1 Introduction

1.1 Pavement Types

There are three general types of roadway pavements, namely flexible, rigid, and composite. Flexible pavements typically consist of asphalt concrete placed over granular base/subbase layers supported by the compacted soil, referred to as the *subgrade*. Some asphalt-paved surfaces consist of a simple bituminous surface treatment (BST), while other, lighter-duty asphalt-surfaced pavements are too thin, to be considered as flexible pavements, (i.e., combined layer thicknesses less than 15 cm). Rigid pavements typically consist of a portland concrete layer placed over the subgrade with or without a middle base layer. Composite pavements are typically the result of pavement rehabilitation, whereby portland concrete is used to cover damaged asphalt concrete or vice versa.

The terms *flexible* and *rigid* relate to the way asphalt and portland concrete pavements, respectively, transmit stress and deflection to the underlying layers. Ideally, a flexible layer transmits uniform stresses and nonuniform deflections, while the opposite is true for a rigid layer. In practice, the stress and deflection distributions in asphalt concrete and portland concrete pavements depend on the relative stiffness of these layers with respect to those of the underlying granular layers. This ratio is much lower for asphalt concrete than portland concrete, which justifies their generic designation as flexible and rigid, respectively. As described in later chapters, this affects significantly the way these two pavement types are analyzed and designed.

Figure 1.1 shows a typical cross section of a flexible pavement. The asphalt concrete layer, which may consist of two or more sublayers, or lifts, is placed on top of the granular base/subbase layers, which are placed on top of the subgrade. A tack coat layer may be applied to provide adhesion between layers, while a seal coat may provide a pavement surface barrier. A fabric or other geotextile placed between the base and the subgrade prevents migration of fines between them, and maintains their integrity. The base layers can be either compacted gravel, referred to as, simply, *granular*, or incorporate cement, referred to as *stabilized*. Typically, the asphalt concrete layer is designed with no interconnected voids (i.e., mix air voids 4–8%), and hence relies on surface runoff for precipitation drainage. Alternatively, asphalt concretes with interconnected voids, (i.e., mix air voids higher than 12%) allow drainage through the surface. This design requires a lower impermeable asphalt concrete layer, to prevent water from penetrating the base layer. Water runoff led to the edge of the pavement can be removed by surface evaporation, ditches, or drainage pipes.

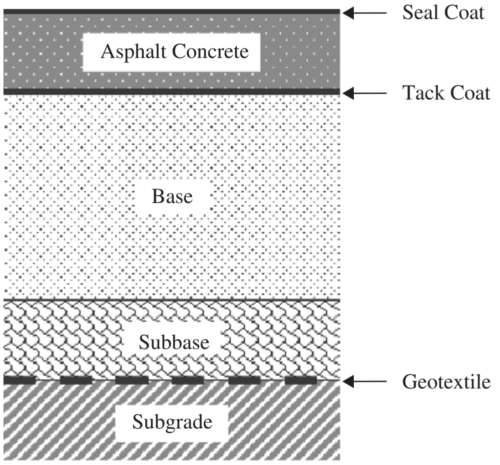

Figure 1.1
Typical Section of an Asphalt Concrete Pavement

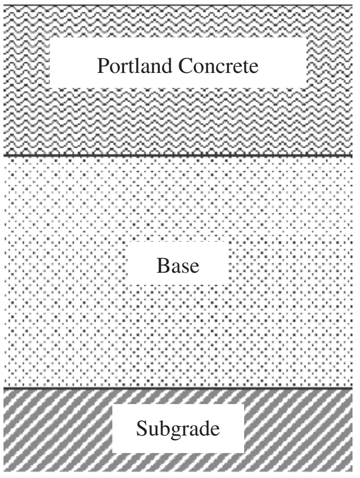

Figure 1.2
Typical Section of a Portland Concrete Pavement

Figure 1.2 shows a typical section of a rigid pavement. The portland concrete layer is placed either directly on top of the subgrade or on top of a granular base layer. Unreinforced portland concrete slabs, such as the one shown in Figure 1.2, tend to crack transversely where thermally induced tensile stresses exceed the tensile strength of the concrete. Hence, they require transverse joints at prescribed intervals. They are constructed by cutting a surface groove using a rotary saw before the concrete is fully cured. These joints, in addition to relieving thermal stresses, need to provide sufficient vertical load transfer between advancement slabs. Under a moving load, sufficient vertical load transfer provides a gradual buildup of stresses under the down stream slab, which controls the migration of moisture and fines under the joint and prevents downstream slab settlement, (i.e., faulting). Load transfer is accomplished either through aggregate interlock along the jagged edges of adjacent slabs (Figure 1.3a) or through dowel bars located at the neutral axis bridging the joint (Figure 1.3b). These dowel bars are smooth and epoxy-coated, to allow free horizontal movement while providing vertical displacement coupling between adjacent slabs. Collapsible end caps allow the expansion of the slabs without generating compressive stress in the dowel. These pavements are referred to as *jointed plain concrete pavements* (JPCP) and *jointed dowel reinforced concrete pavements*

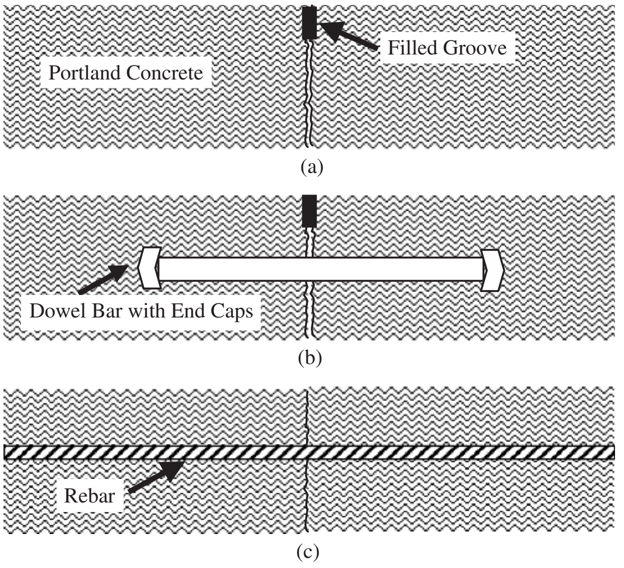

Figure 1.3
Typical Configuration of JPCPs, JDRCPs and CRCPs

(JDRCP), respectively. Continuously reinforced concrete slabs can withstand thermal stresses through the tensile strength of steel, hence they require no joints. The reinforcing steel is consists of deformed tiebars placed on the neutral axis of the slab. Thus, any thermal cracks in the concrete itself are not allowed to open, and the slab retains its structural integrity. These are called *continuously reinforced concrete pavements* (CRCP) (Figure 1.3c). It should be noted that hybrid rigid pavement structures have been developed, consisting of long CRCP slabs jointed through dowels in a JDRCP fashion.

A variety of other joint types are used in concrete pavements, including construction joints allowing continuity of the work between different days (Figure 1.4a) and expansion joints necessary where concrete pavements come against other rigid structures, such as bridge abutments (Figure 1.4b). Overall, the successful design and construction of joints and their reinforcement contributes significantly to the performance of concrete pavements. Reducing vehicle dynamics dictates the randomization of joint spacing, (e.g., 2.1, 2.7,

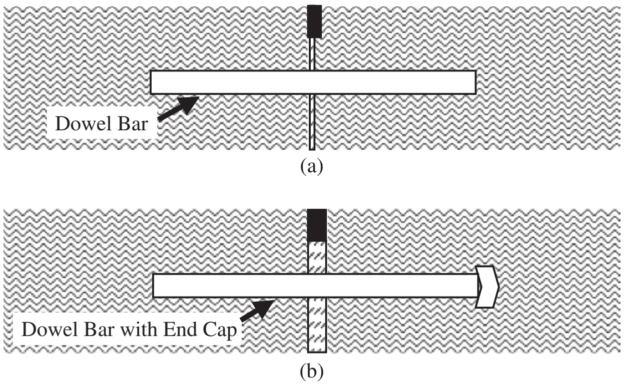

Figure 1.4
Special-Function Portland Concrete Pavement Joints

3.3, and 4.5 meters (m)), as well as their skewed arrangement with respect to the longitudinal axis of the pavement [5].

1.2 Pavement Infrastructure Overview

The staggering size of the roadway pavement infrastructure in the United States can be appreciated by the length inventory data shown in Tables 1.1 and 1.2 for rural and urban pavements, respectively[4]. These tables show centerline kilometers (km) length by roadway functional class, namely interstate, arterials, and collectors. These functional class designations relate to the geometric standards of the roadway, as well as the combination of access and mobility it affords. Minor collectors and local roads were excluded from these tables. Per the October 2006 count, they amounted to 1,584,764 and 1,094,428 centerline kilometers (km) in rural and urban areas, respectively, which brings the total length to 4.2 million km, or approximately 11 times the distance to the moon. The interstate system (74,000 km) and an additional 184,523 km of other freeways comprise the National Highway System (NHS), as designated in 1995 by Public Law 104–59 (6). The NHS represents about 4% of the total roadway pavement mileage but carries over 44% of the vehicle-kilometers traveled.

Table 1.1
Length Inventory (centerline km) of Rural Roadway Pavements (FHWA, 2004)

OWNER/CLASS	PAVEMENT TYPE					
State	**BSTs**	**OTHER LIGHT**	**FLEXIBLE**	**COMPOSITE**	**RIGID**	**TOTAL**
Interstate	455	1688	22911	9606	12590	47250
Other Arterial	1308	6531	104605	24282	14828	151555
Minor Arterial	5200	18865	153257	26145	8151	211619
Major Collector	51850	74984	202889	22531	3132	355386
Subtotal	58813	102068	483663	82564	38701	765809
Federal						
Interstate	—	—	—	—	—	—
Other Arterial	—	13	143	—	2	158
Minor Arterial	—	800	447	3	—	1250
Major Collector	465	2791	1347	—	—	4603
Subtotal	465	3603	1938	3	2	6011
Other						
Interstate	—	—	845	1147	401	2393
Other Arterial	58	77	328	166	604	1233
Minor Arterial	328	1622	2995	182	10	5137
Major Collector	46005	80166	107560	4521	11872	250124
Subtotal	46391	81866	111728	6016	12886	258886
Total	105669	187536	597329	88583	51589	1030707

1.3 Significance of Pavement Infrastructure to the Nation's Economic Activity

Roadway pavements play a very important role in the nation's economic activity. Approximately, 19% of average household expenditures is directly related to transportation (Figure 1.5). The predominant mode of personal transportation is by private motor vehicle, that is, 91.2% of the total vehicle-kilometers[6]. Furthermore, an average 89% of commercial freight transportation is carried by the highway system (Figure 1.6). The vehicle-miles traveled (VMT) is a very good indicator of the health of the economy, as suggested by its strong correlation to the gross domestic product (GDP), that is, the annual sum of goods and services transacted nationwide (Figure 1.7). These simple facts demonstrate the importance of the roadway infrastructure in the nation's economic well-being.

Table 1.2
Length Inventory (centerline km) of Urban Roadway Pavements (FHWA, 2004)

MANAGER/CLASS	PAVEMENT TYPE					
State	**BSTs**	**OTHER LIGHT**	**FLEXIBLE**	**COMPOSITE**	**RIGID**	**TOTAL**
Interstate	66	190	8618	6725	8087	23686
Other Arterial	499	2408	47817	23503	12517	86743
Minor Arterial	954	5412	34141	13118	2379	56003
Major Collector	3215	7546	15852	2535	853	30001
Subtotal	4735	15556	106427	45881	23836	196434
Federal						
Interstate	—	—	—	—	—	—
Other Arterial	—	40	92	—	6	138
Minor Arterial	—	16	60	2	2	79
Major Collector	18	100	45	6	—	169
Subtotal	18	156	196	8	8	386
Other						
Interstate	—	8	512	943	237	1699
Other Arterial	579	3858	18594	3555	3217	29803
Minor Arterial	5517	23669	60106	9991	8464	107745
Major Collector	10530	42728	70074	9999	6817	140148
Subtotal	16626	70262	149286	24488	18734	279396
Total	21378	85974	255909	70376	42578	476217

1.4 Funding Pavements

The value of this infrastructure is in the trillions of dollars. The ongoing annual expenditures for roadway preservation, capacity addition, and new route construction are in the billions, (e.g., the federal-only component of these expenditures in FY 2000 was $16.2 billion[6]). Although these figures include the cost of bridges, they demonstrate the extent of public investment in this vital piece of infrastructure.

Roadway pavements are financed through fuel taxes. Federal taxes on fuel date back to the 1930s. The Federal-Aid Highway Act of 1956 established the Highway Trust Fund and stipulated that 100% of the fuel tax be deposited into the fund. Between 1956 and 1982, the Highway Trust Fund was used solely to finance expenditures for the federal highway program. The Surface Transportation Act of 1982 legislated that approximately 20% of the federal fuel taxes revenues be allocated to a newly created mass transit account and be expended

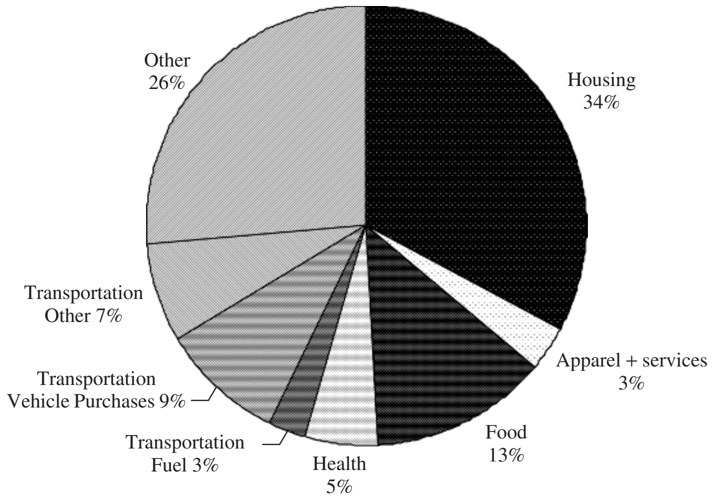

Figure 1.5
Distribution of Household Expenditures; 1999 Data (Ref. 6)

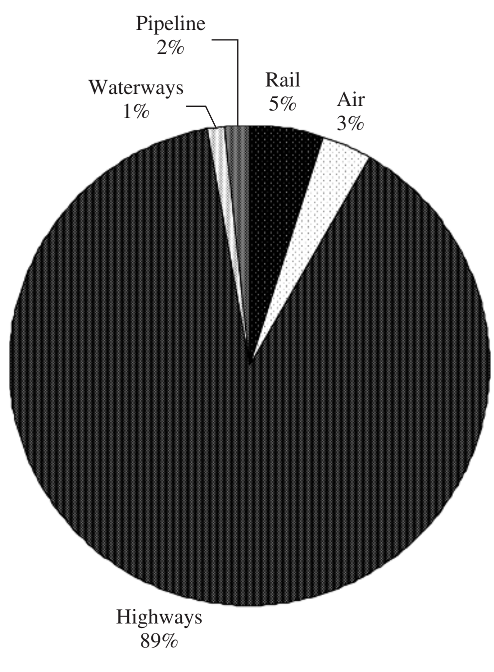

Figure 1.6
Distribution of Freight by Transport Mode; 1996 Data (Ref. 6)

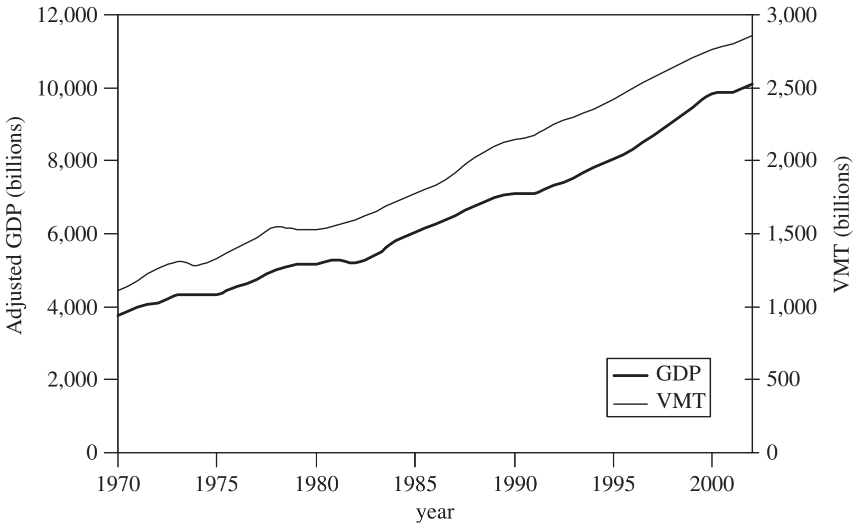

Figure 1.7
Correlation between VMT and GDP; 1970–2002 (Ref. 8)

to improve public transportation. The historic distribution of federal gasoline tax revenues is shown in Table 1.3.

In 2006, federal tax rates for gasoline and diesel were 18.4 cents per gallon and 24.4 cents per gallon, respectively; states impose their own taxes on fuel. As of 2004, the average state rates for gasoline and diesel were 19.1 cents per gallon and 24.4 cents per gallon, respectively[7]. The reason for higher diesel fuel tax rates is to compensate for the pavement damage caused by heavy trucks. For the

Table 1.3
Distribution of Gasoline Tax Revenues (1983–1997) (Ref. 1)

Date	General Revenues	Highways	Mass Transit Account	Other Trust Funds
Before 1983		100.0%		
Apr. 1, 1983		88.9%	11.1%	
Dec 1, 1990	17.7%	70.1%	10.6%	0.7%
Oct. 1, 1993	37.0%	54.3%	8.2%	0.5%
Oct. 1, 1995	23.4%	65.2%	10.9%	0.5%
Jan. 1, 1996	23.5%	65.6%	10.9%	
Oct. 1, 1997		83.9%	15.5%	0.5%

same reason, some states (e.g., Oregon, Idaho, New Mexico) are using a weigh-distance tax to replace part of the consumption-based diesel fuel taxes. This taxes heavy trucks in proportion to their weight and the distance they travel. It has been argued that this and similar taxation approaches provide a more equitable means of taxing various vehicle classes than fuel consumption-based taxes[2].

1.5 Engineering Pavements

The preceding discussion demonstrates clearly the extent of public investment in the roadway pavement infrastructure and its importance in the nation's economic vitality. As a result, engineering pavements requires the utmost care and use of state-of-the art technology, and involves the technology for both maintaining/rehabilitating existing pavements as well as designing/constructing new ones. This technology encompasses the characterization of the materials involved and the structural design of the layers selected to withstand prevailing traffic and environmental conditions. In addition, it necessitates the evaluation of their in-service performance with time as well as their economic implications to both the agency and the user. Although the last two topics relate to the broader subject of pavement management (e.g., Ref. 3), they are an integral part of pavement engineering, hence are included in this book.

1.6 Book Organization

This book contains information on roadway pavement materials, pavement structural analysis, pavement design, and pavement economic analysis. The remaining chapters are organized as follows:

- Chapter 2 describes with the characterization of traffic input.
- Chapters 3 and 4 deal with the characterization of pavement bases/subgrades and aggregates, respectively.
- Chapter 5 addresses asphalt binder and asphalt concrete characterization.

- ❑ Chapter 6 characterize, portland cement and portland concrete.
- ❑ Chapters 7 and 8 describe the analysis of flexible and rigid pavements, respectively.
- ❑ Chapter 9 discusses pavement evaluation.
- ❑ Chapter 10 addresses the environmental effects on pavements.
- ❑ Chapters 11 and 12 deal with the design of flexible and rigid pavements, respectively.
- ❑ Chapter 13 describes pavement rehabilitation.
- ❑ Chapter 14 deals with the economic analysis of alternative pavement designs.

References

[1] Buechner, W. (2006). ''History of the Gasoline Tax.'' American Roads and Transportation Building Association, (www.artba.org).

[2] FHWA (August 1997). Federal Highway Cost Allocation Study, Federal Highway Administration www.fhwa.dot.gov/policy/otps/costallocation.htm.

[3] Haas, R. C. G., W. R. Hudson, and J. Zaniewski, (1994). *Modern Pavement Management*, Krieger Publishing Co., Malabar, FL.

[4] FHWA (2005). ''Highway Statistics; Section V'': *Roadway Extent, Characteristics, and Performance*, Federal Highway Administration. Washington, DC.

[5] PCA (1980). *Joint Design for Concrete Highways and Street Pavements*, Portland Cement Association, Skokie IL.

[6] FHWA (2000). *Our Nation's Highways*, Federal Highway Administration, Washington, DC.

[7] FHWA (2007). State Motor Fuel Tax Rates, 1988–2003, Federal Highway Administration www.fhwa.dot.gov/policy/ohim/hs03/htm/mf205.htm.

[8] FHWA (2006). ''Transportation Air Quality: Selected Facts and Figures,'' Federal Highway Administration, Washington, DC, Publication No. FHWA-HEP-05-045 HEP/12-05(8M)E.

Problems

1.1 Find the length of roads in your state by functional class (i.e., interstate, other arterial, minor arterial, and major collector) and surface type, (i.e., BST, light-duty, flexible, composite, and rigid).

1.2 Find the rate of state tax levied on gasoline and diesel fuel in your state. What was the corresponding amount of total proceeds from the sale of gasoline and diesel fuel for road vehicles in the last year?

1.3 Compute the current annual amount of fuel tax, state and federal, paid for operating a typical privately owned vehicle in your state. Assume that the fuel consumption is 11.8 liters/100 km (20 miles/U.S. gallon) and that the vehicle is driven 24,000 km (15,000 miles) per year.

1.4 What was the percentage of the GNP expended on road transportation last year?