Smith, and J.E. Bruinsma, "Incremental Costs and Performance Benefits of Various Features of Concrete Pavements," FHWA-HRT-04-044, Office of Acquisition and Management, Federal Highway Administration, Washington, D.C., 2004.

Hong Kong Highways Department, Road Note 5 - Road Surface Requirements for High Speed Roads, Government of the Hong Kong Special Administrative Region, Kowloon, Hong Kong, 1983.

Horne, W.B., "Runway Friction Tester Minimum Dynamic Hydroplaning Speed," prepared for ASTM E 17.22/96.1 Task Group Meeting, Atlanta, Georgia, 1998.

Horne, W.B., "Tire Hydroplaning and Its Effects on Tire Traction," *Highway Research Record No. 214*, Transportation Research Board, Washington, D.C., 1968, pp. 24-33.

Hosking, J.R., and G.C. Woodford, "Measurement of Skidding Resistance: Part 1. Guide to the Use of SCRIM," TRRL Report No. LR737, Transport and Road Research Laboratory, Crowthorne, United Kingdom, 1976.

Hossain, M., Z.Q. Siddique, and W.H. Parcells, Jr., *Proceedings, 82nd Annual Meeting of the Transportation Research Board,* Washington, D.C., January 2003.

Huang, B, L.N. Mohammad, and M. Rasoulian, "Three-Dimensional Numerical Simulation of Asphalt Pavement at Louisiana Accelerated Loading Facility," *Transportation Research Record 1764*, Transportation Research Board, Washington, D.C., 2001, pp. 44-58.

Huang, Y.H., *Pavement Analysis and Design*, Prentice Hall, New Jersey, 1993.

Huddleston, I.J., H. Zhou, and R.G. Hicks, "Performance Evaluation of Open-Graded Asphalt Concrete Mixtures Used in Oregon," *Asphalt Paving Technology*, Vol. 60, March 1991, pp. 71-43.

Huet, M., A. de Boissoudy, J.C. Gramsammer, A. Bauduin, and J. Samonos, "Experiments with Porous Asphalt on the Nantes Fatigue Test Track," *Transportation Research Record 1265*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1990, pp. 54-58.

Hultqvist, B.A., "Surface Characteristics and Driving Comfort on Two Swedish Concrete Roads," Session 8, *Proceedings*, *7th International Symposium on Concrete Roads*, Vienna, Austria, October 1994, pp. 167-172.

Hunter, R.N., *Asphalts in Road Construction*, Thomas Telford Publishing, London, Great Britain, 2000.

Idriss, R.L., M.B. Kodindouma, A.D. Kersey, and M.A. Davis, "Multiplexed Bragg Grating Optical Fiber Sensors for Damage Evaluation in Highway Bridges," *Electronic Journal of Smart Materials and Structures* (http://www.iop.org/EJ/journal/SMS), Vol. 7, April 1998, pp. 209-216.

Inman, D.J., Center for Intelligent Materials Systems and Structures, Virginia Tech, Department of Mechanical Engineering, Blacksburg, Virginia, personal communication via e-mail, February 2004.

Isenring, T., H. Koster, and I. Scazziga, “Experiences with Porous Asphalt in Switzerland,” *Transportation Research Record 1265*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1990, pp. 41-53.

Ivey, D.L., E.K. Lehtipuu, and J.W. Button, “Rainfall and Visibility - The View from Behind the Wheel,” Research Report 135-3, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1975.

Jackson, J., M. Clarke, T. Hook, and R. Gibson, “Low Noise Road Surfacing and Durability Trials in New Zealand,” *Asphalt Review*, Vol. 22, No. 4, Australian Asphalt Pavement Association, Kew, Victoria, Australia, December 2003.

Jacob, B., and E. O'Brien, “Weigh-in-Motion of Axles and Vehicles for Europe” (Executive Summary), 4th Framework Program Transport, European RTD Project, RO-96-SC, 403, Laboratoire Central des Ponts et Chaussées and University College, Dublin, 2002.

Jacob, B., E.J. O'Brien, and W. Newton, “Assessment of the Accuracy and Classification of Weigh-in-Motion Systems: Part 2, European Specification,” *Heavy Vehicle Systems*, Vol. 7, No. 2-3, 2000, pp. 153-168.

Jahren, C.T., “Best Practices for Maintaining and Upgrading Aggregate Roads in Australia and New Zealand,” Report MN/RC-P2002-01, Minnesota Department of Transportation, St. Paul, Minnesota, 2000.

Jehaes, S., “Tests of WIM Systems in Cold Climates,” *Proceedings, Final Symposium of the Project WAVE* (1996-1999), *Weigh-in-Motion of Road Vehicles*, Edited by Bernard Jacob, Paris, France, 1999, pp. 285- 296.

Johnson, C., “I-35W and Mississippi River Bridge Anti-Icing Project Operational Evaluation Report,” Report No. 2001-22, Minnesota Department of Transportation, St Paul, Minnesota, 2001.

Johnson, W.A., A. C. Stein, and J. R. Hogue, “Full-Scale Testing Devices to Reduce Splash and Spray,” Report No. DOT-HS 806-694, National Highway Traffic Safety Administration, Washington, D.C., 1985.

Johnson, W.A., A.C. Stein, and J.R. Hogue, “Repeatability of Spray Tunnel Measurements,” Final Report by Systems Technology, Inc., for National Highway Traffic Safety Administration, Washington, D.C., 1990.

Jones, D., “Specialist Concrete Pavement Surfaces,” *Quarry Management*, Vol. 12, QMJ Publishing Ltd., 7 Nottingham, United Kingdom, 1999.

Jones, K.B., and J. Omundson, "Evaluation of Lightweight Profilers for Construction Smoothness Evaluation," Report No. MLR-02-02, Office of Materials, Iowa Department of Transportation, Ames, Iowa, 2004.

Jurriaans, G., J.M.M. Van Der Loo, and J.S. Van Der Vloedt, "New Opinions in the Friction Problematic with Brushed Textures and Exposed Aggregates," Session 8, *Proceedings*, *7th International Symposium on Concrete Roads*, Vienna, Austria, October 1994, pp. 167-172.

Kam, K.K., and D.F. Lynch, "Use of Friction Course Mixes in Ontario," *Transportation Research Record 1115*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1993, pp. 203-215.

Kamplade, J., "Low Noise Concrete Pavements in Germany," Session 8, *Proceedings*, *7th International Symposium on Concrete Roads*, Vienna, Austria, October 1994, pp. 103-108.

Kandhal, P.S., "Design, Construction, and Maintenance of Open-Graded Asphalt Friction Courses," *Information Series 115*, National Asphalt Pavement Association, Lanham, Maryland, 2002.

Kandhal, P.S., "How Asphalt Pavements Mitigate Tire-Pavement Noise," *Better Roads*, Vol. 73, No. 11, November 2003.

Kandhal, P.S., and F. Parker, Jr., "Aggregate Tests Related to Asphalt Concrete Performance in Pavements," *NCHRP Report 405*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 1998.

Kandhal, P.S., and L.A. Cooley, Jr., "Accelerated Laboratory Rutting Tests: Evaluation of the Asphalt Pavement Analyzer," NCHRP Report 508, National Cooperative Highway Research Program, National Academy of Sciences, Washington, D.C., 2003.

Karamihas, S., R.W. Perera, T.D. Gillespie, and S. Kohn, "Diurnal Changes in Profile of Eleven Jointed PCC Pavements," 7th International Conference on Concrete Pavements, Orlando, Florida, 2001, pp. 69-80.

Karamihas, S.M., "Assessment of Profiler Performance for Construction Quality Control with Simulated Profilograph Index," *Proceedings, 83rd Annual Meeting of the Transportation Research Board*, Washington, D.C., January 2004.

Kenis W.J., "Predictive Design Procedures, VESYS Users Manual, An Interim Design Method for Flexible Pavements Using the VESYS Structural Subsystem," *Final Report FHWA-RD-77-154*, Federal Highway Administrartion, Washington, D.C., 1977.

Kim, S.W., I. Cho, J.H. Lee, J. Park, D.H. Yi, and D. Cho, "A New Method for Accurately Estimating the Weight of Moving Vehicles Using Piezoelectric Sensors and Adaptive-Footprint Tire Model," *Vehicle Systems Dynamics*, Vol. 39, No. 2, 2003, pp. 135-148.

Kim, Y.R., H-J Lee, and D. N. Little, "Fatigue Characterization of Asphalt Concrete Using Viscoelasticity and Continuum Damage Theory," *Journal of the Association of Asphalt Paving Technologists*, Vol. 66, 1997a, pp. 520-569.

Kim, Y.R., H-J Lee, Y. Kim, and D.N. Little, "Mechanistic Evaluation of Fatigue Damage Growth and Healing of Asphalt Concrete: Laboratory and Field Experiments," *Proceedings, 8th International Conference on Asphalt Pavements*, Seattle, Washington, 1997b, pp. 1089-1107.

Kistler, "Weigh In Motion: The First System for Monitoring at High Speeds," Commercial Advertising Brochure, Kistler Instrument Corporation, Amherst, New York, 2003.

Knapton, J., and M. Meletiou, "The Structural Design of Heavy Duty Pavements for Ports and Other Industries," The British Pre-cast Concrete Federation, Ltd. (for Interpave), Leicester, United Kingdom, 1996.

Koppa, R.J., V.J. Pezoldt, R.A. Zimmer, M.N. Deliman, and R. Flowers, "Development of a Recommended Practice for Heavy Truck Splash and Spray Evaluations," Report RF 7143, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1990.

Kuennen, T., "Small Changes Will Bring Big Changes to Roads," *Better Roads Magazine*, Des Plaines, Illinois, July 2004.

Kuennen, T., "Technologies Boost Concrete Pavement Smoothness" *Better Roads Magazine*, Des Plaines, Illinois, March 2003.

Kulakowski, B.T., and D.W. Harwood, "Effect of Water Film Thickness on Tire-Pavement Friction," *Surface Characteristics of Roadways: International Research Technologies, ASTM STP 1031*, American Society of Testing and Materials, Philadelphia, Pennsylvania, 1990, pp. 50-60.

Kummer, H.W., and W.E. Meyer, "Tentative Skid-Resistance Requirements for Main Rural Highways," *NCHRP Report 37,* National Cooperative Highway Research Program, Highway Research Board, National Research Council, National Academy of Sciences, Washington, D.C., 1967.

La Torre, F., L Ballerini, and N. Di Volo, "Correlation between Longitudinal Roughness and User Perception in Urban Areas," *Journal of the Transportation Research Board No. 1806*, The National Academies, Washington, D.C., 2002.

LaCroix, J.E., and D.R. Schwartz, "Factors Influencing the Riding Quality of New Pavement Surfaces," Physical Research Report No. 65, Illinois Department of Transportation, Springfield, Illinois, 1975.

Larsen, D.A., "Evaluation of Lightweight Non-Contact Profilers for Use in Quality Assurance Specifications on Pavement Smoothness," Report No. 2225-1-99-8, Office of Research and Materials, Connecticut Department of Transportation, Rocky Hill, Connecticut, 1999.

Lefebvre, G., Porous Asphalt, PIARC, Technical Committee on Flexible Roads, Technical Committee on Surface Characteristics, Belgium, 1993.

Lenke, L.R., and R.A. Graul, "Development of Runway Rubber Removal Specifications Using Friction Measurements and Surface Texture for Control," *The Tire Pavement Interface, ASTM STP 929*, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1986, pp. 72-88.

Leonard, D., and L. Francken, "An Improved Tool for Structural Design of Flexible, Composite and Rigid Structures," *Proceedings, 9th International Conference on Asphalt Pavement*s, Copenhagen, Denmark, August 2002.

Little, D.N., J.W. Button, P.W. Jayawickrama, M. Solaimanian, and B. Hudson, "Development of Statistical Wet Weather Model to Evaluate Frictional Properties at the Pavement-Tire Interface on Hot Mix Asphalt Concrete," Report 1707-3, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2001.

Litzka, J., "Austrian Experiences with Winter Maintenance on Porous Asphalt," *Proceedings, Ninth International Conference on Asphalt Pavements*, International Society for Asphalt Pavements, Copenhagen, Denmark, 2002, pp. 4:3-3.

Litzka, J., "Noise Reducing Surfaces," *Proceedings*, *7th International Symposium on Concrete Roads*, Vienna, Austria, October 1994, pp. 171-186.

Luo Y., "Effect of Pavement Temperature on Frictional Properties of Hot-Mix-Asphalt Pavement Surfaces at the Virginia Smart Road," Master's Thesis Submitted to the Faculty of Virginia Polytechnic Institute and State University, Blacksburg, Virginia, January 2003.

Lytton, R.L., J. Uzan, E.G. Fernando, R. Roque, D. Hiltunen, and S.M. Stoffels, "Development and Validation of Performance Prediction Models and Specifications for Asphalt Binders and Paving Mixes," Report No. SHRP-A-357, Strategic Highway Research Program, National Research Council, Washington, D.C., 1993.

Ma, S., and Caprez, M., "The Pavement Roughness Requirement for WIM," *First European Conference on Weigh-in-Motion of Road Vehicles*, Switzerland, 1995.

Mahboub, K., and E.G. Williams, "Construction of Large-Stone Asphalt Mixes (LSAMs) in Kentucky," *Transportation Research Record 1282*, Transportation Research Board, Washington, D.C., 1990, pp. 41-44.

Mamlouk, M.S., "Effect of Vehicle-Pavement Interaction on Weigh-in-Motion Equipment Design," *International Journal of Vehicle Design-Heavy Vehicle Systems*, Third Engineering Foundation Conference, The Netherlands, June 1996.

Martin, P.T., and Y. Feng, "Detector Technology Evaluation," Department of Civil and Environmental Engineering," Traffic Laboratory, University of Utah, 2003.

Martinez, J.E., J.M. Lewis, and A.J. Stocker, "A Study of Variables Associated with Wheel Spin-Down and Hydroplaning," Report No. 147-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1972.

Masad, E., V.K. Jandhyala, J. Dasgupta, N. Somadevan, and N. Shashidhar, "Characterization of Air Void Distribution in Asphalt Mixes Using X-ray Computed Tomography," *Journal of Materials in Civil Engineering,* ASCE, Vol. 15 No. 2, 2002, pp. 122-129.

Masad, E.A., D.N. Little, L. Tashman, S. Saadeh, T. Al-Rousan, and R. Sukhwani, "Evaluation of Aggregate Characteristics Affecting HMA Concrete Performance," Research Report ICAR 203-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2003.

Maycock, G., "The Problem of Water Thrown Up by Vehicles on Wet Roads," Report No. 4, British Road Research Laboratory, Crowthorne, Berkshire, United Kingdom, 1966.

McCall, B., and W.C. Vodrazka, "States' Successful Practices Weigh-In-Motion Handbook," Federal Highway Administration, Washington, D.C., 1997.

McCoy, P.T., and G. Pesti, "Smart Work Zone Technology Evaluations: Speed Monitoring Displays and Condition-Responsive, Real-Time Travel Information Systems," Institute of Transportation Engineers, Washington, D.C., 2001.

McGillivray, R.T., and B.A. Laurion, "Development of Design and Construction Standards for Seaport Pavement Systems," *Proceedings, Ports '01 Conference*, American Society of Civil Engineers, Ports and Harbors Committee of the Coasts, Oceans, Ports and Rivers Institute, U.S. Section of the Permanent International Association of Navigation Congresses (PIANC), Norfolk, Virginia, 2001, pp. 13.

Measures, R.M., A.T. Alavie, R. Maaskant, M. Ohn, S. Karr, and S. Huang, "A Structurally Integrated Bragg Grating Laser Sensing System for a Carbon Fiber Prestressed Concrete Highway Bridge," *Electronic Journal of Smart Materials and Structures* (http://www.iop.org/EJ/journal/SMS), Vol. 4, April 1995, pp. 20-30.

Mehregany, M., "Microelectromechanical Systems," *Circuits and Devices Magazine*, Vol. 9, No. 4, July 1993, pp. 14-22.

Menyu, Y., and Z. Qisen, "Research on the Design Method of Asphalt Pavement," *Proceedings, 8th International Conference on Asphalt Pavements*," Seattle, Washington, August 1997.

MnRoad, Project Meeting Minutes, "Portable Non-Intrusive Traffic Detection System (PNITDS)," December 16, 2003.

Mondal, A., A.J.T. Hand, and D.R. Ward, "Evaluation of Lightweight Non-Contact Profilers," Report No. FHWA/IN/JTRP-2000/6, Indiana Department of Transportation, 2000.

Monismith, C.L., J.T. Harvey, T. Bressette, C. Suszko, and J. St. Martin, "The I-710 Freeway Rehabilitation Project: Mix and Structural Section Design, Construction Considerations and Lessons Learned," *Proceedings, International Symposium on Design and Construction of Long-Lasting Asphalt Pavements*," Auburn University, Auburn, Alabama, June 2004.

Moore, A.B., and E.A. Whitehurst, "A Study of Pavement Skid Resistance at High Speeds and at Locations Shown to be Focal Points of Accidents," Phase I Report, The University of Tennessee, Department of Civil Engineering, Knoxville, Tennessee, June 1970.

Moore, A.B., and J.B. Humphreys, "High-Speed Skid Resistance and the Effects of Surface Texture on the Accident Rate," *Skid Resistance of Highway Pavements, ASTM STP 530*, American Society for Testing and Materials, 1973, pp. 91-100.

Mortimer, R.G., J. Monaco, H.L. Crothers, "Effect on Visibility of Wet Weather Spray from Heavy Goods Vehicles," *Vision in Vehicles*, Elsevier Science Publishers, Amsterdam, The Netherlands, 1986, pp. 355-363.

Mulholland, P.J., "Structural Design Criteria for Residential Street Pavements," *Proceedings, Combined Conference of the 13th Australian Road Research Board and 5th Road Engineering Association of Asia and Australasia*, Vermont South, Victoria, Australia, August 1986.

Mulholland, P.J., "Structural Design Guide for Residential Street Pavements: Preliminary Draft," Research Report ARR 150, Australian Road Research Board, Vermont South, Victoria, Australia, 1987.

NAPA, "HMA Pavement Mix Type Selection Guide," IS 128, National Asphalt Pavement Association and Federal Highway Administration, Lanham, Maryland, 2000.

NAPA, "Thin Hot Mix Asphalt Surfacings," IS 110, National Asphalt Pavement Association, Lanham, Maryland, 1995.

National Transportation Safety Board, "Special Study: Fatal Highway Accidents on Wet Pavement." NTSB, Washington, D.C., 1980.

NCHRP, "Aggregate Tests for Portland Cement Concrete Pavements: Review and Recommendations," Research Results Digest 281, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 2003.

NCHRP, "Open-Graded Friction Courses for Highways," *NCHRP Synthesis No. 49*, National Cooperative Highway Research Program, National Academy of Sciences, Washington, D.C., 1978.

NCHRP, "Systems for Design of Highway Pavements," *Research Digest No. 227*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 1998.

Nelson, P.M., and P.G. Abbott, "Acoustical Performance of Pervious Macadam Surfaces for High-Speed Roads," *Transportation Research Record 1265*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1990, pp. 25-33.

Netherlands Institute for Road Safety Research, *Skidding Accidents*, Institute for Road Safety Research, Voorburg, The Netherlands, 1970.

NHTSA, "Splash and Spray Suppression: Technological Developments in the Design and Testing of Spray Reduction Devices for Heavy Trucks (Report to Congress), National Highway Traffic Safety Administration, Washington, D.C., 1994.

Nicholls, J.C., "Assessment of Axoflex, the Redland Thin Asphalt Surface Course, TRL Report 218, Transport Research Laboratory, Crowthorne, Berkshire, United Kingdom, 1997.

Nicholls, J.C., "Assessment of Millom Hitex, the Bardon Thin Asphalt Surface Course," Report No. TRL 292, Transport Research Laboratory, Crowthorne, Berkshire, United Kingdom, 1998.

Nixon, N., "New Paving Designs and Materials – Breaking Away from Tradition," *Transportation Research Circular 459*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1996, pp. 122-128.

Nunn, M., "Long-Life Flexible Roads," *Proceedings, 8th International Conference on Asphalt Pavements*," Seattle, Washington, August 1997.

Nunn, M.E., A. Brown, D. Weston, and J.C. Nicholls, "Design of Long-Life Flexible Pavements for Heavy Traffic," TRL Report 250, TRL Limited, Crowthorne, Berkshire, United Kingdom, 1997.

ODOT, "Port-of-Entry Advanced Sorting System (PASS) Operational Test," Report No. FHWA-OR-RD-99-15, Oregon Department of Transportation, Policy Unit, Policy and Research Section, Salem, Oregon, 1998.

Oh, J.H., "Field Monitoring and Modeling of Pavement Response and Service Life Consumption Due to Overweight Truck Traffic" Ph.D. Dissertation, Texas A&M University, College Station, Texas, 2004.

ORNL, "Better Ways to Weigh Trucks," Oak Ridge National Laboratory Review, Vol. 33, No. 3 (http://www.ornl.gov/info/ornlreview/v33_3_00/weigh.htm), Oak Ridge, Tennessee, 2000.

Oshinski, E., Personal communication via e-mail dated September 17, 2003.

Owusu-Antwi, E., and M. Darter, "Improved Concrete Pavement Design Methodology for Better Performance," *SP-181, Recent Developments in the Design and Specification of Concrete Pavement Systems*, American Concrete Institute, Farmington Hills, Michigan, 1999.

Packard, R.G., *Thickness Design for Concrete Highway and Street Pavements*, Portland Cement Association, Skokie, Illinois, 1984.

Page, G.C., "Open-Graded Friction Courses: Florida's Experience," *Transportation Research Record 1427*, Transportation Research Board, National Academy of Sciences, Washington, DC, 1993, pp. 1-4.

Park, S.W., Y.R. Kim, and R.A. Schapery, "A Viscoelastic Continuum Damage Model and Its Application to Uniaxial Behavior of Asphalt Concrete," *Mechanics of Materials*, Vol. 24, No. 4, 1996, pp. 241-255.

Parkinson, D., "United Kingdom Development of Thin Wearing Courses," The Institute of Asphalt Technology, Stanwell, Middlesex, United Kingdom, 1995.

PCA, "Thickness Design for Concrete Highway and Street Pavements," EB109.01P, Portland Cement Association, Skokie, Illinois, 1984.

Pearce, V., "Filtering through: ITS Is Increasingly Recognized as a Critical Component in Maintaining Traffic Flow through Roadwork Zones," University of California, Berkeley, California, 2000.

Pendleton, O.J., "Prediction of the Effect of Wind on Splash and Spray Test Results," SAE Technical Paper 881877, Society of Automotive Engineers, Inc, Warrendale, Pennsylvania., 1988.

Pennsylvania State University, "Proposed Design Guidelines for Improving Pavement Surface Drainage," The Pennsylvania Transportation Institute, The Pennsylvania State University, State College, Pennsylvania, 1998.

Perera, R.W., and S.D. Kohn, "Issues in Pavement Smoothness: A Summary Report," NCHRP Web Document 42, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., 2002.

Perera, R.W., and S.D. Kohn, *LTTP Data Analysis: Factors Affecting Pavement Smoothness*, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington D.C., 2001.

Perez-Jimenez, F.E., and J. Gordillo, "Optimization of Porous Mixes through the Use of Special Binders," *Transportation Research Record 1265*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1990, pp. 59-68.

Perez-Jimenez, F.E., and M.A. Calzada-Perez, "Analysis and Evaluation of the Performance of Porous Asphalt: The Spanish Experience," *Surface Characteristics of Roadways: International Research and Technologies, ASTM STP1031*, W.E. Meyer and J. Reichert, Editors., American Society for Testing and Materials, Philadelphia, 1990, pp. 512-527.

Perkins, S.W., and J.A. Lapeyre, "Instrumentation of a Geosynthetic-Reinforced Flexible Pavement System," *Transportation Research Record 1596*, Transportation Research Board, Washington, D.C., 1997, pp.31-38.

Perrin, J., P.T. Martin, and B. Coleman, "Testing the Adverse Visibility Information System Evaluation (ADVISE): Safer Driving in Fog," 81st Transportation Research Board Meeting, Washington, D.C., 2002.

Phillips, S.M., and P. Kinsey, "Advances in Identifying Road Surface Characteristics Associated with Noise and Skidding Performance," *Proceedings, PIARC Surface Characteristics 2000*, Nantes, France, 2000.

Pidwerbesky, B.D., B.D. Steven, and G. Arnold, "Subgrade Strain Criterion for Limiting Rutting in Asphalt Pavements," *Proceedings, 8th International Conference on Asphalt Pavements*," Seattle, Washington, August 1997.

Pilkington, G.G., II, "Splash and Spray," *Surface Characteristics of Roadways: International Research and Technologies, ASTM STP1031*, W.E. Meyer and J. Reichert, Eds., American Society for Testing and Materials, Philadelphia, 1990, pp. 528-541.

Pilli, S.Y., "Floating-Car Road Weather Information Monitoring System," *Transportation Research Record 1741*, Transportation Research Board, Washington, D.C., 2001, pp. 3-5.

Pines, K.J., and P.A. Lovell, "Conceptual Framework of a Remote Wireless Health Monitoring System for Large Civil Structures," *Electronic Journal of Smart Materials and Structures* (http://www.iop.org/EJ/journal/SMS), Vol. 7, October 1998, pp. 627-636.

Placer, J. "Fuzzy Variable Speed Limit Device Modification and Testing," Report No. AZ-466(2), Department of Computer Science and Engineering, University of Arizona, Department of Transportation, Phoenix, Arizona, 2001.

Potter, J.C., R.S. Rollings, and W.R. Barker, "Corps of Engineers Low-Volume Road Design," *Transportation Research Record 1128*, Transportation Research Board, Washington, D.C., 1987, pp. 90-94.

Raemae, P., J. Raitio, V. Anttila, and A. Schirokoff, "Effects of Weather Controlled Speed Limits on Driver Behaviour on a Two-Lane Road," *Proceedings, Conference on Traffic Safety on Three Continents*, Moscow, Russia, September 2001, pp. 784-792.

Ramos, S., E.G. Fernando, J. Oh, and J. Ragsdale, "Evaluation of Effects of Routine Overweight Trucks on SH4/48," Research Report 4184-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2004.

Rao, C.E., J. Barenberg, M.B. Snyder, and S. Schmidt, *Effects of Temperature and Moisture on the Response of Jointed Concrete Pavement Behavior*, 7th International Conference on Concrete Pavements, Orlando, Florida, 2001, pp. 23-37.

Rawool, S., E. Fernando, and R. Walker, "Project 0-4385 Literature Review," Interoffice Memorandum, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2002.

Read, S.A., "Construction Related Temperature Differential Damage in Asphalt Concrete Pavements," Master's Thesis, University of Washington, Seattle, Washington, 1996.

Rizenbergs, R.L., J.L. Burchett, and C.T. Napier, "Skid Resistance of Pavements," *Skid Resistance of Highway Pavements, ASTM STP 530*, American Society for Testing and Materials, 1973, pp. 138-159.

Rocci, S., "Skid Resistance and Rideability," *Proceedings*, *7th International Symposium on Concrete Roads*, Vienna, Austria, October 1994, pp. 187-191.

Rodway, B., "Boeing's Full-Scale Pavement Rutting Test," *Proceedings, AAPA 10th International Flexible Pavements Conference*, Vol. 2, Perth, Australia, 1997.

Rodway, B., and L.J. Wardle, "Layered Elastic Design of Heavy-Duty and Industrial Pavements," *Proceedings, Australian Asphalt Pavement Association Pavements Industry Conference*, Surfers Paradise, Australia, 1998.

Roe, P.G., "Research on Road Surface Skidding Resistance in the UK," Paper No. PA3448/99, Transport Research Laboratory, Crowthorne, United Kingdom, 1999.

Roe, P.G., D.C. Webster, and G. West, "The Relation between the Surface Texture of Roads and Accidents," TRRL Research Report 296, Transport and Road Research Laboratory, Crowthorne, United Kingdom, 1991.

Rogge, D., and E.A. Hunt, "Development of Maintenance Practices for Oregon F-Mix," Interim Report No. FHWA-OR-RD-00-01, Research Group, Oregon Department of Transportation, Salem, Oregon, 1999.

Rossi, P., and F. LeMaou. "New Method for Detecting Cracks in Concrete Using Fiber Optics," RILEM, Materials and Structure 22, 1989, pp. 437-442.

Ruiz, A., R. Alberola, F. Perez, and B. Sanchez, "Porous Asphalt Mixtures in Spain," *Transportation Research Record 1265*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1990, pp. 87-94.

Saarelainen S., H. Onninen, H. Kangas, and J. Pihlajamaki, "Full-Scale Accelerated Testing of a Pavement on Thawing Frost-Susceptible Subgrade," *Proceedings, International Conference on Accelerated Pavement Testing*, Reno, Nevada, 1999.

Sabey, B.E., "Accidents: Their Cost and Relation to Surface Characteristics," Presented at Symposium of the Cement and Concrete Assn., Birmingham, England, November 1973.

Sainton, A., "Advantages of Asphalt Rubber Binder for Porous Asphalt Concrete," *Transportation Research Record 1265*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1990, pp. 69-81.

Salgado, R., and D. Kim, "Effects of Heavier Truck Loadings and Super-Single Tires on Subgrades," Report No. FHWA/IN/JTRP-2002/20, Purdue University, West Lafayette, Indiana, 2002.

Sandberg, U., "Spray Protectors: Testing of Efficiency," Report No. 17A, Swedish National Road and Traffic Research Institute, Linkoping, Sweden, 1978.

Sanders, J.M., "Happy Motoring on Interstate Highways: Hi-Tech Fog Warning System Developed at Georgia Tech Will Issue Advisories to Motorists," *International Municipal Signal Association Journal*, Vol. 39, No.6, Newark, New York, 2001, pp. 58-61.

Scarpas, A., R. Al-Khoury, C. Van Gurp, and S.M. Erkens, "Finite Element Simulation of Damage Development in Asphalt Concrete Pavements," *Proceedings, 8th International Conference on Asphalt Pavements*, University of Washington, Seattle, Washington, 1997, pp. 673-692.

Schofield, G., "Design and Maintenance of Residential Street Pavements," Royal Melbourne Institute of Technology, Melbourne, Victoria, Australia, 1986.

Schreck, R.J., "White SMA? Yes-and It's Skid Resistant, Too," *HMAT-Hot Mix Asphalt Technology*, National Asphalt Pavement Association, Lanham, Maryland, January/February 2004.

Schreuder, D.A., "Open-Graded Asphalt Road Surfaces and Traffic Safety," Stichting Centrum Vor Regelgeving en Onderzoek in de Grond, The Netherlands, 1988.

Schulz, W.L., J.M. Seim, E. Udd, M. Morrell, H.M. Laylor, G.E. McGill, and R. Edgar, "Traffic Monitoring/Control and Road Condition Monitoring Using Fiber Optic-Based Systems," *Proceedings, International Society for Optical Engineering* Vol. 3671, p. 109-117, *Smart Structures and Materials 1999: Smart Systems for Bridges, Structures, and Highways*, Steve C. Liu; Ed., 1999.

Scullion, T., and Y. Chen, "Using Ground-Penetrating Radar for Real-Time Quality Control Measurements on New HMA Surfaces," Report FHWA/TX-00/1702-5, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1999.

Sebaaly, P.E., R. Siddharthan, D.L. Huft, and D. Bush, "Impact of Heavy Vehicles on Pavement Responses," *Proceedings, 6th International Conference on the Bearing Capacity of Roads, Railways and Airfields*, Lisbon, Portugal, June 2002.

Sebesta, S., and T. Scullion, "Using Infrared Imaging and Ground-Penetrating Radar to Detect Segregation in Hot-Mix Overlays," Report FHWA/TX-03/4126-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2002.

Sherard, T.D., "Suppression of Vehicle Splash and Spray," SAE Paper No. 730718, Society of Automotive Engineers, Warrendale, Pennsylvania, 1973.

Si, Z. "Characterization of Microdamage and Healing of Asphalt Concrete Mixtures," Ph.D. Dissertation, Texas A&M University, College Station, Texas, 2001.

Sigler, P.A., "Relative Slipperiness of Floor and Deck Surfaces," Report No. 100, U.S. Department of Commerce, Building Materials and Structures, Washington, D.C., 1943.

Skszek, S.L., "State-of-the-art Report on Non-Traditional Traffic Counting Methods," Report FHWA-AZ-01-503, Arizona Department of Transportation, Phoenix, Arizona, 2001.

Smallridge, M., and A. Jacob, "The ASCE Port and Intermodal Yard Pavement Design Guide," *Proceedings, Ports '01 Conference*, American Society of Civil Engineers, Ports and Harbors Committee of the Coasts, Oceans, Ports and Rivers Institute, U.S. Section of the Permanent International Association of Navigation Congresses (PIANC), Norfolk, Virginia, 2001, pp. 10.

Smith, G.R., *NCHRP Synthesis of Highway Practice 263: State DOT Management Techniques for Materials and Construction Acceptance*, Transportation Research Board, National Research Council, Washington, D.C., 1998.

Smith, K.L, K.D. Smith, L.D. Evans, T.E. Hoerner, M.I. Darter, and J.H. Woodstrom, *Smoothness Specifications for Pavements,* National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., 1997.

Sohn, H., G. Park, J.R. Wait, N.P. Limback, and C.R. Farrer, "Wavelet-Based Active Sensing for Delamination Detection in Composite Structures," *Electronic Journal of Smart Materials and Structures* (http://www.iop.org/EJ/journal/SMS), Vol. 13, February 2004, pp. 153-160.

Sommer, H. "Developments for the Exposed Aggregate Technique in Austria," Session 8, *Proceedings*, *7th International Symposium on Concrete Roads*, Vienna, Austria, October 1994, pp. 133-136.

Stidger, R.W., "Good Winter Maintenance Boosts Road Safety," *Better Road Magazine*, June 2002.

Stinglhammer, H. and H. Krenn, "Noise Reducing Exposed Aggregate Surfaces: Experience and Recommendations," Session 8, *Proceedings*, *7th International Symposium on Concrete Roads*, Vienna, Austria, October 1994, pp. 137-140.

Stroup-Gardiner, M., and E.R. Brown, "Segregation in Hot-Mix Asphalt Pavements, NCHRP Report 441, Transportation Research Board, National Research Council, Washington, D.C., 2000.

Suchetka, D., “Sensor Devices May Tell of Ice,” *The Charlotte Observer* [online], January 24, 2001.

Swan, M., and S.M. Karamihas, “Using a Ride Quality Index for Construction Quality Control and Acceptance Specifications,” *Proceedings, 82nd Annual Meeting of the Transportation Research Board*, Washington, D.C., January 2003.

TAI, “Thickness Design – Asphalt Pavements for Highways and Streets,” MS-1, Ninth Edition, The Asphalt Institute, Lexington, Kentucky, 1999.

Tappeiner, W.J., “Open-Graded Asphalt Friction Courses,” Report No. IS 115, National Asphalt Pavement Association, Riverdale, Maryland, 1993.

The Asphalt Institute, *Thickness Design - Asphalt Pavements for Heavy Wheel Loads*, Manual Series No. 23, The Asphalt Institute. Lexington, Kentucky, 1986. (www.asphaltinstitute.org).

The Highways Agency, *Design Manual for Roads and Bridges*, HD 26/01, Vol. 7, Section 2, London, United Kingdom, 2001.

Theyse, H.L., M. De Beer, and F.C. Rust, “Overview of South African Mechanistic Pavement Design Method,” *Transportation Research Record 1539*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1996.

Thompson, M., “Workshop 4: Flexible Pavement PCN Calculations for Heavier Aircraft,” *Proceedings, 6th International Conference on the Bearing Capacity of Roads, Railways and Airfields*, Lisbon, Portugal, June 2002.

Thompson, M., and N. Garg, “Wheel-Load Interaction: Critical Airport Pavement Responses, *Proceedings, Airport Pavement Technology Transfer Conference*, Atlantic City, New Jersey, April 1999.

Thompson, M., and S. Carpenter, “Design Principles for Long-Lasting HMA Pavements,” *Proceedings, International Symposium on Design and Construction of Long-Lasting Asphalt Pavements*,” Auburn University, Auburn, Alabama, June 2004.

Thompson, M., F. Gomez-Ramirez, and M. Bejarano, “ILLI-PAVE Based Flexible Pavement Design Concepts for Multiple Wheel Heavy Gear Load Aircraft,” *Proceedings, 9th International Conference on Asphalt Pavements*, Copenhagen, Denmark, August 2002.

TRB, “Critical Issues in Transportation 2002,” *TR News*, Transportation Research Board, The National Academies, Washington, D.C., November-December 2001.

Trimm, D.H., and D.E. Newcomb, “Perpetual Pavement Design: An Introduction to the PerRoad Program,” Asphalt Pavement Alliance, Washington, D.C., 2004.

TRIP (The Road Information Program), “Keep Both Hands on the Wheel: Cities with the Bumpiest Rids and Strategies to Make our Roads Smoother,” Washington, D.C., 2003.

Tromp, J.P.M., "Splash and Spray by Lorries," Institute for Road Safety Research SWOV, Leidschendam, The Netherlands, 1985.

Tubas, N.S., S.T. McDonald, and J.R. Treat, "Radar and Anti-Lock Braking Payoff Assessment: Tri-Level Study of the Causes of Accidents," Vol. II, U.S. Department of Transportation Report HS-801 631, Indiana University Institute for Research in Public Safety, Bloomington, Indiana, 1975

Tudor, L.H., A. Meadors, and R. Plant II, "Deployment of Smart Work Zone Technology in Arkansas," Transportation Research Record 1824, Transportation Research Board, Washington, D.C., 2003, pp. 9-14.

Tutumluer, E., and M.R. Thompson, "Anisotropic Modeling of Granular Bases in Flexible Pavements," *Transportation Research Record No. 1577*, Transportation Research Board, National Research Council, Washington, D.C., 1997, pp. 18-26.

TxDOT, "Crossroads of the Americas: Trans Texas Corridor Plan - Report Summary," (http://www.dot.state.tx.us/ttc/ttc_report_summary.pdf) Texas Department of Transportation, Public Information Office, Austin, Texas, June 2002.

TxDOT, "Pavement Design Manual," Texas Department of Transportation, Austin, Texas, located at http://manuals.dot.state.tx.us/docs/coldesig/forms/pdm.pdf, December 2003.

TxDOT, "Use of PFC to Improve the Performance of CRCP," Technical Advisory, Construction and Bridge Divisions, Texas Department of Transportation, February 11, 2003.

Udd, E., and M. Kunzler, "Development and Evaluation of Fiber Optic Sensors," FHWA-OR-RD-30-14, Blue Road Research, Gresham, Oregon, 2003.

Ullidtz, P., "Analytical Tools for Design of Flexible Pavements," *Proceedings, 9th International Conference on Asphalt Pavements*, Copenhagen, Denmark, August 2002.

Van der Zwan, J.T., T. Goeman, H.J.A.J. Gruis, J.H. Swart, and R.H Oldenburger, "Porous Asphalt Wearing Courses in the Netherlands: State-of-the-Art Review," *Transportation Research Record 1265*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1990, pp. 95-110.

Van Heystraeten, G., and C. Moraux, "Ten Years' Experience of Porous Asphalt in Belgium," *Transportation Research Record 1265*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1990, pp. 34-40.

Vavrik, W.R., G. Huber, W.J. Pine, S.H. Carpenter, and R. Bailey, "Bailey Method for Gradation Selection in HMA Mixture Design," *Transportation Research Circular No. E-C044*, Transportation Research Board, Washington, D.C., 2002.

Vehicle Detector Clearinghouse, "A Summary of Vehicle Detection and Surveillance Technologies Used in Intelligent Transportation Systems," Southwest Technology Development Institute, New Mexico State University, 2003.

Veith, A.G., "Tires – Roads – Rainfall – Vehicles: The Traction Connection," *Frictional Interaction of Tire and Pavement, ASTM STP 793*, American Society for Testing and Materials, 1983, pp. 3–4.

Verhaeghe, B.M.J.A., F.C. Rust, G.D. Airey, and R.M. Vos, "Fatigue and Deformation Characteristics of Large-Aggregate Mixes for Bases," *Proceedings, 6th Conference on Asphalt Pavements for Southern Africa*, Vol. 1, Cape Town, South Africa, October 1994.

Viner, H.E., P.G. Roe, A.R. Parry, and R. Sinhal, "High and Low-Speed Skidding Resistance: The Influence of Texture on Smooth and Ribbed Tyre Friction," Transport Research Laboratory, Crowthorne, Berkshire, United Kingdom, 2000.

Wada, Y., H. Miura, R. Tada, and Y. Kodaka, "Evaluation of an Improvement in Runoff Control by Means of a Construction of an Infiltration Sewer Pipe under a Porous Asphalt Pavement," Water Science and Technology, Vol. 36, No. 8-9, 1997, pp. 397-402.

Walubita, L.F, A. Epps Martin, S.H. Jung, C.J. Glover, G.S. Cleveland, and R.L. Lytton, "Two Approaches to Predict Fatigue Life of Hot Mix Asphalt Concrete Mixtures,"Paper submitted for publication at the 84th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2005.

Wambold J.C., J.J. Henry, and R.R. Hegmon, "Skid Resistance of Wet-Weather Accident Sites," *The Tire Pavement Interface, ASTM STP 929*, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1986, pp. 47-60.

Wambold, J.C., J.J. Henry, C.E. Antle, B.T. Kulakowski, W.E. Meyer, A.J. Stocker, J.W. Button, and D.A. Anderson, "Pavement Friction Measurement Normalized for Operational, Seasonal, and Weather Effects," Report No. DTFH61-84-C-00078, Federal Highway Administration, 1987.

Wambold, J.C., W.E. Meyer, and J.J. Henry, "New-Generation Skid Testers for the 1990s," *Surface Characteristics of Roadways: International Research Technologies, ASTM STP 1031*, American Society of Testing and Materials, Philadelphia, Pennsylvania 1990, pp. 138-153.

Wang, K.C.P., G. Weiguo, X. Li, R.P. Elliott, and J. Daleiden, "Data Analysis of Real-Time System for Automated Distress Survey," *Transportation Research Record 1806*, Transportation Research Board, Washington, D.C., 2002, pp. 101-109.

Wardle, L.J., and B. Rodway, "APSDS: A New Tool for Airport Pavement Design," *Journal of the International Civil Aviation Organization*, Vol. 51, No. 7, Montreal, Canada, September 1996.

Wardle, L.J., G. Youdale, and B. Rodway, "Current Issues for Mechanistic Pavement Design," *Proceedings, 21st Australian Road Research Board and 11th The Road Engineering Association of Asia and Australasia Conference*, Cairns, Australia, May 2003.

Weir, D.H., J.F. Strange, and R.K. Heffley, "Reduction of Adverse Aerodynamic Effects of Large Trucks," Report No. FHWA-RD-79-84, Federal Highway Administration, Washington, D.C., 1978.

Werkmeister, S., A.R. Dawson, and F. Wellner, "Permanent Deformation Behavior of Granular Materials and the Shakedown Theory", *Journal of the Transportation Research Board No. 1757*, Transportation Research Board, Washington, D.C., 2001, pp. 75-81.

WHI, "Characteristics of Trucks and Truck Combinations," 1st Edition, Subcommittee on Splash and Spray, Western Highway Institute, San Francisco, California, 1973.

White, S.R., N.R. Sottos, P.H. Geubelle, J.S. Moore, M.R. Kessler, S.R. Sriram, E.N. Brown, and S. Viswanathan, "Autonomic Healing of Polymer Composites," *Nature*, Vol. 409, (www.nature.com), February 2001, pp. 794-797.

White, T.D., J.E. Haddock, A.J.T. Hand, and H. Fang, "Contributions of Pavement Structural Layers to Rutting of Hot Mix Asphalt Pavements," *NCHRP Report 468*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 2002.

Williams, H., "A Note on Skid Resistance and the Road Profile," *Tire Science and Technology*, Vol. 3, Akron, Ohio, 1975.

Witczak, M.W., K. Kaloush, T. Pellinen, M. El-Basyouny, and H. Von Quintus, "Simple Performance Test for Superpave Mix Design," NCHRP Report 465, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., 2002.

World Highways, "Texas DOT Seeks European Cooperation," Route One Publishing Ltd., Huntingdon House, Kent, United Kingdom, November/December 2003.

Yager, R.W., *Physics of Tire Traction*, D.F. Hays and A.L Browne, Eds. Plenum Press, New York, 1974, pp. 25-63.

Yager, T.J., "Aircraft/Ground-Vehicle Friction Measurement Study," *Surface Characteristics of Roadways: International Research Technologies, ASTM STP 1031*, American Society of Testing and Materials, Philadelphia, Pennsylvania 1990, pp. 154-167.

Yandell, W.O., "The Prediction of the Behavior of Elasto-Plastic Roads during Repeated Rolling Using the Mechano-Lattice Analogy and the Results of Cyclic Load Material Tests," *Highway Research Record 374*, Highway Research Board, Washington, D.C., 1971.

Yandell, W.O., and G. Behzadi, "Rutting Prediction of Twelve Accelerated Loading Facility (ALF) Trials," *Proceedings, Accelerated Pavement Testing 1999 International Conference*, Reno, Nevada, October 1999.

Yandell, W.O., and R.L. Lytton, "Residual Stresses Due to Traveling Loads and Reflection Cracking," Report No. *FHWATX79-207-6*, Texas Transportation Institute (for Texas Department of Highways and Public Transportation), College Station, Texas, 1979.

Yandell, W.O., P. Taneerananon, and V. Zankin, "Prediction of Tire-Road Friction from Surface Texture and Tread Rubber Properties," *Frictional Interaction of Tire and Pavement, ASTM STP 793*, American Society for Testing and Materials, 1983, pp. 304–322.

Zeyher, A., "West Virginia's Foggy Bottom: Motorists on I-64 Get Needed Visibility Warnings at Saint Alban's Bridge," *Roads and Bridges*, Vol. 41, No. 1, January 2003.

Zollinger, D.G. (editor), *SP-181, Recent Developments in the Design and Specification of Concrete Pavement Systems*, American Concrete Institute, Farmington Hills, Michigan, 1999.

Zwahlwn, H.T., A. Russ, and S. Vatan, "Evaluation of ODOT Roadway/Weather Sensor Systems for Snow and Ice Removal Operations: Part 1, RWIS," Ohio Research Institute for Transportation and the Environment, Ohio Department of Transportation, Office of Maintenance Administration, Columbus, Ohio, 2003.