CHAPTER 7

Vehicle Operating Cost Impacts

Better to be wise by the misfortunes of others than by your own.

—*Aesop (560 B.C.)*

INTRODUCTION

Vehicle costs are direct expenses that comprise the costs of vehicle ownership (fixed) and vehicle operation (variable). The latter category, typically referred to as *vehicle operating costs* (VOCs), varies with vehicle use and is typically expressed in cents per mile traveled by a vehicle. For most transportation modes, VOC involves energy use, tires, maintenance, repairs, and mileage-dependent depreciation. Fixed vehicle costs are those that are largely independent of vehicle use and are generally unaffected by transportation improvements; examples are insurance costs, time-dependent depreciation, financing, and storage. Such costs are therefore typically excluded from VOC impact evaluation of projects.

VOC *savings* or *benefits* of a transportation improvement or intervention simply refer to *the reduction in vehicle operating costs compared to an existing situation or a base-case alternative*.

For areawide or corridor-level projects involving multimodal systems, an improvement in any part of the system can affect VOCs of the other parts or other modes. For example, service improvement in commuter rail or provision of a bus rapid transit along a corridor can affect the level of service on highway facilities in the same corridor because the shift of some travelers from automobile to transit would lead to improved highway level of service due to reduced congestion and thus, lower vehicle operating costs at the highway section.

In this chapter we identify VOC components and factors and present a procedural framework for assessing the VOC impacts of transportation improvements. Then a comparison of various VOC estimation methodologies and software for the highway mode, is presented.

7.1 COMPONENTS OF VEHICLE OPERATING COST

The components of vehicle operating cost are the individual items associated with vehicle operation on which expenses are directly incurred. These include the costs of energy needed to propel the vehicle, fluids, and other light consumables associated with mechanical working of the drivetrain, occasional replacement of the vehicle's contact surfaces with the guideway, vehicle repair and maintenance, and vehicle depreciation.

7.1.1 Fuel

Fuel is a key component of vehicle operating costs. For highway vehicles for instance, fuel costs can account for 50 to 75% of usage-related costs. Fuel cost can be estimated on the basis of fuel efficiency and unit fuel price. Fuel efficiency, in turn, depends primarily on vehicle class, type, age, and speed. Automobile associations, petroleum institutes, and government energy agencies publish fuel prices (dollars per gallon) on a regular basis. In the United States, the average prices of gasoline and diesel in 2005 were \$2.2 and \$2.4, respectively (USDOE, 2005b). Fuel prices for VOC computation purposes should be derived by subtracting the federal and state gasoline taxes from retail prices. On a mileage basis, the unit costs of fuel (including oil) in 2003–2004 ranged from approximately 7 cents per vehicle-mile for small autos to over 21 cents per vehicle-mile for large trucks (Barnes and Langworthy, 2003; AAA, 2005). Generally, very low speeds, steep uphill grades, and curves lead to higher fuel consumption rates and hence higher overall fuel costs. In the Highway Economic Requirements System (HERS) model (FHWA, 2002), the change in vehicle fuel efficiencies across the years is accounted for in VOC estimation using an adjustment factor.

7.1.2 Shipping Inventory

The inventory cost of cargo (freight transportation) is a special category of user cost. The entity that ships the cargo (the *client*) is a user of a shipping service made available by a *carrier*. In the course of transporting perishable or valuable cargo, the client incurs holding costs that represent an opportunity cost: If at the beginning of the shipment, the client had a cash amount worth the cargo being shipped, such an amount would have earned some interest by the time the cargo reaches its destination. So by having the cargo transported, the client

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is foregoing some benefits. Higher inventory costs are generally directly related to cargo value, greater cargo perishability, higher prevailing opportunity cost of money, and slower speed of the shipping vehicle. To compute the inventory cost for a given vehicle class, an hourly discount rate is typically determined and multiplied by the average value of shipments undertaken by that vehicle class (FHWA, 2002). AASHTO (2003) recommends that the inventory costs of cargo per vehicle-mile should be applied to the unit user cost attributed to cargo-carrying transportation vehicles. The most significant VOC factors that affect the shipping inventory costs are speed and delay, but cargo value and interest rate also can be influential. Higher cargo value and interest rates and greater travel or transfer delay translate to higher unit costs of shipping inventory, and higher speeds lead to lower inventory costs. For example, at a 10% interest rate, two trucks each shipping $100,000 cargo, one traveling at 60 mph and the other at 50 mph, incur inventory costs of approximately 2.5 and 6 cents per mile, respectively (AASHTO, 2003).

7.1.3 Lubricating Oils for Mechanical Working of the Drivetrain

The lubricating oil cost includes the cost of engine oil, transmission fluids, brake fluids, and other similar consumables associated with the operation of vehicle engine and drive train. Oil cost is a product of unit price (dollars/quart) and consumption rates (quarts/mile). The consumption rates depend on the amount of use as well as characteristics of the guideway and vehicle, and operational conditions such as speed, delay, grade, and curves. Typically, the cost of this set of VOC components is reported together with fuel costs, but some sources report them separately. In 2005 dollars, oil costs ranged from $1.73 to $4.32 per quart (Appendix A7.2).

7.1.4 Preservation of the Vehicle–Guideway Contact Surface

At their points of contact, both the vehicle and guideway experience deterioration due to wear and tear. For highways and runways, the vehicle contact is a tire; for railways, the contact is typically a steel wheel. Updated tire costs (2005 dollars) from the HERS technical report (Appendix A7.2), are as follows: $54.71 per tire for small autos, $86.54 for medium-sized to large autos, $95.39 for four-tire single-unit trucks, $95.38 for six-tire single-unit trucks, $230.10 for single-unit trucks of three or more axles, and $569.74 for combination trucks. Of the various VOC factors, pavement condition, grade, curvature, and speed changes are those that most influence the rate of wear of contact surfaces (Thoresen and Roper, 1996).

7.1.5 Vehicle Repair and Maintenance

Repair and maintenance costs are incurred on vehicle parts that need replacement or replenishment after some amount of use. For gasoline-powered vehicles, these include the cost of batteries, alternators, fuel pumps, air pump, tire rims, electrical parts such as bulbs and fuses, and so on. These costs also include costs of replacing parts due to crashes, misuse, or other adversarial factors. In some methodologies, the cost of vehicle repair and maintenance is not reported separately but is added to other nonfuel costs. In Year 2005 dollars, the unit cost of vehicle repair and maintenance generally ranged from 4.7 cents per vehicle-mile for small to medium-sized vehicles to 9.3 cents per vehicle-mile for trucks (AAA, 2005). Vehicle repair and maintenance are influenced by pavement condition, curvature, and to a lesser extent, speed, grade, and speed change.

7.1.6 Depreciation

Vehicle depreciation is a function of vehicle usage (miles of travel) and vehicle age (years since manufacture). Table 7.1 presents the depreciation costs of selected vehicle classes and types. It can be seen that mileage-based depreciation rates are similar across vehicle classes: This seems reasonable because the lower initial cost of cars is balanced by their shorter service lives compared with trucks, so the net effect is that rates of mileage-based depreciation are similar across vehicle types (Barnes and Langworthy, 2003). Mileage-based depreciation costs can account for a significant fraction of overall vehicle operating costs. In some literature, the cost of vehicle depreciation is reported together with other nonfuel costs.

The values presented in Table 7.1 are average values. Depreciation rates actually vary by factors such as grade, curves, surface condition, and speed. An improvement in the transportation facility can produce a smoother pavement and improved driving conditions (through reduced stop-and-go situations). Also, all other factors remaining the same, increased speed can lead to reduced depreciation rates, as illustrated by Figure 7.1 for straight constant-speed sections (FHWA, 2002).

7.1.7 VOC Data Sources and Average National VOC Rates

Data on the trends in VOC component prices and consumption rates are available from published and online national resources. These are produced by a number of

Table 7.1 Average Vehicle Depreciation Costs (2005 Dollars)

	Total Depreciation (cents/h)	Average Travel (mi/y)	Mileage-Related Depreciation (cents/mi)	Mileage-Related Depreciation (cents/h)	Time-Related Depreciation (cents/h)
Small autos	219	11,575	14	80	139
Medium-sized to large autos	257	11,575	12	73	185
Four-tire Single-unit trucks	278	12,371	6	36	242
Six-tire	393	10,952	10	55	338
3+ axles Combination trucks	1,122	15,025	22	209	913
3 or 4 axles	946	35,274	7	129	817
5+ axles	1,017	66,710	8	232	785

Source: Cost values are updated from their 1995 values in FHWA (2002).

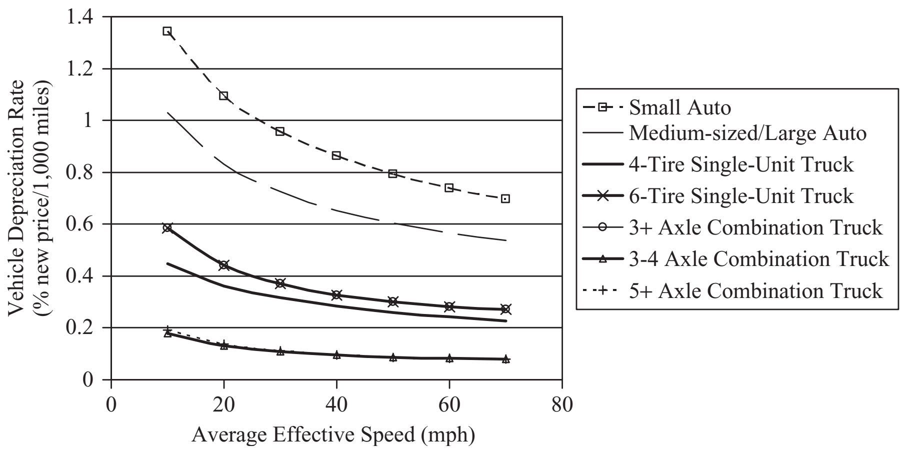

Figure 7.1 Depreciation rate by speed for straight sections (from FHWA, 2002.).

organizations, such as the International Energy Agency, Oak Ridge National Laboratory, national automobile associations, energy agencies, petroleum institutes, and private organizations, including Runzheimer International. Also, national agencies such as the Bureau of Labor Statistics in the United States provide monthly reports on changes in the prices paid by consumers for commodities including vehicle oil and tires, using the consumer and producer price indices. Table 7.2 presents the prices of selected VOC components by vehicle type.

7.2 FACTORS THAT AFFECT VEHICLE OPERATING COST

For all modes of transportation, vehicle operating costs are affected by factors such as vehicle–operator characteristics, economic factors, condition and other characteristics of the fixed transportation facility, and policy–institutional factors. Although we focus on highway transportation in this section, the principles and concepts can be adapted to other transportation modes. Figure 7.2 shows the categories of highway VOC factors.

7.2.1 Vehicle Type

Vehicle operating costs are influenced by size, class, and other vehicle characteristics. Trucks and buses generally have higher operating costs than automobiles, as they consume more fuel and oil and have higher prices for their vehicle parts. Even for a given vehicle type, there could be changes in VOC over time due to improved vehicle technology and fuel efficiency. If the analyst seeks to carry out long-term VOC impact evaluation, future levels of fuel efficiency could be extrapolated from past trends and duly factored in the VOC computation process.

Table 7.2 Average Vehicle Operating Costs (Cents/Vehicle Mile)

	Fuel and Oil	Maintenance and Repair	Tires	Mileage-Dependent Depreciation	Total
Small autos	5.4	3.5	0.5	13.9	20.59
Medium-sized autos	6.44	4.12	1.58	12.5	20.59
Large autos	7.50	4.33	1.90	12.5	22.17
SUVs	8.34	4.33	1.58	12	22.70
Vans	7.50	4.12	1.69	12	21.75
Trucks	21.41	11.09	3.70	10.6	44.64

Source: Costs are updated to 2005 from the following: nontruck fuel, maintenance and repair, and tires, AAA (2005); truck fuel, maintenance and repair, and tires, Barnes and Langworthy (2003); and, depreciation estimations and projections are on the basis of data from FHWA (2002).

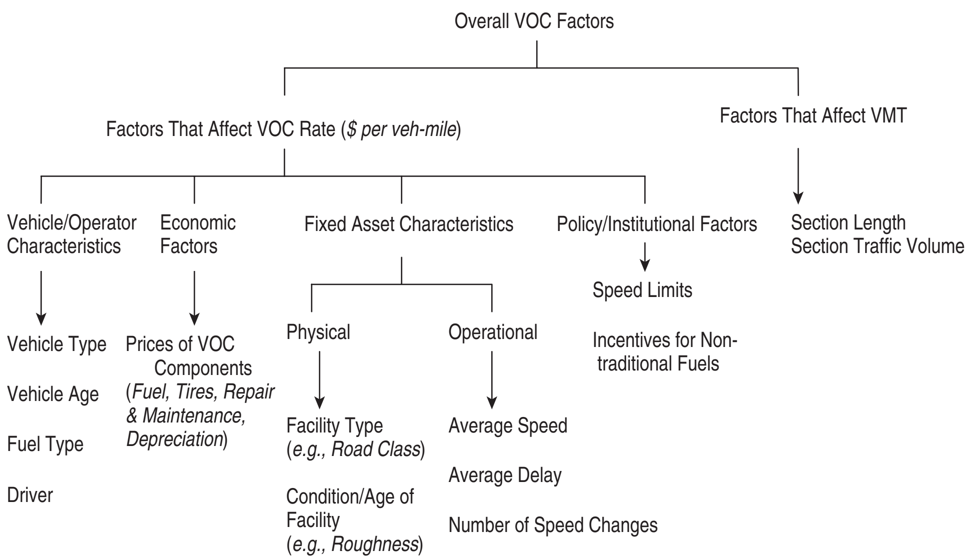

Figure 7.2 Factors that affect highway vehicle operating costs.

In some cases, analysts may seek the operating costs associated with bicycling and walking to facilitate a more comprehensive comparison of transportation alternatives that include these modes. A standard bicycle with basic accessories can cost $100 to $500 with annualized maintenance costs of $20 to $40 for tire replacement, tire pumping, and security; for walking, the main consumable is that of footwear, which typically lasts 500 to 5000 miles of walking distance (VTPI, 2004). The human energy use associated with walking and cycling may be considered a benefit rather than a cost, particularly if traveling using these transportation modes substitute for other exercise activities.

7.2.2 Fuel Type

The uncertainties in supply and increasing costs of fossil fuels coupled with their adverse environmental effects have led to growing use of alternative energy sources for transportation. In evaluating the impacts of transportation improvements, therefore, analysts need to account for the increasing percentage of alternative-fuel vehicles in the traffic stream. At the current time, electric and hybrid vehicles have relatively high purchase costs (150 to 200% of the price of a comparable gasoline car). Electric cars require new battery sets every 20,000 to 30,000 miles costing $2000 to $3000 (averaging 6 to 15 cents per vehicle-mile), and consume 0.25 to 0.5 kWh per mile, so energy costs average 2 to 5 cents per kWh based on typical residential energy rates (USDOE, 2005a). The maintenance costs, including battery replacements, are significantly higher for electric cars (over four fold) compared to hybrid or conventional cars (VTPI, 2005). Even with traditional fuels, there are differences in cost across fuel types: in 2005, the average price of diesel was approximately 10% higher than that of regular leaded gasoline. Also, there are price differences across the three standard grades of gasoline.

7.2.3 Longitudinal Grade

Uphill movements impose additional loads on vehicle engines and therefore require greater consumption of energy compared to downhill or level movements. For downhill trips, fuel consumption is lower than for uphill or level trips, but increased brake applications may lead to increased wear and tear of brake linings and therefore to increased cost of the brake maintenance component of VOC. Figure 7.3 illustrates the general relationships between grade and VOC at various speeds. Generally, overall VOC is lowest for sections with gentle downward slopes (0 to −4%). Table 7.4 shows how the vehicle operating cost for medium-sized automobiles can be determined for a given speed and longitudinal grade. Detailed equations that indicate the effect of grade on the consumption of fuel and for other VOC components, are provided in Appendix A7.1 and the HERS manual (FHWA, 2002). The rate of consumption of each VOC component is subsequently multiplied by the unit price of the component and appropriate adjustment factors for fuel efficiency and pavement condition to determine the overall cost of the component.

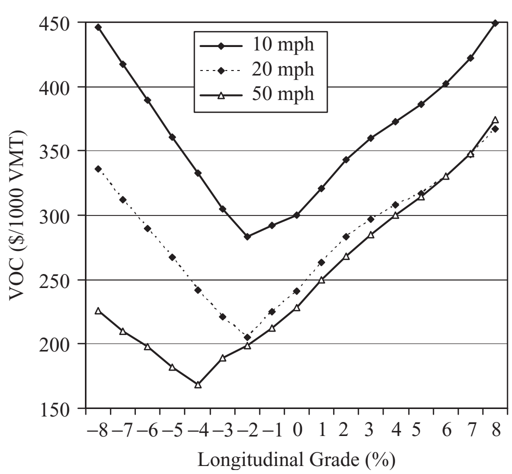

Figure 7.3 Impact of longitudinal grade on medium-sized automobile VOC at various speeds. (Based on data from Zaniewski, 1982.)

Example 7.1 A 2.15-mile section of State Road 25 on rolling terrain received major improvements in vertical alignment. The average grade of the section was reduced from 3.2% to 2.5%. Traffic volume and composition, and speed were the same after the improvement. Assume that the traffic stream has a 50:50 directional split and is composed primarily of medium-sized automobiles, and the traffic volume is 43,340 vpd. In both cases, the average speed is 50 mph. What is the first year user benefit in terms of VOC?

SOLUTION
Before improvement:

Uphill traffic: VOC at +3.2% grade = $275/1000 VMT

Downhill traffic: VOC at −3.2% grade

= $190/1000 VMT

Average: $232.5/1000 VMT

After improvement:

Uphill traffic: VOC at +2.5% grade = $260/1000 VMT

Downhill traffic: VOC at −2.5% grade

= $200/1000 VMT

Average: $230/1000VMT

Change in unit costs:

$$(\text{VOC}_{\text{before}} - \text{VOC}_{\text{after}}) \quad \text{or} \quad (U_1 - U_2)$$

$$= \$2.5/1000 \text{ VMT} = \$0.0025/\text{VMT}$$

First-year user benefits

$$= (0.5)(U_1 - U_2)(\text{VMT}_1 + \text{VMT}_2)$$

$$= (0.5)(0.0025)(2)(43{,}340 \times 2.15 \times 365) = \$85{,}028$$

7.2.4 Vehicle Speed

Vehicle operating speed is the dominant factor in determining VOC (Bennett, 1991; Thoresen and Roper, 1996; Bennett and Greenwood, 2001; FHWA, 2002). Transportation improvements influence travel speeds and therefore can profoundly affect VOC. For some vehicles, fuel consumption decreases with increasing speed to a certain point, after which there is little significant change (or sometimes, an increase) in fuel consumption with increasing speed. Factors that affect operating speeds, and subsequently influence fuel VOC, are speed limits (set by policy) and traffic conditions (which vary by the time of day—peak vs. nonpeak). In this section we discuss the impact of speed on shipping inventory costs and present some VOC models based on speed and other factors.

(*a*) *Inventory Shipping* Inventory cost is affected by vehicle speed and is calculated as follows (AASHTO, 2003):

$$U_{IC} = (100)\frac{r}{(365)(24)}\frac{1}{S}P \tag{7.1}$$

where U_{IC} is the user inventory cost in cents per vehicle-mile, r the annual interest rate, P the cargo value in dollars, and S the vehicle speed in miles per hour.

Example 7.2 Due to a new speed limit policy, the average truck operating speed on a certain interstate freeway increased from 56.5 mph to 61.2 mph. Find the decrease in shipping inventory costs per year for trucks that comprise 22% of the overall traffic stream of 82,500 vehicles per day (vpd). Each truck hauls an average of $1.5 million worth of goods daily. Assume an 8% interest rate.

SOLUTION Using equation (7.1), the daily changes in inventory costs per truck due to the change in travel speed, ΔU_{IC}, can be estimated as follows:

$$\Delta U_{IC} = (100)\frac{r}{(365)(24)}\left(\frac{1}{S_0} - \frac{1}{S_1}\right)P$$

$$= (100)\left(\frac{0.08}{8760}\right)\left(\frac{1}{56.5} - \frac{1}{61.2}\right)(\$1{,}500{,}000)$$

$$= 1.9178 \text{ cents/vehicle-mile}$$

number of trucks per year

$$= (0.22)(82{,}500)(365) = 6{,}624{,}750$$

total reduction in inventory cost for all trucks per year

$$= (1.9178/100)(6{,}624{,}750) = \$127{,}050 \text{ per mile}$$

(*b*) *VOC Models and Look-up Table Based on Speed and Vehicle Class* Hepburn (1994) developed a VOC model for urban roadways that considers the sum of four VOC components (tires, vehicle depreciation, maintenance, and fuel) as a function of two VOC factors: speed and vehicle class. The model is particularly useful for evaluating VOC impacts of transportation interventions that mostly yield a change in average operating speeds or policies that cause a shift in vehicle class distribution. The Hepburn function is as follows:

For "low" average travel speeds (<50 mph) : $\text{VOC} = C + \dfrac{D}{S}$

Table 7.3 Parameters for Hepburn's VOC–Speed Model (2005 Cents)

Vehicle Type	C	D	a_0	a_1	a_2
Small automobile	24.8	45.5	27.2	0.035	0.00021
Medium-sized automobile	28.5	95.3	33.5	0.058	0.00029
Large automobile	29.8	163.4	38.1	0.093	0.00033

For "high" average travel speeds (>50 mph) : $\text{VOC} = a_0 - a_1 S + a_2 S^2$

where VOC is in cents/mile, S is speed (mph) and C, D, a_0, a_1, and a_2 are coefficients that are functions of vehicle class. The coefficient values are provided in Table 7.3.

The Hepburn model assumes that depreciation depends entirely on vehicle use and that the depreciation rate is constant throughout vehicle life. Furthermore, the model is for tangent, level, and urban road sections with pavement roughness assumed to remain constant over time, and all VOC component costs assumed to vary with distance, with the exception of fuel cost, which varies with speed. It does not explicitly consider the consumption rates and prices of individual VOC components for each vehicle class but is nevertheless useful for quick estimation of VOC.

Example 7.3 A straight and level urban arterial has an average operating speed of 35 mph. What is the unit VOC of medium-sized automobiles that use this highway?

SOLUTION Knowing the values of C and D from Table 7.3,

$$\text{VOC} = C + \frac{D}{S} = 28.5 + \frac{95.3}{35}$$

$$= 31.22 \text{ cents/vehicle-mile}$$

(*c*) *VOC Models Based on Speed, Grade, and Vehicle Class* Zaniewski (1982) provided a VOC model as a function of speed, grade, and vehicle class. Table 7.4 presents the VOCs for medium-sized autos, with updated cost values. If the project section consists of several segments with different grades or VMTs, the unit VOC (dollars/vehicle-mile) is estimated separately for each segment. It should be noted, however, that the vehicles at the time of the Zaniewski study (ca. 1980) had 17% lower fuel efficiency than vehicles in 1997 (FHWA, 2002), and even lower compared to vehicles in 2005. As

Table 7.4 VOC by Vehicle Speed and Roadway Grade[a]

	Speed (mph)													
Grade(%)	5	10	15	20	25	30	35	40	45	50	55	60	65	70
8	591	507	451	414	403	395	398	406	414	422	444	467	477	492
7	552	476	424	391	379	369	369	376	385	393	417	444	454	467
6	526	454	406	372	361	347	346	352	362	372	398	422	430	444
5	499	435	389	358	346	333	332	335	346	354	376	395	410	429
4	481	421	379	347	333	319	317	322	329	338	352	367	387	412
3	459	406	364	335	322	309	307	310	317	322	332	340	367	395
2	435	387	347	319	307	297	292	297	301	302	314	319	346	377
1	403	362	325	297	288	279	272	272	279	282	292	301	322	346
0	376	338	302	272	264	255	247	247	254	257	273	287	301	319
−1	367	329	288	254	243	235	232	235	237	239	254	265	282	299
−2	357	319	273	231	212	217	219	223	225	225	237	246	264	284
−3	385	344	292	249	228	209	197	191	212	213	225	235	250	270
−4	422	376	322	273	250	227	212	202	195	190	217	225	239	255
−5	461	407	350	301	276	249	231	217	212	205	204	197	228	243
−6	499	439	379	327	301	273	250	235	228	223	231	213	210	228
−7	537	470	406	352	325	299	273	255	247	237	232	227	223	219
−8	914	503	437	379	350	324	297	279	265	255	249	239	235	228

[a]Cost/1000 VMT for medium-sized autos in 2005 dollars.

such, Table 7.4 should be used after stating the necessary assumptions regarding fuel efficiency, or after making due adjustments for fuel efficiency changes over the years.

Example 7.4 A highway section consists of two segments A and B that have the characteristics listed in Table E7.4 Determine the total vehicle operating costs for each segment. Assume that all vehicles are medium-sized automobiles, and assume further that the values in Table 7.4 reflect current fuel consumption rates.

Table E7.4 Highway Segment Data

	Segment A	Segment B
Traffic volume (ADT)	5320	8580
Average grade (%)	+4.0	+1.5
Speed (mph)	30	50
Length (miles)	5.7	2.6
Directional split	68% on upward slope, 32% on downward slope	45% on upward slope, 55% on downward slope

SOLUTION Given the average speeds and grades, the unit vehicle operating cost is determined from Table 7.4 as follows:

Segment A:

$$\text{Unit VOC} = (319)(0.68) + (227)(0.32)$$
$$= \$289.56 \text{ per 1000 VMT}$$
$$\text{VMT} = (5.7)(5320) = 30{,}324 \text{ vehicle-miles daily}$$
$$\text{Overall VOC} = (\$289.56)(30{,}324) = \$8{,}781 \text{ per day}$$

Segment B:

$$\text{Unit VOC} = (292)(0.45) + (232)(0.55)$$
$$= \$259 \text{ per 1000 VMT}$$
$$\text{VMT} = (2.6)(8580) = 22{,}308 \text{ vehicle-miles daily}$$
$$\text{Overall VOC} = (259)(22{,}308)$$
$$= \$5{,}778 \text{ per day}$$

(*d*) *VOC Models Based on Speed, Gradient, Curvature, and Pavement Condition* Some VOC models, such as the World Bank's HDM (Bennett and Greenwood, 2001) and the HERS model (FHWA, 2002), estimate the unit cost of each VOC component as a function of speed, grade, and pavement condition. This is done for basic sections (straight sections with constant speed), and then excess vehicle operating costs due to speed changes and curvature are calculated. The excess VOC is added to the basic costs to yield the overall VOC for the section.

7.2.5 Delay

Nodes and links in the networks of various transportation modes may often experience delay, which translates into higher vehicle operating costs. In evaluating transportation improvements at such facilities, VOC costs, particularly for fuel and inventory, can be expressed as a function of time delay. On highway links, for instance, delay can involve decelerating to a stop, idling, and accelerating from a stopped position. Such stop-and-go traffic leads to additional strain on a vehicle, which is translated into higher use of fuel and oil. All three phases involve fuel consumption rates that generally exceed that of constant-speed travel. The primary share of overall delay costs is attributed to acceleration of vehicles after being slowed or stopped rather than fuel consumed in decelerating or idling during delay periods (AASHTO, 2003). The impact of travel delay on VOC (fuel and inventory shipping cost components) can be estimated using a methodology provided by AASHTO (2003). In the methodology, the analyst estimates the delay with and without improvement using field measurements (applicable only to the existing situation), simulation, or analytical travel delay models. Using the estimated change in delay, fuel consumption rates per minute of delay (Table 7.5) and fuel price (Appendix A7.2), the total cost of delay can be calculated. This is repeated for each vehicle class. Example calculations are provided below.

(*a*) *Change in Fuel Costs due to Delay Change* For a given vehicle class, the change in fuel costs due to a change in travel delay is found as follows (AASHTO, 2003):

$$\text{change in fuel VOC} = g(D_0 - D_1)p$$

where: g is the fuel consumption in gallons per minute of delay (from Table 7.5), $D_0 - D_1$ = change in delay (minutes) due to the transportation improvement, and p is the price of fuel. The parameters g and p are specific to vehicle class.

Example 7.5 Modernization and optimization of the traffic signal system at a busy urban arterial yielded, on average, a 9-minute reduction in delay per trip for users of the arterial. The traffic volume is 4300 vph and is composed of 25% small autos, 30% large autos, 25% SUVs, 10% two-axle single-unit trucks, 5% three-axle single-unit trucks, and 5% multiple-unit trucks. After improvement, average free-flow speed increases from 45 mph to 50 mph, and traffic volume and composition remain unchanged. Determine the reduction in fuel costs during peak hours due to the decrease in delay. Assume that fuel cost is \$2.20 per gallon. Use the fuel consumption rates provided in Table 7.5, and assume simple averages across vehicle classes.

Table 7.5 Fuel Consumption (Gallons) per Minute of Delay by Vehicle Type

Free-Flow Speed (mph)	Small Automobile	Large Automobile	SUV	Two-Axle Single-Unit Truck	Three-Axle Single-Unit Truck	Multiple-Unit Truck
20	0.011	0.022	0.023	0.074	0.102	0.198
25	0.013	0.026	0.027	0.097	0.133	0.242
30	0.015	0.030	0.032	0.122	0.167	0.284
35	0.018	0.034	0.037	0.149	0.203	0.327
40	0.021	0.038	0.043	0.177	0.241	0.369
45	0.025	0.043	0.049	0.206	0.280	0.411
50	0.028	0.048	0.057	0.235	0.321	0.453
55	0.032	0.054	0.065	0.266	0.362	0.495
60	0.037	0.060	0.073	0.297	0.404	0.537
65	0.042	0.066	0.083	0.328	0.447	0.578
70	0.047	0.073	0.094	0.360	0.490	0.620
75	0.053	0.080	0.105	0.392	0.534	0.661

Source: Adapted from AASHTO (2003).

Table E7.5 Estimation of Change in Fuel Consumption Costs due to Delay

	Small Auto	Large Auto	SUV	Two-Axle Single-Unit Truck	Three-Axle Single-Unit Truck	Multiple-Unit Truck	Total
Traffic volume (vph)	1075	1290	1075	430	215	215	4300
Fuel consumption rate (gals/min)	0.025	0.043	0.049	0.206	0.280	0.411	
Fuel price ($/gal)	$2.2 (average for all vehicle classes)						
Change in delay due to the improvement, $D_0 - D_1$	9 min (average for all vehicle classes) per peak hour						
Change in fuel consumption costs	$532	$1098	$1043	$1754	$1192	$1750	$7369

SOLUTION The traffic volume for each vehicle class is determined by multiplying the percentage composition by the total traffic volume. Using Table 7.5, the fuel consumption rates are determined, and the change in fuel consumption cost is presented in Table E7.5.

Therefore, the total reduction in fuel costs during the peak hours due to the decrease in delay is $7,369/hr

(*b*) *Change in Shipping Inventory Costs due to Delay* Example 7.2 provided a method to evaluate the impact of a change in shipping speed (due to a transportation improvement) on inventory costs. AASHTO (2003) provides a methodology for estimating the impact of time delay on shipping operating costs, as follows: The change in inventory cost per shipping vehicle due to a change in delay is given by $\Delta I(D) = I(D)\Delta D$, where ΔD is the change in delay (in minutes) and

$$I(D) = \text{inventory costs (cents per vehicle-minute)}$$
$$= (100)\frac{r}{(365)(24)(60)}P$$

where r is the interest rate (per annum) and P is the dollar value of the cargo being transported by the shipping vehicle.

In some cases, the analyst is provided with an estimate of the expected change in delay, but in other cases, change in delay will need to be estimated (by calculating the delay before and after the improvement). Delay can be estimated on the basis of prevailing traffic conditions and road inventory. Methodologies for estimating delay are found in available literature, such as the *Highway Economics Requirements System* (HERS) *Technical Manual* (FHWA, 2002, pp. 4-7 to p. 4–10).

Example 7.6 A freeway was constructed in 2005 to bypass a city center. This improvement led to a 10-minute reduction in travel delay per trip for shippers who transport goods across the city. If the average value of cargo is $265,000 per truck and the interest rate is 6%, determine (a) the shipping inventory costs per vehicle before the construction, (b) the reduction in shipping inventory costs due to the construction in 2005, and (c) the change in user benefits accrued to shippers in 2005 compared to pre-construction conditions. The pre-construction period daily truck traffic (ADTT) was 33,000, and the trip time was 1.5 hours. Assume a 5% ADTT increase due to induced demand.

SOLUTION
(*a*) *Shipping Inventory Cost per Truck*
The unit inventory cost of the shipment before improvement can be calculated as follows:

$$I(D) = P \times [r/(365 \times 24 \times 60)] = (\$265{,}000) \times [0.06/(365 \times 24 \times 60)] = \$0.03025/\text{truck-minute}$$

The unit inventory cost after the improvement is the same as that before the improvement because there is no change in the total cargo value and the annual interest rate. Since the travel time reduces by 10 minutes after the improvement, the total inventory cost saved due to the improvement is

$$\text{Change in unit inventory cost} = \$0.03025/\text{truck-minute} \times 10 \text{ minutes} = \$0.3025/\text{truck}$$

(*b*) *Reduction in Shipping Inventory Cost*
The unit shipping inventory cost in dollars/truck-mile, U, can be calculated as follows:
Before Improvement:

$$U_{\text{before}} = \$0.03025/\text{truck-minute} \times (60/S_{\text{before}})$$
$$= \$1.815T/L \text{ per truck-mile}$$

where S_{before} = average speed before improvement (mph) $= L/T$, L = average truck trip length (miles) and T = average truck trip time (hours).

$$\text{Total yearly inventory cost} = (\$1.815T/L)(ADTT)(L)(365)$$

After Improvement:

$$U_{\text{after}} = \$0.03025/\text{truck-minute} \times (60/S_{\text{after}}) = \$1.815[T - (10/60)]/L \text{ per truck-mile}$$

$$\text{Total yearly inventory cost} = \{\$1.815[T - (10/60)]/L\}/\{1.05ADTT(L)(365)\}$$

Therefore, the reduction in total shipping inventory cost = Total yearly inventory cost before the improvement−Total yearly inventory cost after the improvement $= 1.815\ ADTT(365)\ [T - 1.05\{T - (10/60)\}] = 1.815ADTT(365)\ [0.175 - 0.05T] = \$2,186,168$ in the first year.

(*iii*) *Change in User Benefits (or Change in Consumer Surplus)*

The change in user benefits can be calculated based on the change in consumer surplus, which is given by the following formula:

$$\begin{aligned}\text{User benefits} &= \frac{1}{2}(U_{\text{before}} - U_{\text{after}}) \times (VMT_{\text{before}} + VMT_{\text{after}})\\ &= \frac{1}{2}([(1.815(10/60)/L)][2.05ADTT(L)(365)]\\ &= \$3,734,703.\end{aligned}$$

7.2.6 Speed Changes

Vehicles travel at different speeds due to geometric and/or traffic conditions. It has been shown that the more frequent the speed change of a vehicle, the higher the associated operating cost, particularly its fuel component. When vehicles slow down or pick up speed, they experience additional strain that is translated into a higher use of fuel and oil. As such, highway projects that smoothen traffic flow by reducing the frequency and intensity of speed changes ultimately reduce the costs of vehicle operation.

An extreme case of speed change is stop−start conditions, which are usually typical of city driving. Barnes and Langworthy (2003) showed that for maintenance, repair, and depreciation, worsening stop−start conditions will increase costs of fuel consumption and to a smaller extent, the costs of maintenance, repair, and depreciation.

Table 7.6 Percent Decrease in VOC from City to Highway Driving Conditions[a]

VOC Component	Automobile	Pick-up/ Van/SUV	Commercial Truck
Fuel	29%	23%	24%
Maintenance/repair	16%	14%	13%
Depreciation	16%	14%	13%
Total	20%	17%	18%

Source: Data from Barnes and Langworthy (2003).
[a]Pavement in good condition (PSI = 3.5 or above) assumed for both cases.

Table 7.6 can be used to estimate the impact of a change in driving conditions on VOC, for each vehicle class.

VOC Model Based on Speed-Change Frequency: For each vehicle class, VOC equations in the *HERS Technical Manual* (FHWA, 2002) can be used to estimate the total unit costs of speed changes per thousand vehicle-miles, as the sum of speed change costs due to five VOC components (fuel, oil, tires, maintenance and repair, and vehicle depreciation). The template for VOC computations is shown in Table 7.7. The set of equations for computing the rate of consumption of each VOC component, including at speed-change frequency, is presented in Appendix A7.1.

7.2.7 Horizontal Curvature

A vehicle negotiating a horizontal curve requires extra energy to counter centrifugal forces in order to stay in a radial rather than a tangential path. Furthermore, the side friction increases tire wear and tear, and the

Table 7.7 Percent Decrease in VOC from Poor to Good Pavement Conditions[a]

VOC Component	Automobile	Pickup/ Van/SUV	Commercial Truck
Fuel	0%	0%	0%
Maintenance/repair	20%	21%	20%
Tires	18%	17%	20%
Depreciation	21%	20%	20%
Total	15%	13%	11%

Source: Data from Barnes and Langworthy (2003).
[a]Good pavement, PSI = 3.5 or above (i.e., $IRI = 85$ or below); poor pavement, PSI = 2.5 or below (i.e., IRI = 170 or above); highway driving (not city driving) assumed for both cases.

frequency and cost of maintenance and replacement. The VOC due to curves involves fuel, tire, and maintenance and repair, and is typically expressed as a function of the rate of consumption and unit prices of these VOC components, vehicle type, and average speed. In the HERS methodology, VOC for curve negotiation speed is estimated separately for sections with low speeds (<55 mph) and those with high speeds (>55 mph).

(*a*) *Low-Speed Sections* VOC due to curve negotiation at these sections is estimated using VOC vs. curve–degree tables from Zaniewski (1982). These tables show the costs due to curves for each vehicle type as a function of curvature and speed.

(*b*) *High-Speed Sections* In the HERS manual, the VOC due to curves for each vehicle type is calculated using the rate of consumption of VOC component for curve sections, by vehicle class, the unit prices of VOC components, and the adjustment factor for VOC component. The set of equations for VOC consumption rates at curve sections is presented in Appendix A7.1. An example computation is provided in Section 7.3.2.

7.2.8 Road Surface Condition

To some extent, pavement roughness, often measured in terms of the present serviceability index (PSI) or international roughness index (IRI), can affect the maintenance, tire, repair, and depreciation cost components of VOC. This is because the motion of vehicle tires on a rough pavement surface is associated with greater resistance to movement, which can lead to higher levels of fuel consumption compared to traveling at a similar speed on a smooth surface; and a bumpy ride, which leads to increased vibration and wear and tear of vehicle parts. Also, an indirect effect of poor pavement conditions is that road users may be forced to drive at lower speeds, leading to higher fuel consumption. Transportation projects such as resurfacing that improve pavement surfaces can therefore lead to reductions in VOCs.

Zaniewski (1982) suggested that there can be significant impacts of pavement roughness on nonfuel vehicle operating cost components, particularly for rough pavements. Most other research on the relationship between pavement condition and VOC has been conducted outside the United States by the World Bank and other international agencies. Examples include a New Zealand study (Opus Central Laboratories, 1999) which suggests that at superior levels of pavement condition (low roughness), increments in condition have relatively little incremental effect on vehicle operating cost (Figure 7.4), and that additional costs of vehicle operation start to accrue only when the IRI exceeds approximately 100 in/mi (3.33 m/km). For paved roads in poor condition and for gravel roads, changes in road surface condition can lead to significant reductions in VOC. Barnes and Langworthy (2003) reported on a previous study that suggested that a unit increase in IRI (in m/km) can generally lead to an increase of $200 (1.67 cents/vehicle-mile, assuming 12,000 annual mileage) in vehicle maintenance and repair costs alone. Also, Barnes and Langworthy (2003) developed adjustment factors for all VOC components combined, as a function of pavement condition (Figure 7.5). They assumed a baseline PSI of 3.5 or better (an IRI of

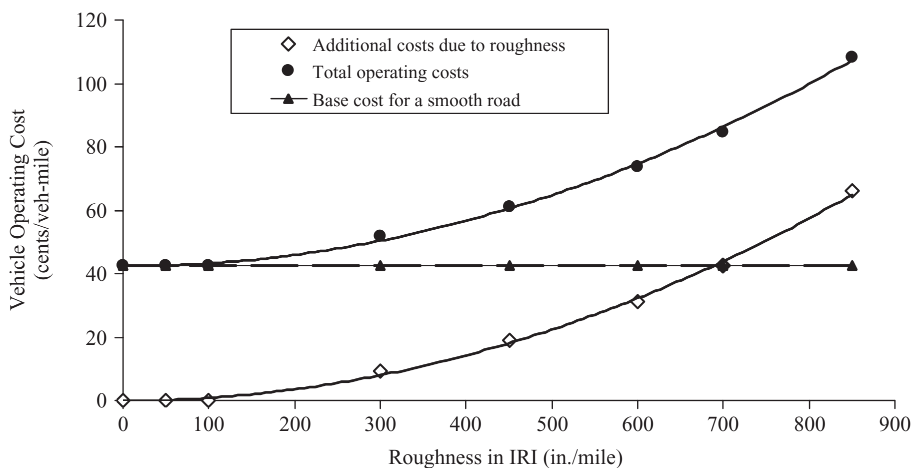

Figure 7.4 Relationship between VOC and pavement roughness. (Adapted from Opus Central Laboratories, 1999.)

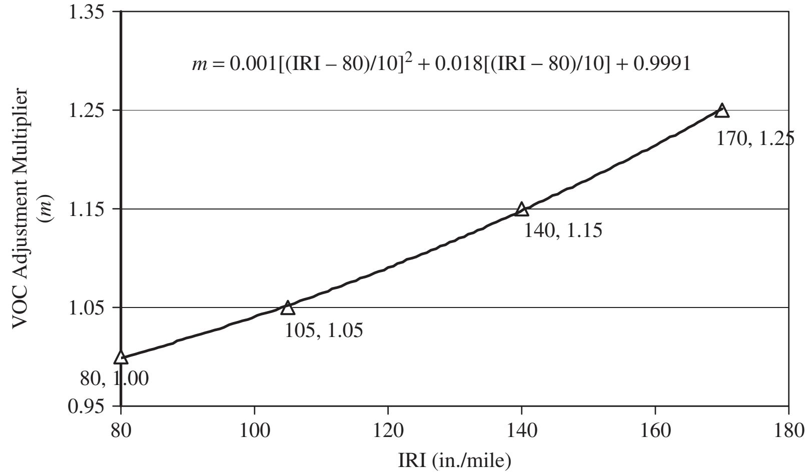

Figure 7.5 VOC adjustments for pavement roughness levels.

about 85 in/mi or 1.35 m/km), at which further increases in pavement condition would have no impact on operating costs, and then adjusted for three levels of rougher pavement as shown in the figure. The figure can be used to estimate the VOC corresponding to a given pavement condition. For the depreciation component, there seem to be relatively few studies that have explicitly shown a relationship with pavement roughness. However, it seems obvious that in the long term, a vehicle which is operated on a rough pavement surface is likely to lose its value faster than one that is operated on a smooth-surfaced pavement.

Example 7.7 A warranty HMA resurfacing project on Interstate 599 yielded a performance jump of 40 IRI (in/mi). If the base vehicle operating cost is \$143 per 1000 vehicle-miles, (a) determine the change in unit VOC due to resurfacing. Use the Barnes and Langworthy relationship. The IRI before improvement was 110 in/mi. (b) If the traffic volume is 67,500 vpd and the section is 6.5 miles in length, determine the overall change in VOC.

SOLUTION (a) *Before improvement*: IRI = 110 in/mi, and the VOC adjustment multiplier is given by

$$m = (0.001)\left(\frac{110-80}{10}\right)^2 + (0.018)\left(\frac{110-80}{10}\right) + 0.9991 = 1.06$$

$$\text{VOC} = (1.06)(143) = \$151.58/1000 \text{ VMT}$$

After improvement: IRI = 110 − 40 = 70 in/mi, m = 1.00 since 70 is less than 80, and therefore VOC = \$143/1000 VMT. Change in unit VOC = 151.58 − 143 = \$8.58/1000 VMT.

(b) Overall change in VOC = (\$8.58)(67,500)(365)(6.5)/1000 = \$1.374 million.

Table 7.7 presents the percentage changes in VOC for pavements that transition from poor condition (PSI of 2 or higher) to good condition (PSI of 3.5 or lower) under the given highway conditions. VOCs corresponding to intermediate values of pavement condition can be determined by interpolation. This table can therefore be used to estimate the impact of changes in pavement condition (within the PSI range given) on VOC for each VOC component or for all components combined, in response to a pavement improvement project.

Example 7.8 After replacing a highway pavement section that had 2.5 PSI and a total VOC value of \$152/1000 VMT for automobiles, the pavement now has a PSI value of 3.7. Estimate the new automobile VOC.

SOLUTION From Table 7.7, the average adjustment in VOC upon pavement improvement from poor to good condition is a 15% reduction, that is, (0.85)(152) = \$129.2/1000 VMT.

FHWA's HERS methodology duly incorporates the effect of pavement conditions on the individual VOC components of oil consumption, tire wear, and depreciation, and this can be done for each of six vehicle classes. Also, HERS utilizes a pavement condition adjustment factor to account for differences in pavement condition relative to a reference pavement condition. These factors are provided in Appendix A7.3.

7.2.9 Other VOC Factors

Other factors that can influence the cost of vehicle operation include driver behavior, condition of vehicle, vehicle weight, prices of vehicle maintenance (reflected in costs of labor, vehicle consumables, and spare parts), and weather severity. Operating costs for transit vehicles (such as buses and trolleys) are also affected by other factors, such as transit schedules (which typically depend on passenger demand) and vandalism.

7.3 PROCEDURE FOR ASSESSING VOC IMPACTS

The framework for assessing VOC impacts of transportation interventions (Figure 7.6) revolves around three tasks:

1. Estimating the unit VOC rates (i.e., dollars/vehicle-mile) with and without intervention
2. Estimating the amounts of travel (VMT) with and without the intervention
3. Calculating the user VOC benefits of intervention

7.3.1 Steps for Assessing the Impacts

Step 1: Define the Analysis Area This involves identification of the project and its limits and provides vital benchmarks for collecting project data such as grades, section length, average operating speeds, and other data needed for VOC estimation.

Step 2: Describe the Transportation Intervention Different interventions have different impacts on VOC factors and consequently, on VOC components. For example, for evaluating a highway project or policy change that influences only vehicle speed, there may be no need to collect data on grades. Therefore, this step helps the analyst to select the appropriate VOC factors for the analysis and could therefore guide in selecting the appropriate methodology or software to be used. Fuel cost typically dominates VOC, and fuel price and vehicle fuel efficiency values are determinants of vehicle fuel costs.

Step 3: Consider the Base-Case Scenario The base case typically refers to the current condition without intervention or improvement. It may also refer to a future condition without an intervention.

Steps 4 to 6: Establish the Values of Relevant VOC Factors. Use Models, Look-up Tables, or Graphs to Determine VOC per Vehicle-Mile Data on average speeds, grades, pavement condition, vehicle-type distribution, and/or other relevant VOC factors are collected for the "with" and "without" intervention scenarios. By applying data from the selected models or look-up tables, the unit vehicle operating cost (dollars/vehicle-mile) is estimated. This is done for both the base case and the intervention scenario. Depending on the appropriate VOC factors, the analyst may choose from a variety of models, such as those described below.

(a) *Hepburn (1994) VOC Model* As described in Section 7.2.4(b), this model estimates VOC as a function of speed and vehicle class only. The VOC components considered are: tires, vehicle depreciation, maintenance, and fuel. This model is useful for highway transportation interventions that mostly yield a change in average operating speeds only.

(b) *1982 FHWA VOC Model* This model, developed by Zaniewski (1982), is based on two VOC factors: speed and grade (Table 7.4). For highway transportation projects that involve significant changes in grade through extensive vertical realignment, this method can be used instead of the Hepburn model. Details are provided in Section 7.2.4(c).

(c) *FHWA HERS (1999) Model* This is probably the most comprehensive of all VOC models currently in use in the United States. It considers a wide array of VOC factors: speed, speed changes, curvature, pavement condition, and vehicle class and five VOC components: fuel, oil, tires, vehicle depreciation, and maintenance and repair. To facilitate the analysis, a software package is available (FHWA, 2002). Use of the HERS methodology for steps 4, 5, and 6 of the framework, is described in Section 7.3.2 and Example 7.11.

(d) *AASHTO (2003) Model* This model presents for each automobile class, a single VOC (aggregated for all VOC components), in reference to 1999 unit vehicle operating costs reported by AAA. Updated values of the AAA's unit VOC values can be found on the AAA Web site and in its publications. These values are generally not decomposed by VOC factors or their levels, and it may be assumed that they represent the unit costs under average conditions of the VOC factors In AASHTO (2003), the VOC components for which VOC is reported individually are fuel and inventory. Fuel costs are presented as a function of speed and vehicle class and inventory costs are presented as a function of the value of the inventory, interest rate, and shipping delay.

(e) *The World Bank's HDM Model* This model helps to estimate VOC for motorized and nonmotorized vehicles that operate on paved or unpaved roads (Bennett and Greenwood, 2001). It considers a wide range of VOC factors: speed, speed changes, curvature, pavement condition, and vehicle class; and VOC components; fuel, oil, tires, vehicle depreciation, and maintenance and repair.

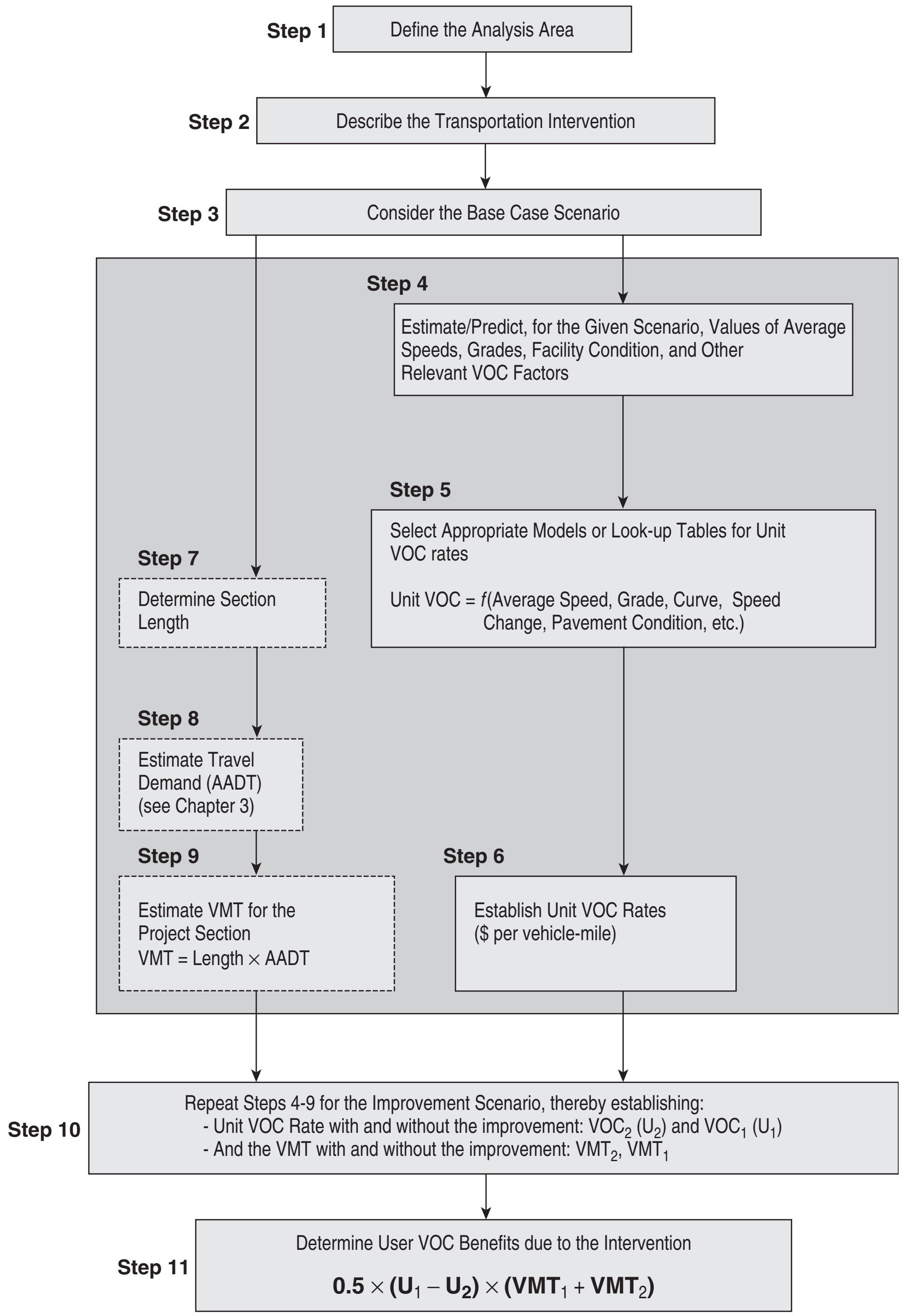

Figure 7.6 Framework for estimating VOC impacts of highway interventions.

(f) *Australia's NIMPAC Model* This model helps to estimate VOC for motorized and nonmotorized vehicles (Thoresen and Roper, 1996). Detailed estimates are provided for different VOC components, and their effects on the various VOC factors are described.

Steps 7 to 9: Determine the Section Length and Travel Demand (AADT), and Estimate the VMT These parameters are computed for the base case as well as the intervention scenario. The section length generally remains the same after intervention unless the project entails significant vertical or horizontal alignment or length extension. Traffic volumes rarely remain the same after improvement—they increase due to induced travel and attracted traffic from other routes. Chapter 3 discussed how travel demand can be estimated for a link in a transportation network.

Step 10: Repeat Steps 4 to 9 for the Intervention Scenario By the end of this stage of the framework, the analyst should have established the values of the following parameters: VOC_1 or U_1, VOC_2 or U_2, VMT_1, and VMT_2. This is done for each vehicle class and facility segment under consideration.

Step 11: Determine the User Overall VOC Savings Due to Intervention The overall VOC savings are determined for each vehicle class or road segment under consideration, and the sum of all savings is computed. In the latter case, computation of the user benefits of VOC will depend on whether demand is elastic or inelastic. When demand is inelastic (therefore precluding any induced, generated, or diverted trips), the user VOC benefit occurring from an improved transportation system is taken as the product of the reduction in the unit VOC and the number of vehicle-miles. When demand is elastic and there are induced trips, the increase in supply results in a lower cost of transportation and subsequently, increased demand. Then the user VOC benefit is given by $(0.5)(U_1 - U_2)$ $(VMT_1 + VMT_2)$.

Example 7.9 An ambitious portfolio of ITS programs at a certain 14.5-mile urban freeway is expected to increase average operating speed from 35 mph to 50 mph. Determine the change expected in the total VOC of medium-sized automobiles due to the improvement. Assume a traffic volume of 76,250 vpd, that medium-sized vehicles constitute 35% of the traffic stream, and that the traffic volume increases by 5% after improvement.

SOLUTION

Before improvement:

$$U_1 \text{ or } VOC_1 = C + \frac{D}{S} = 28.5 + \frac{95.3}{35}$$
$$= 31.22 \text{ cents/vehicle-mile}$$
$$VMT_1 = (14.5)(0.35)(76{,}250) = 386{,}969 \text{ per day}$$

After improvement:

$$U_2 \text{ or } VOC_2 = 28.5 + \frac{95.3}{50}$$
$$= 30.41 \text{ cents/vehicle-mile}$$
$$VMT_2 = (14.5)(0.35)(76{,}250)(1.05)$$
$$= 406{,}317 \text{ per day}$$

User VOC benefit due to the improvement

$$= (0.5)(VOC_1 - VOC_2)(VMT_1 + VMT_2)$$
$$= (0.5)(0.3122 - 0.3041)(386{,}969 + 406{,}317)$$
$$= \$3212 \text{ per day}$$

Example 7.10 As part of its upgrade to a state highway, a certain section of county road is to receive vertical realignment through massive cut-and-fill earthwork operations. The project comprises two segments with the characteristics given in Table E7.10. Determine the user VOC benefit per year due to the improvement.

SOLUTION *Segment 1:*

Before improvement: From Table 7.4, unit VOC,

$$U_1 = (332 \times 0.52) + (231 \times 0.48) = \$283.52/1000\,\text{VMT}$$
$$VMT_1 = (0.87)(65{,}200) = 56{,}720 \text{ vehicle-miles}$$

Table E7.10 Characteristics of the Base Case and Improvement Scenarios

	Before Improvement				After Improvement			
	Length (miles)	Traffic Volume (ADT)	Grade(%)	Speed	Length (miles)	Traffic Volume (ADT)	Grade(%)	Speed
Segment 1: 52% uphill, 48% downhill	0.87	65,200	5.0	35	0.86	68,000	2.0	50
Segment 2: 60% uphill, 40% downhill	1.2	53,200	2.0	45	1.2	54,300	1.5	50

After improvement: Similarly, unit VOC

$U_2 = (302 \times 0.52) + (225 \times 0.48) = \$265.04/1000\,\text{VMT}$

$\text{VMT}_2 = (0.86)(68{,}000) = 58{,}480$ vehicle-miles

$$\begin{aligned}\text{VOC benefit} &= (0.5)(U_1 - U_2)(\text{VMT}_1 + \text{VMT}_2)\\ &= (0.5)(283.52 - 265.04)\\ &\quad (56{,}720 + 58{,}480)(365/1000)\\ &= \$388{,}537\end{aligned}$$

Segment 2:

Before improvement: Unit VOC,

$U_1 = (301 \times 0.6) + (225 \times 0.4) = \$270.60/1000$ VMT

$\text{VMT}_1 = (1.2)(53{,}200) = 63{,}840$ vehicle-miles

After improvement: Unit VOC,

$$\begin{aligned}U_2 &= (292 \times 0.6) + (232 \times 0.4)\\ &= \$268/1000\ \text{VMT}\end{aligned}$$

$\text{VMT}_2 = (1.2)(54{,}300) = 65{,}160$ vehicle-miles

$$\begin{aligned}\text{VOC benefits} &= (0.5)(U_1 - U_2)(\text{VMT}_1 + \text{VMT}_2)\\ &= (0.5)(270.6 - 268)(63{,}840 + 65{,}160)(365/1000)\\ &= \$62{,}210\end{aligned}$$

Total VOC benefits due to the improvement = $(388,527 + 61,210) = $449,747 per year.

7.3.2 Implementation of Steps 4 to 6 Using the HERS Method

In HERS, VOC (CSOPCST) is estimated as the sum of operating cost per thousand vehicle-miles due to following VOC components: fuel, oil, tires, maintenance and repair, and vehicle depreciation, separately assuming a *basic* section (straight and level section with no speed change). Then the *excess* VOC is computed separately for *speed-change sections* and *curved sections* and added to the basic section costs to obtain the overall VOC for the entire highway segment.

The cost is calculated for each vehicle type and VOC component. This is done for basic sections (Table 7.8a), speed-change sections (Table 7.8b), and curved sections (Table 7.8c).

- *Rates of consumption of VOC components*. Appendix A7.1 presents equations for estimating the rate of consumption of various VOC components at constant speed, excess consumption for speed changes and curved sections, for different vehicle classes.
- *Unit costs of VOC components*. These are provided in Appendix A7.2 or in the HERS manual (FHWA, 2002).
- *Pavement condition adjustment factors for VOC components*. These are provided in Appendix A7.3 or in the HERS manual (FHWA, 2002).
- *Component adjustment factors*. These factors reflect reductions in consumption rates of various VOC components between 1980 and 1997. As these are the most recent values available, they are included in Appendix A7.4 (FHWA, 2002).

Example 7.11 It is proposed to improve a certain 5.2-mile urban arterial section. The section is straight with no speed changes. Assume that the current volume is 41,000 vpd of small autos and a 6% traffic growth after the improvement. Estimate the constant-speed operating

Table 7.8 HERS VOC Computation Templates
(a) Basic Sections

VOC Component	(a) Rate of Consumption per 1000 VMT	(b) Pavement Condition Adjustment Factor	(c) Unit Cost	(d) Component Adjustment Factor	(e) = (a) × (b) × (c/d) Total Cost ($/1000 VMT)
Fuel (FC)	CSFC gallons	PCAFFC	COSTF	FEAF	
Oil (OC)	CSOC quarts	PCAFOC	COSTO	OCAF	
Tire (TW)	CSTW % worn	PCAFTW	COSTT	TWAF	
Maintenance and repair (MR)	CSMR % of average cost	PCAFMR	COSTMR	MRAF	
Depreciation (VD)	CSVD % of new price	PCAFVD	COSTV	VDAF	
					$\sum e$ = CSOPCST

Table 7.8 (*continued*)
(b) Excess VOC due to Speed Change

VOC Component	(a) Excess Rate of Consumption per 1000 VMT	(b) Unit Cost ($)	(c) Component Adjustment Factor	(d) = (a) × (b/c) Total Cost ($/1000 VMT)
Fuel (FC)	VSFC gallons	COSTF	FEAF	
Oil (OC)	VSOC quarts	COSTO	OCAF	
Tire (TW)	VSTW % worn	COSTT	TWAF	
Maintenance and repair (MR)	VSMR % of average cost	COSTMR	MRAF	
Depreciation (VD)	VSVD % of new price	COSTV	VDAF	
				$\sum d$ = VSCOPCST

(c) Excess VOC at High-Speed Curved Sections

VOC Component	(a) Excess Rate of Consumption per 1000 miles	(b) Unit Cost ($)	(c) Component Adjustment Factor	(d) = (a) × (b/c) Total Cost ($/1000 VMT)
Fuel, FC	CSFC gallons	COSTF	FEAF	
Tire, TW	CSTW % worn	COSTT	TWAF	
Maintenance and Repair, MR	CSMR % of average cost	COSTMR	MRAF	
				$\sum d$ = COPCST

cost per thousand vehicle-miles (CSOPCST) due to each of five VOC components (fuel, oil, tires, maintenance and repair, and vehicle depreciation). The road conditions without the improvement (expected values with the improvement are shown in parentheses) are as follows: average grade, 3% (2.5%); pavement condition, 3.1 (4.2) PSR; and average speed, 23 (35) mph.

SOLUTION (*1*) *Unit costs of VOC components* These are given in Table E7.11.1 along with component adjustment factors from the HERS Manual.

(*2*) *Pavement condition adjustment factors before and after improvement* The equations in Appendix A7.3 are used to compute the pavement condition adjustment factors (PCAFOC) for small autos:

Fuel: PCAFFC = 1, for before and after improvement.

Oil: $\text{PCAFOC}_{\text{before}}$

$$= 2.64 + 0.0729\text{PSR}^2 - 0.722\text{PSR}$$
$$= 2.64 + (0.0729)(3.1^2) - (0.722)(3.1) = 1.102$$

Tire wear: $\text{PCAFTW}_{\text{before}}$

$$= 2.40 - 1.111 \ln(\text{PSR})$$
$$= 2.40 - 1.111 \ln(3.1) = 1.143$$

Maintenance and repair: $\text{PCAFMR}_{\text{before}}$

$$= 3.19 + 0.0967\text{PSR}^2 - 0.96\text{PSR}$$
$$= 3.19 + (0.0967)(3.1^2) - (0.96)(3.1) = 1.143$$

Vehicle depreciation: $\text{PCAFVD}_{\text{before}}$

$$= 1.136 - 0.106 \ln(\text{PSR})$$
$$= 1.136 - 0.106 \ln(3.1) = 1.016$$

Pavement condition adjustment factors after improvement are computed using the same equations and on the basis of improved PSR (4.2).

(*3*) *Rates of consumption of VOC components before improvement* The equations in Appendix A7.1 are used, as shown below:

Table E7.11.1 Adjustment Factors and Unit Costs by VOC Component

VOC Component	Unit Cost, ($)	Component Adjustment Factor
Fuel (FC)	COSTF = 0.871	FEAF = 1.536
Oil (OC)	COSTO = 3.573	OCAF = 1.05
Tire (TW)	COSTT = 45.20	TWAF = 1.0
Maintenance and repair (MR)	COSTMR = 84.10	MRAF = 1.0
Depreciation (VD) price/vehicle	COSTV = 18,117	VDAF = 1.30

[a]From FHWA (2002).

Fuel: $CSFC_{before}$

$$= 100.82 - 4.9713S + 0.11148S^2 - 0.0011161S^3 + (5.1089 \times 10^{-6})S^4 + 3.0947G$$

$$= 100.82 - (4.9713)(23) + (0.11148)(23)^2 - (0.0011161)(23)^3 + (5.1089 \times 10^{-6})(23)^4 + (3.0947)(3)$$

$$= 42.587 \text{ gals/1000 VMT}$$

Oil: $CSOC_{before}$

$$= \exp[2.7835 - 0.79034\ln(S) - 1.1346/S^{1.5} + 0.65342G^{0.5}]$$

$$= \exp[2.7835 - 0.79034\ln(23) - 1.1346/23^{1.5} + (0.65342)(3^{0.5})] = 4.165 \text{ quarts/1000 VMT}$$

Tire wear: $CSTW_{before}$

$$= \exp[-2.55 + 0.0001621S^2 + 0.01441S + 1.473\ln(G) - 0.001638SG]$$

$$= \exp[-2.55 + (0.0001621)(23^2) + (0.01441)(23) + 1.473\ln(3) - (0.001638)(23)(3)]$$

$$= 0.534\% \text{ worn/1000 VMT}$$

Maintenance and repair needs: $CSMR_{before}$

$$= 48.3 + 0.00865S^2 + 0.0516SG$$

$$= 48.3 + (0.00865)(23^2) + (0.0516)(23)(3)$$

$$= 56.436 \text{ (\% average cost/1000 VMT)}$$

Depreciation rate: $CSVD_{before}$

$$= 2.2 + 0.001596S - 0.38\ln(S)$$

$$= 2.2 + (0.001596)(23) - 0.38\ln(23)$$

$$= 1.045\% \text{ new price/1000 VMT}$$

(*4*) *VOC computation for the before-improvement case* Results are summarized in Table E7.11.2.

In this example, excess VOC computation is not needed because the section is a straight constant-speed section, and therefore involves only basic section costs. Furthermore, there is no need to repeat the computation for other vehicle classes because the traffic stream is comprised primarily of small autos.

(*5*) *Rates of consumption of VOC components after improvement* The rates of consumption of VOC components for small autos at constant speed at the new average effective speed (S) and new gradient (G %) are:

Fuel: $CSFC_{after}$

$$= 100.82 - 4.9713S + 0.11148S^2 - 0.0011161S^3 + (5.1089 \times 10^{-6})S^4 + 3.0947G$$

$$= 100.82 - (4.9713)(35) + (0.11148)(35)^2 - (0.0011161)(35)^3 + (5.1089 \times 10^{-6})(35)^4 + (3.0947)(2.5)$$

$$= 30.938 \text{ gals/1000 VMT}$$

Oil consumption rate: $CSOC_{after}$

$$= \exp[2.7835 - 0.79034\ln(S) - 1.1346/S^{1.5} + 0.65342G^{0.5}]$$

$$= \exp[2.7835 - 0.79034\ln(35) - 1.1346/35^{1.5} + (0.65342)(2.5^{0.5})]$$

$$= 2.722 \text{ quarts/1000 VMT}$$

Tire wear: $CSTW_{after}$

$$= \exp[-2.55 + 0.0001621S^2 + 0.01441S + 1.473\ln(G) - 0.001638SG]$$

$$= \exp[-2.55 + (0.0001621)(35^2) + (0.01441)(35)$$

Table E7.11.2 VOC Computation for the Before-Improvement Case

VOC Component	(a) Rate of Consumption, per 1000 VMT	(b) Pavement Condition Adjustment Factor	(c) Unit Cost, ($)	(d) Component Adjustment Factor	(e) = (a) × (b) ×(c/d) Total Cost ($/1000 VMT)
Fuel (FC)	42.587	1	0.871	1.536	24.149
Oil (OC)	4.165	1.102	3.573	1.05	15.619
Tire (TW)	0.00534	1.143	45.2	1	0.276
Maintenance and repair (MR)	0.564	1.143	84.1	1	54.215
Depreciation (VD)	0.01045	1.016	18,117	1.3	147.963
					$\sum e$ = CSOPCST = 242.222

Table E7.11.3 VOC Computation for the After-Improvement Case

VOC Component	(a) Rate of Consumption per 1000 VMT	(b) Pavement Condition Adjustment Factor	(c) Unit Cost, ($)	(d) Component Adjustment Factor	(e) = (a) × (b) ×(c/d) Total Cost ($/1000 VMT)
Fuel (FC)	30.938	1	0.871	1.536	17.544
Oil (OC)	2.722	0.894	3.573	1.05	8.281
Tire (TW)	0.00527	0.805	45.2	1	0.192
Maintenance and repair (MR)	0.6341	0.864	84.1	1	46.075
Depreciation (VD)	0.00905	0.984	18,117	1.3	124.104
					$\sum e$ = CSOPCST = 196.196

Table E7.11.4 Total User VOC Benefits

	Before Improvement	After Improvement
VOC ($/1,000 VMT)	242.222	196.196
VMT (in thousands)	(41,000/1,000)(5.2) = 213.6	226
Total User Benefits = 0.5(242.222 − 196.196)(213.6 + 226) = $10,107 per day		

$$+ 1.473\ln(2.5) - (0.001638)(35)(2.5)]$$

$$= 0.527\% \text{ tire wear}/1000 \text{ VMT}$$

Maintenance and repair: $\text{CSMR}_{\text{after}}$

$$= 48.3 + 0.00865S^2 + 0.0516SG$$

$$= 48.3 + (0.00865)(35^2) + (0.0516)(35)(2.5)$$

$$= 63.41\% \text{ average cost}/1000 \text{ VMT}$$

Depreciation rate: $\text{CSVD}_{\text{after}}$

$$= 2.2 + 0.001596S - 0.38\ln(S)$$

$$= 2.2 + (0.001596)(35) - 0.38\ln(35)$$

$$= 0.905\% \text{ new price}/1000 \text{ VMT}$$

(6) VOC computation for the after-improvement case The results are summarized in Table E7.11.3.

(7) Evaluation The total user VOC benefits are estimated in Table E7.11.4.

7.4 SPECIAL CASE OF VOC ESTIMATION: WORK ZONES

Transportation improvements aim at providing a better level of service. A paradoxical twist, however, is that during the implementation (construction) period (typically lasting a few days to one or more years) users may suffer a severe deterioration of levels of service along the affected transportation corridor. For example, work zones for highway rehabilitation and maintenance can significantly raise the costs of safety, travel time, and vehicle operation. Fortunately, the duration of the work zone is typically very small compared with the service life of the facility, so the reduction in operating costs due to the improved facility over its service life far outweighs the increase in operating costs due to the associated work zones. When traffic demand exceeds work-zone capacity, traffic flow becomes constricted and a queue is formed. The stop-and-go conditions at work-zone queues translate into increased frequency of speed changes and delay, and consequently, higher user costs. In some cases, voluntary or involuntary traffic detours by road users, in a bid to avoid a highway work zone, add to travel distance. In such cases, even if the VOC rates remain the same, VMT increases and therefore the overall VOC increases. Most agencies make conscious efforts to reduce the extra costs of vehicle operation, safety and travel time by adopting optimal values of work zone configuration parameters such as timing, duration, scope, and traffic control.

7.5 SELECTED SOFTWARE PACKAGES THAT INCLUDE A VOC ESTIMATION COMPONENT

The multiplicity of VOC components and factors lend a considerable degree of complexity to the process of VOC estimation. There are a number of software packages that can help in estimating vehicle operating cost, as part of typically an overall economic efficiency analysis. A brief discussion of the features of each selected package is herein provided.

7.5.1 AASHTO Method

AASHTO's User Benefit Analysis for Highways (AASHTO, 2003) spreadsheet package estimates safety, travel time, and VOC impacts as part of overall economic analysis. VOC is estimated separately for two categories of VOC components: fuel and "other" (tires, maintenance, etc.). For other VOCs, AASHTO (2003) refers to a 1999 AAA table that presents average automobile operating costs irrespective of VOC factor levels. On the other hand, fuel VOC is given as a function of vehicle type and speed, a relationship adopted from the Cohn et al. (1992) study.

7.5.2 HERS Package: National and State Versions

The HERS methodology (FHWA, 2002) helps estimate the impacts of VOC (as well as safety and travel time) associated with highway widening, pavement improvement, and alignment enhancement at a network level but can also be used for evaluating individual projects. HERS calculates unit VOCs (i.e., VOC per VMT) on the basis of five VOC components (fuel consumption, oil consumption, tire wear, maintenance and repair, and depreciable value) as a function of several VOC factors (speed, speed change, horizontal curves, and vehicle type). The process involves three stages:

1. Constant-speed VOC calculated as a function of average speed, grade, and pavement condition
2. Excess VOC due to speed-change cycles
3. Additional excess VOC as a function of road curvature

The HERS VOC estimation models are derived from consumption rates and prices that were established by Zaniewski (1982), with some adjustments made on the basis of information from Claffey and Associates (1971) and Daniels (1974). All five VOC components are included in the calculation of VOCs at constant-speed sections and also in determination of the excess VOC due to speed-change cycles. In calculating the excess costs due to curves, only the following VOC components are considered: fuel, tire wear, and maintenance and repair. Data needed to run the HERS package include retail prices of gasoline and diesel, cost of oil and tires, mileage-based maintenance costs per mile for new automobiles, new vehicle prices for medium-weight and heavy trucks, and price indices. These data are largely available on the Internet and in published reports. The national version of HERS contains data that generally reflect an average of national conditions, while the state version allows users to input state-specific data.

7.5.3 HDM-4 Road User Effects

HDM-4 road user effects (HDM-RUE) is a special module of the World Bank's Highway Development and Management, Version 4 (HDM-IV) that estimates vehicle operating cost for road segments, duly incorporating the effects of operating speed and congestion. The software can generate output data relating VOC to each of several factors, such as road grade, pavement roughness, surface texture, speed change, congestion, and speed (Bennett and Greenwood, 2001). Also, HDM-RUE can incorporate "willingness to pay" costs in the VOC estimation. In place of the default data, local data can be used to recalibrate the VOC model. The model includes detailed analyses such as

VOC estimation for heavy truck trailers and mechanistic modeling of tire consumption.

7.5.4 Surface Transportation Efficiency Analysis Model

In the VOC module of the surface transportation efficiency analysis model (STEAM), vehicle operating cost is estimated separately for fuel and nonfuel components (DeCorla-Souza and Hunt, 1999). Fuel consumption is considered variable (with operating speed) for autos and trucks but is considered fixed for local and express buses and for light and heavy rail. For auto and truck only, nonfuel costs are considered fixed per mile regardless of speed. Nonfuel costs include tires and maintenance but exclude mileage-based depreciation and oil consumption. For speed estimation, STEAM uses demand data directly from the traffic assignment step of the four-step transportation demand model. An analyst can quickly investigate the impact of different fuel costs without having to adjust each of the speed–consumption estimates by multiplying the fuel consumption amount at a given average speed by the fuel cost. STEAM enables the user to carry out uncertainty analysis and yields confidence intervals for its VOC outputs. Besides vehicle operating costs, other performance measures analyzed by STEAM are the user costs of safety and delay, and emissions.

7.5.5 Other Models That Include a VOC Estimation Component

The packages described above, some to a greater extent than others, enable the analyst first to estimate the unit cost of vehicle operation and then use the estimated VOCs and other data to obtain the overall VOC (for all vehicles using a system within a given time period). On the other hand, there are other packages that do not estimate unit VOCs but rather, utilize prior established unit VOCs for overall VOC estimation, which is then entered into an overall economic analysis procedure. These include:

1. *The California life-cycle benefit–cost analysis model (Cal-B/C)*, which uses a look-up table for fuel consumption of three vehicle types (autos, trucks, and buses) in gallon/mile estimates. To calculate total fuel costs, fuel consumption is multiplied by fuel cost per gallon, excluding taxes. Nonfuel costs are estimated on a per-mile basis (System Metrics Group and Cambridge Systematics, 2004).
2. *MicroBencost*, which enables the calculation of unit (per vehicle-mile) and overall vehicle operating cost (as well as safety and delay user costs) for a wide range of projects, such as new highway and bridge construction, bypasses, pavement preservation, lane addition, safety projects, railroad crossing projects, and HOV lanes. Default values include the unit operating cost of each vehicle class. The program estimates these costs for eight vehicle types and each hour of the day and duly accounts for traffic growth over time. It should be noted that the MicroBencost procedures for estimating the VOC of intersections differs significantly from the 1977 AASHTO procedures (McFarland et al., 1993).

7.6 COMPARISON OF VOC ESTIMATION METHODS AND SOFTWARE

7.6.1 Levels of Detail

Most models use fuel, oil, tire, and maintenance cost components. Many models assume that VOC factors are primarily vehicle type and speed. Other factors, such as curves, grades, and speed changes, have been used in only a few models. Inclusion of all components and factors in VOC estimation poses significant data and modeling challenges that may not be justified by the relatively small gain in the overall accuracy of results (Forkenbrock and Weisbrod, 2001). The VOC estimation models in HERS, MicroBencost, and HDM-RUE are relatively more comprehensive than are other models. Bein (1993) reviewed VOC models in use worldwide and suggested that VOC estimation methodologies that are based on fuel consumption and speeds may be more appropriate than those that use a wider array of VOC components or factors because fuel consumption rates and speeds are easily measurable. From these perspectives, the STEAM methodology (Cambridge Systematics, 2000) which separates the fuel component from other VOC components, can be expected to provide good estimates of VOC, particularly where detailed data are unavailable.

7.6.2 Data Sources

Most models for fuel consumption utilize results from a common source. The MicroBencost model derived its data from the FHWA 1982 study (Zaniewski, 1982). Also, for unit costs and consumption rates of VOC components, StratBencost (a companion package of MicroBencost) utilized data from HERS. In turn, data on the consumption rates of VOC components data used in HERS were obtained from the 1982 FHWA study. The STEAM model relies on several sources, including the 1982 FHWA study. It should be noted, however, that STEAM uses fixed-cost-per-mile unit VOC costs and does not include mileage-based depreciation.

SUMMARY

Most VOC methodologies estimate unit vehicle operating costs (dollars/VMT) as a function of travel speeds. Other VOC factors are road class, vehicle type, prevailing traffic condition, roadway gradient, roadway curvature, and road surface type and condition. Some methodologies, such as HERS and HDM provide vehicle operating cost equations that account for these factors. While the use of such equations typically yields more reliable VOC estimates, data for such detailed VOC estimation methods may not always be available.

In evaluating the future VOC impacts of a proposed project, the analyst must contend with the inherent uncertainties in the VOC estimation process. Future projections of VOC component types, rates, and unit costs are based on current (or at most foreseeable) trends of vehicle technology, and the economy. With the advent of vehicles that operate on electricity, natural gas, hybrids, and improved gasoline engines, the fuel component of VOC is subject to future uncertainties. Also, increased longevity of vehicles translates into reduced depreciation rates and therefore affect that cost of mileage-related depreciation. Furthermore, existing VOC methodologies cover only the key aspects of VOC components. Other relatively minor components that are excluded at the current time may play a more visible role in future, and may need to be accounted for at that time. Another area of uncertainty is that of VOC factors. Urban growth, changes in speed limits, implementation of managed lanes, and redesignation of highways (typically upgrades to higher classes) are likely to result in operating speeds and speed-change frequencies that are different from their respective levels envisaged at the time of evaluation. Increased or decreased economic development may also affect the expected inventory costs of vehicle operation. Furthermore, facility physical deterioration may result in pavement, runway, or guideway surface conditions that differ from projected trends and may therefore result in VOC values that differ from the expected values.

EXERCISES

7.1. Sectional improvements are proposed for an existing highway to ease traffic flow between a suburb and a downtown area. For the existing road, the overall length is 8 miles, the average grade is 4.5%, the AADT is 13,500, the v/c ratio is 0.7, and the average operating speed is 35 mph. There are three sharp curves (10 degrees and 1.5 miles each), at which the speed limit is 25 mph. There are 30% trucks in the traffic stream. After the project is completed, the new road will be 6.5 miles long with an average grade of 2%. It is expected that the traffic volume will increase by 10% due to induced and diverted traffic, and a v/c ratio of 0.5 and operating speed of 55 mph are expected. One of the curves will be eliminated and the other two curves will be rendered less sharp: 4 degrees). Determine the annual benefits of the new project from the perspective of vehicle operating costs only.

7.2. Before physical and operational improvements at a 12-mile urban interstate freeway, the traffic volume was 100,000 per day and the unit VOC was 0.41 cent/VMT. After the improvements, it is estimated that the traffic volume increased to 125,000 per day and the VOC reduced to 0.31 cent/VMT. Determine the user VOC benefits of the project.

7.3. The speed limit at a 4.2-mile highway section was recently changed from 35 mph to 45 mph. Using (**a**) Hepburn's VOC model and (**b**) FHWA's model, determine the expected change in the unit and overall VOC of medium-sized automobiles due to the improvement. Assume that operating speeds are generally 5 mph higher than the speed limits. Also, assume a flat terrain and a traffic volume of 6,250 vpd comprised of medium-sized vehicles. The traffic volume increases by 5% after the change in speed limit. Compare your answers from parts (a) and (b).

7.4. In upgrading a 12-mile four-lane state highway section to an Interstate highway, it is proposed to carry out geometric improvements. The changes in grade, travel demand, and speed predicted to occur after the upgrade are presented in Table EX7.4. Determine the overall VOC savings due to the upgrade. Use the FHWA 1982 VOC estimation model.

7.5. A 7.5-mile two-lane urban arterial received a series of traffic flow improvements, such as construction of passing lanes, deceleration lanes, and channelization. Due to these improvements, the average traffic flow speed on a roadway increased from 26 mph to 34 mph. The average grade of the roadway is 2%, and the direction split is 55% uphill and 45% downhill. The traffic volume of 9000 vpd comprises: small automobiles, 25%; medium-sized automobiles, 60%; large automobiles, 15%. Assume zero truck traffic. After the improvement, the traffic volume increases by 8% due to induced demand, and the share of small vehicles decreases by 6% while those of medium-sized and large vehicles increase by 3% each.

Table EX7.4[a] Traffic and Geometric Characteristics[a]

	Before Improvement			After Improvement		
	Traffic Volume (ADT)	Grade (%)	Speed (mph)	Traffic Volume (ADT)	Grade (%)	Speed (mph)
Segment A:						
50% traffic uphill, 50% downhill	18,500	−2.5	50	6,800	−1.0	70
Segment B:						
55% traffic uphill, 45% downhill	34,320	+3.0	50	5,430	+1.5	70

[a]Assume that directional splits and road length remain the same after the upgrade. Assume medium-sized vehicles only.

(a) Determine the VOC benefits of the improvement using Hepburn's model.

(b) Determine the VOC benefits of medium-sized vehicles only using FHWA's 1982 methodology. Compare your results with that of the Hepburn model and comment on any differences.

(c) How could the Hepburn model be improved?

7.6. A change in speed limit policy resulted in decreased average truck operating speed on the Brandon Expressway from 69.7 mph to 57.2 mph. What is the overall percentage increase in shipping inventory costs per year? Shipping trucks make up 35% of the traffic stream. The AADT is 121,540. The average value of daily cargo per truck is $0.32 million. Assume that the prevailing interest rate is 7.5%.

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The national automobile associations (of the United States, Canada, UK, etc.) generally present the average cost per mile of operating a passenger vehicle in terms of fuel, oil, maintenance, and tire replacement and maintenance costs on the basis of vehicle type, model, driving style, and origin of travel. They may also provide the costs of routine servicing, repairs and replacements, and warranties.

The U.S. Department of Energy's brochure *A Primer on Gasoline Prices*, an Energy Information Administration brochure, is available at http://www.eia.doe.gov/pub/oil_gas/petroleum/analysis_publications/primer_on_gasoline_prices/html/petbro.html.

National petroleum institutes (of the United States, Canada, UK, etc.) provide summaries of the retail price of gasoline and their price trends in terms of month. These prices are also categorized into regions, subregions, states or provinces, and cities.

The U.S. Bureau of Labor Statistics provides monthly reports on changes in the prices paid by urban consumers for a representative basket of goods and services, including oil and tires for four-tire vehicles, accessible at www.bls.gov/cpi. For larger vehicles, the appropriate index for tires is the producer price index, which is accessible at www.bls.gov/ppi/home.htm.

APPENDIX A7.1: FHWA (2002) HERS MODELS FOR VOC COMPUTATION[1]

[1]The following abbreviations are used in this appendix:
S, average effective speed (mph)
G, gradient (%)
D, degree of curvature
GR, grade (%)
CSMAX, maximum speed during speed-change cycle
CSFC, constant-speed fuel consumption (gal/1000 VMT)
CSOC, constant-speed oil consumption (qt/1000 VMT)
CSTW, constant-speed tire wear (% worn/1000 VMT)
CSMR, constant-speed maintenance and repair (% average cost/1000 VMT)
CSVD, constant-speed depreciation (% new vehicle price/1000 VMT)
SCCFC, excess fuel consumption for speed-change cycles (gal/1000 cycles)
SCCOC, excess oil consumption for speed-change cycles (qt/1000 cycles)
SCCMR, excess maintenance and repair for speed-change cycles (% average cost/1000 cycles)
SCCD, excess depreciation for speed-change cycles (% new price/1000 cycles)
CFC, excess fuel consumption due to curves (gal/1000 VMT)
CTW, excess tire wear due to curves (% worn/1000 VMT)
CMR, excess maintenance and repair due to curves (% average cost/1000 VMT)

Table A7.1.1 VOC for Fuel Consumption at Constant Speed on Straight Sections (CSFC)

(a) Small Automobile	
$G \geq 0$	$\text{CSFC} = 100.82 - 4.9713S + 0.11148S^2 - 0.0011161S^3 + (5.1089 \times 10^{-6})S^4 + 3.0947G$
$G < 0$ and $S \leq 40$	$\text{CSFC} = (91.045 - 4.0552S + 0.060972S^2 + 4.0504G + 0.4227G^2)/(1 - 0.014068S + 0.0004774S^2 - 0.045957G + 0.0054245G^2)$
$G < 0$ and $S > 40$	$\text{CSFC} = 23.373 + 3.6374G + 0.21681G^2 + (72.562/[1 + \exp(-[(S - 81.639)/7.4605)])]$
(b) Medium-Sized/Large Automobile	
$S \leq 40$	$\text{CSFC} = 88.556 - 3.384S + 1.7375G + 0.053161S^2 + 0.18052G^2 + 0.076354SG$
$S > 40$	$\text{CSFC} = 85.255 - 2.2399S + 2.7478G + 0.028615S^2 + 0.041389G^2 + 0.046242SG$
(c) Four-Tire Truck	
$G \geq 0$ and $20 < S < 55$	$\text{CSFC} = 115.41 - 3.6397S + 7.0832G + 0.050662S^2 - 0.34401G^2 + 0.096956SG$
$G \geq 0$ and $S \leq 20$	$\text{CSFC} = 120.7 + -5.0201S + 0.1088S^2 + 9.8816G - 1.3755G^2 + 0.11582G^3$
$G < 0$ and $S \leq 10$	$\text{CSFC} = 161.2 - 6.622S - 87.758\ln(S)/S - 1.0889G^2 - 0.13217G^3$
$G < 0$ and $10 < S \leq 20$	$\text{CSFC} = 106.31 - 2.7456S + 5.0147G - 0.001281S^2 + 0.94555G^2 + 0.19499SG$
$G < 0$ and $20 < S < 55$	$\text{CSFC} = 351.5 - 184.42\ln(S) + 0.71838G + 28.297[\ln(S)]^2 + 1.0105G^2 + 2.8947G\ln(S)$
$G \geq 1.5$ and $S \geq 55$	$\text{CSFC} = 110.4 + 0.000249S^3 - 18.93\ln(S) + 8.06G$
$-2.5 \leq G < 1.5$ and $S \geq 55$	$\text{CSFC} = (28.77 + 0.183655S + 3.34032G)/(1 - 0.0074966S - 0.049703G)$
Otherwise	$\text{CSFC} = \exp(2.784 + 0.02014S + 0.06881G)$
(d) Six-Tire Truck	
$G \geq 0$ and $S < 55$	$\text{CSFC} = 298.60 - 13.131S + 53.987G + 0.30096S^2 - 4.7321G^2 - 0.88407SG - 0.0020906S^3 + 0.22739G^3 + 0.02875SG^2 + 0.0045428S^2G$
$G < 0$ and $S < 55$	$\text{CSFC} = 273.05 - 9.2427S + 58.195G + 0.14718S^2 + 6.7665G^2 - 1.3785SG - 0.00046068S^3 + 0.13884G^3 - 0.079555SG^2 + 0.012622S^2G$
$G \geq 1.5$ and $S \geq 55$	$\text{CSFC} = 361.11 - 8.1978S + 11.186G + 0.077607S^2 - 0.27665G^2 - 0.035211SG$
$G < 1.5$ and $S \geq 55$	$\text{CSFC} = 101.5 + 0.000186S^3 + 1.102G^2 + 18.22G$
(e) 3+ Axle Single-Unit Truck	
$G \geq 3$ and $S \leq 20$	$\text{CSFC} = 68.536 + 12.823S + 122.45G + 0.023896S^2 + 0.36758G^2 - 6.2014SG$
$3 \geq G \geq 0$ and $S \leq 20$	$\text{CSFC} = 254 - 3.0854S - 2.177G - 0.063346S^2 + 24.848G^2 + 4.3101SG + 0.0012816S^3 - 1.2432G^3 - 1.6437SG^2 + 0.0013556S^2G$
$G < 0$ and $S \leq 20$	$\text{CSFC} = (259.66 - 19.925S + 0.49931S^2 - 0.0045651S^3 - 1.5876G)/(1 - 0.058535S + 0.00077356S^2 - 0.14916G + 0.024241G^2)$
$G > 3$ and $S > 20$	$\text{CSFC} = 290.45 - 2.598S + 25.823G + 0.024983S^2 - 2.2654G^2 + 0.21897SG$
$3 \geq G \geq 0$ and $S > 20$	$\text{CSFC} = 1208.8 - 586.87\ln(S) + 80.955[\ln(S)]^2 + 93.99G - 13.477G^2$
$0 > G \geq -3$ and $S > 20$	$\text{CSFC} = \exp(6.0673 - 0.1139S + 0.023622S\ln(S) + 0.79191G - 0.022171G^3)$
$G < -3$ and $S > 20$	$\text{CSFC} = (-1.3978/(1 + (((S - 40.215)/-11.403)^2))) + (47.024/(1 + (((G + 0.01611)/5.4338)^2))) + (-26.724)/(1 + (((S - 40.215)/-11.403)^2)))(1/(1 + (((G + 0.01611)/5.4338)^2)))$
(f) 3–4 Axle Combination-Unit Truck	
$S > 20$ and $3 \geq G \geq -3$, or $S \leq 20$ and $G \geq -3$	$\text{CSFC} = (1087.9 - 576.71\ln(S) + 82.039[\ln(S)]^2 + 22.325G)/(1 - 0.17121\ln(S) - 0.035147G)$
$G < -3$	$\text{CSFC} = -239.17 + 61.115\ln(S) + 2221.9/S - 4411.6\exp(-S)$
$S > 20$ and $G > 3$	$\text{CSFC} = \exp(4.5952 + 0.0049349S\ln(S) + 0.31272G)$
(g) 5+ Axle Combination-Unit Truck	
$3 \geq G \geq -3$	$\text{CSFC} = (1618.8 - 864.83\ln(S) + 124.88[\ln(S)]^2 + 32.087G)/(1 - 0.16247\ln(S) - 0.07074G + 0.011717G^2 - 0.0011606G^3)$
$G < -3$	$\text{CSFC} = -305.94 + 76.547\ln(S) + 2737.7/S - 5493.1\exp(-S)$
$G > 3$	$\text{CSFC} = (1607 - 986.23\ln(S) + 149.01[\ln(S)]^2 + 84.747G)/(1 - 0.17168\ln(S) - 0.021455G)$

Source: FHWA (2002).

Table A7.1.2 VOC for Oil Consumption at Constant Speed (CSOC)

(a) Small Automobile	
$G > 0$ and $S < 55$	$\text{CSOC} = \exp(2.7835 - 0.79034\ln(S) - 1.1346/S^{1.5} + 0.65342G^{0.5})$
$G \geq 0$ and $55 \leq S \leq 70$	$\text{CSOC} = -170.4 + 34.02\ln(S) + 1939/S + 0.4747G - 0.003296SG$
$G \geq 0$ and $S \geq 70$	$\text{CSOC} = -170.4 + 34.02\ln(S) + 1939/S + 0.27G$
$G \leq 0$ and $S < 55$	$\text{CSOC} = 1.0435 + (327.89/((1 + (((S + 7.1977)/3.0141)^2)) \times (1 + (((G + 8.0484)/2.8984)^2))))$
Otherwise	$\text{CSOC} = -170.4 + 34.02\ln(S) + 1939/S$
(b) Medium-sized/Large Automobile	
$G > 0$ and $S < 55$	$\text{CSOC} = \exp(-1.5698 + 9.8768/S^{0.5} - 7.6187S + 0.70702G^{0.5})$
$G \geq 0$ and $55 \leq S < 70$	$\text{CSOC} = 9.5234 - 0.29873S + 0.0026913S^2 + 0.28997G^{1.00129}$
$G \geq 0$ and $S \geq 70$	$\text{CSOC} = -173.3 + 34.6\ln(S) + 1973/S + 0.29G$
$-3 \leq G \leq 0$ and $15 \leq S < 55$	$\text{CSOC} = 0.42295 + 0.35839S - 0.029984S^2 + 0.0010392S^3 - 0.000016196S^4 + 9.3539 \times 10^{-8}S^5 - 0.0024G$
$G < -3$ and $15 \leq S < 55$	$\text{CSOC} = 1/(-0.18739 + 0.0014953S^{1.5} - 1.7461/G)$
$G \leq 0$ and $S < 15$	$\text{CSOC} = \exp(1.7713 - 0.12178S^{0.5}\ln(S) + 0.14636G + 0.11002G^2 + 0.0082804G^3)$
Otherwise	$\text{CSOC} = -173.3 + 34.6\ln(S) + 1973/S$
(c) Four-Tire Truck	
$G > 0$ and $S < 50$	$\text{CSOC} = \exp(2.47 - 0.604\ln(S) - 0.00994GR^2 + 0.277G - 0.001248SG)$
$G > 0$ and $50 \leq S \leq 70$	$\text{CSOC} = 16.41 + 0.004424S^2 - 0.5255S + 1.296G - 0.2664\ln(S)G$
$G > 0$ and $S > 70$	$\text{CSOC} = 16.41 + 0.004424S^2 - 0.5255S + 0.19G$
$\min(-3.5, -S/6.0) < G \leq 0$ and $S < 50$	$\text{CSOC} = 8.45 + 0.0000352S^3 - 0.00567S^2 + 0.370S - 4.12\ln(S)$
$G < \min(-3.5, -S/6.0)$ and $S < 50$	$\text{CSOC} = \exp(0.92 - 0.000295S^2 - 0.751\ln(S) - 0.0269GR^2 - 0.584G)$
Otherwise	$\text{CSOC} = 16.41 + 0.004424S^2 - 0.5255S$
(d) Six-Tire Truck	
$G > 0$ and $S < 55$	$\text{CSOC} = \exp(3.8424 - 0.93964\ln(S) - 1.7418/S + 0.80327G^{0.5})$
$G > 0$ and $S \geq 55$	$\text{CSOC} = 51.76 + 0.002513S^2 - 14.29\ln(S) + 0.7485G$
$-1.5 < G \leq 0$ and $S < 55$, or $-S/10 \leq G \leq 0$ and $S < 55$	$\text{CSOC} = 13.98 + 0.0000603S^3 - 0.00857S^2 + 0.523S - 6.17\ln(S)$
$G < -S/10$ and $S \geq 70$	$\text{CSOC} = \exp(1.41 + 0.000519S^2 - 0.0845S - 0.0344G^2 - 0.649G)$
Otherwise	$\text{CSOC} = 51.76 + 0.002513S^2 - 14.29\ln(S)$
(e) 3+ Axle Single-Unit Truck	
$G > 0$ and $S < 55$	$\text{CSOC} = \exp(4.36 + 0.00711S - 0.869\ln(S) - 0.01712GR^2 + 0.338G)$
$\min(-1.5, -S/12.5) < G \leq 0$ and $S < 55$	$\text{CSOC} = 20.2 + 0.0000724S^3 - 0.0103S^2 + 0.662S - 8.52\ln(S)$
$G \leq \min(-1.5, -S/12.5)$ and $S < 55$	$\text{CSOC} = \exp(1.77 + 0.00055S^2 - 0.0769S - 0.0343GR^2 - 0.646G)$
$G > 0$ and $S \geq 55$	$\text{CSOC} = 22.85 + 0.006514S^2 - 0.7188S + 1.615G$
$-S/12.5 \leq G \leq 0$ and $S \geq 55$, or $G \leq 0$ and $S \geq 90$	$\text{CSOC} = 22.85 + 0.006514S^2 - 0.7188S$
Otherwise	$\text{CSOC} = \exp(1.77 + 0.00055S^2 - 0.0769S - 0.0343GR^2 - 0.646G)$
(f) 3–4 Axle Combination-Unit Truck	
$G > 0$ and $S < 45$	$\text{CSOC} = \exp(3.92 - 0.661\ln(S) - 0.01718GR^2 + 0.361G - 0.000640SG)$
$G > 0$ and $45 \leq S \leq 70$	$\text{CSOC} = 78.59 + 0.003813S^2 - 21.76\ln(S) + 2.1254G - 0.0109SG$
$G > 0$ and $S > 70$	$\text{CSOC} = 78.59 + 0.003813S^2 - 21.76\ln(S) + 1.41G$
$\min(-1.5, -S/12.5) < G \leq 0$, or $G \leq 0$ and $S \geq 70$	$\text{CSOC} = 20.2 + 0.0000724S^3 - 0.01034S^2 + 0.662S - 8.52\ln(S)$
Otherwise	$\text{CSOC} = \exp(1.85 + 0.000458S^2 - 0.0746S - 0.0336GR^2 - 0.638G)$

Table A7.1.2 (*continued*)

(g) 5+ Axle Combination-Unit Truck	
$G > 0$ and $S < 55$	$\text{CSOC} = \exp(4.60 - 0.668\ln(S) - 0.01879GR^2 + 0.394G - 0.000873SG)$
$G > 0$ and $S \geq 55$	$\text{CSOC} = 9.383 + 0.003478S - 0.271S + 3.040G$
$\min(-1.5, -S/15.0) < G \leq 0$ and $S < 55$	$\text{CSOC} = 42.6 + 0.000189S^3 - 0.0273S^2 + 1.633S - 18.96\ln(S)$
$\min(-1.5, -S/15.0) < G \leq 0$ and $S \geq 55$	$\text{CSOC} = 9.383 + 0.003478S^2 - 0.271S$
$G \leq \min(-1.5, -S/15.0)$ and $S < 55$	$\text{CSOC} = \exp(2.52 + 0.000397S^2 - 0.0675S - 0.0353GR^2 - 0.652G)$
$G \leq \min(-1.5, -S/15.0)$ and $S \geq 55$	$\text{CSOC} = 115.8 + 0.5094S - 37.27\ln(S) - 3.064G$

Table A7.1.3 VOC for Tire Wear at Constant Speed (CSTW)

(a) Small Automobile	
$G \geq 2.5$ and $S < 55$	$\text{CSTW} = \exp(-2.55 + 0.0001621S^2 + 0.01441S + 1.473\ln(G) - 0.001638SG)$
$G \geq 2.5$ and $S \geq 55$	$\text{CSTW} = 1.314 + 0.000733S^2 - 0.05758S + 0.01514G^2 + 0.003997SG$
$0 < G < 2.5$ and $S < 15$, or $-S/20 < G < 2.5$ and $S \geq 15$	$\text{CSTW} = 0.1959 + 2.51 \times 10^{-6}S^3 - 0.0352\ln(S) + 0.01754G^2 + 0.00348SG$
$-1.5 < G \leq 0$ and $S < 15$, or $-S/10 < G \leq -S/20$ and $S \leq 15$	$\text{CSTW} = 0.0604 + 2.92 \times 10^{-8} \times S^4 + 0.0000796S^2 + 0.0274G^2 + 0.074G + 0.0000568S^2G$
Otherwise	$\text{CSTW} = \exp(-5.39 - 0.000895S^2 + 0.0962G + 2.83\ln(-G) - 0.00397SG)$
(b) Medium-sized/Large Automobiles	
$G \geq 2.5$ and $S < 55$	$\text{CSTW} = \exp(-2.39 + 0.0001564S^2 + 0.01367S + 1.475\ln(G) - 0.001586SG)$
$0 < G < 2.5$ and $S < 15$, or $-S/20 \leq G < 2.5$ and $15 \leq S < 55$	$\text{CSTW} = 0.229 + 2.65 \times 10^{-6}S^3 - 0.0403\ln(S) + 0.0214G^2 + 0.00392SG$
$-1.5 < G \leq 0$ and $S < 15$, or $-S/10 < G < -S/20$ and $15 \leq S < 55$	$\text{CSTW} = 0.08 + 3.0 \times 10^{-6}S^3 + 0.029G^2 + 0.0828G + 0.000056S^2G$
$G \leq -1.5$ and $S < 15$, or $G \leq -S/10$ and $15 \leq S < 55$	$\text{CSTW} = \exp(-5.22 - 0.000771S^2 + 0.0843G + 2.81\ln(-G) - 0.00323SG)$
$G \geq 0.5$ and $S \geq 55$	$\text{CSTW} = 1.318 + 0.000743S^2 - 0.05661S + 0.01941G^2 + 0.00417SG$
$-S/10 + 1 < G < 0.5$ and $S \geq 55$, or $G < 0.5$ and $S \geq 80$	$\text{CSTW} = -0.2022 + 0.000237S^2 + 0.0213G^2 - 1.0322G + 0.3099\ln(S)G$
Otherwise	$\text{CSTW} = -0.2613 + 0.000164S^2 + 0.02065G^2 + 0.005452SG - 0.03975\ln(S)G$
(c) Four-Tire Truck	
$G \geq 2.5$ and $S < 55$	$\text{CSTW} = \exp(-2.08 + 0.0001517S^2 + 0.012S + 1.367\ln(G) - 0.001389SG)$
$0 < G < 2.5$ and $S < 15$ or $-S/20 < G < 2.5$ and $15 \leq S < 55$	$\text{CSTW} = 0.297 + 2.9 \times 10^{-6}S^3 - 0.0421\ln(S) + 0.0234G + 0.00429SG$
$-2.5 < G \leq 0$ and $S < 15$ or $-S/10 < G \leq -S/20$ and $15 \leq S \leq 55$	$\text{CSTW} = 0.1294 + 3.64 \times 10^{-6}S^3 + 0.0324G^2 + 0.1085G + 0.0000631S^2G$

(*continued overleaf*)

Table A7.1.3 (*continued*)

$G \leq -2.5$ and $S < 15$ or $G < -S/10$ and $15 \leq S \leq 55$	$CSTW = \exp(-5.45 - 4.13 \times 10^{-6}S^3 - 0.01377S + 2.79\ln(-G))$
$G \geq 0.5$ and $S \geq 55$	$CSTW = 1.365 + 0.000736S^2 - 0.05471S + 0.0197G^2 + 0.004395SG$
$(-S/10 + 1) < G < 0.5$ and $S \geq 55$ or $G < 0.5$ and $S \geq 80$	$CSTW = abs(-0.1554 + 0.000258S^2 + 0.0205G^2 - 0.05138G + 0.005058SG)$
Otherwise	$CSTW = \max(0.01, -0.2177 + 0.000208S^2 + 0.02376G^2 + 0.005895SG - 0.03288\ln(S)G)$
(d) Six-Tire Truck	
$G \geq 2.5$ and $S < 55$	$CSTW = \exp(-1.572 + 0.0000943S^2 + 0.01509S + 1.65\ln(G) - 0.001535SG)$
$G \geq 2.5$ and $S \geq 55$	$CSTW = 2.206 + 0.001267S^2 - 0.09683S + 0.07733GR^2 + 0.01096SG$
$0 < G < 2.5$ and $S < 15$, or $-S/25 < G < 2.5$ and $S \geq 15$	$CSTW = 0.353 + 4.5 \times 10^{-6}S^3 - 0.0556\ln(S) + 0.0855GR^2 + 0.01012SG$
$-1.5 < G \leq 0$ and $S < 15$; or $-S/14 < G < -S/25$ and $S \geq 15$	$CSTW = 0.104 + 5.37 \times 10^{-8}S^4 + 0.0001578S^2 + 0.1282GR^2 + 0.222G + 0.000168S^2G$
Otherwise	$CSTW = \exp(-3.16 - 3.35 \times 10^{-6}S^3 - 0.0308S + 2.28\ln(-G) - 0.00377SG)$
(e) 3 + Axle Single-Unit Truck	
$G \geq 2.5$ and $S < 55$	$CSTW = \exp(-1.71 + 0.0000511S^2 + 0.01134S + 1.575\ln(G) - 0.001038SG)$
$G \geq 2.5$ and $S \geq 55$	$CSTW = 1.085 + 0.000405S^2 - 0.03274S + 0.05955G^2 + 0.00577SG$
$-0.5 < G < 2.5$ and $S < 15$, or $-S/30 < G < 2.5$ and $S \geq 15$	$CSTW = 0.0896 + 0.0001308S^2 + 0.0552G^2 + 0.1181G + 0.00402SG$
$-S/20 < G \leq -S/30$ and $S \geq 15$	$CSTW = 0.0345 + 0.000387S^2 + 0.257G^2 + 0.01988SG$
Otherwise	$CSTW = \exp(-3.30 - 0.0275S + 0.1868G + 2.92\ln(-G) - 0.00275SG)$
(f) 3–4 Axle Combination-Unit Truck	
$G > 3$	$CSTW = 0.27453 - 0.016411S + 0.090845G + 0.00035502S^2 + 0.047978G^2 + 0.0042709SG$
$G < -3$	$CSTW = abs(-0.14758 + 0.01337S + 0.0040158G - 0.000053182S^2 + 0.052391G^2 + 0.0044432SG)$
$-3 \leq G \leq 3$	$CSTW = 0.15566 - 0.0058457S + 0.041763G + 0.00021374S^2 + 0.056992G^2 + 0.0050156SG$
(g) 5+ Axle Combination-Unit Truck	
$G \geq 2.5$ and $S < 55$	$CSTW = \exp(-1.6 + 0.0000684S^2 + 0.00608S + 1.567\ln(G) - 0.000762SG)$
$G \geq 2.5$ and $S \geq 55$	$CSTW = 1.122 + 0.000357S^2 - 0.03264S + 0.06295G^2 + 0.005081SG$
$-0.5 < G < 2.5$ and $S < 15$ or $-S/35 < G < 2.5$ and $S \geq 15$	$CSTW = 0.1432 + 1.248 \times 10^{-6}S^3 + 0.0639G^2 + 0.1167G + 0.00332SG$
$G \geq -S/35$ and $S \geq \max(15, -25G)$	$CSTW = -0.1283 + 1.442 \times 10^{-6}S^3 + 0.01044S + 0.208G^2 + 0.01337SG$
Otherwise	$CSTW = \exp(-3.05 - 1.5 \times 10^{-6}S^3 - 0.01358S + 2.13\ln(-G) - 0.001779SG)$

Table A7.1.4 VOC for Maintenance and Repair at Constant Speed (CSMR)

(a) Small Automobile	
$G \geq 0$	$\text{CSMR} = 48.3 + 0.00865S^2 + 0.0516SG$
$-1.5 \leq G < 0$ and $S \leq 25$, or $G < 0$ and $25 < S < 55$ and $S \geq -12.2G + 4$	$\text{CSMR} = 45.1 + 0.00582S^2 + 0.23S + 0.0502SG$
$G < -1.5$ and $S \leq 25$, or $G < 0$ and $25 < S < 55$ and $S < -12.2G + 4$	$\text{CSMR} = -5.83 - 0.01932S^2 - 23.4G$
$-0.14S + 3.6 < G < 0$ and $S \geq 55$	$\text{CSMR} = 73.35 + 0.01397S^2 - 0.7398S + 0.04994SG$
Otherwise	$\text{CSMR} = 4.27 - 0.0208S^2 - 23.63G$
(b) Medium-Sized/Large Automobile	
$G \geq 0$	$\text{CSMR} = 48.4 + 0.00867S^2 + 0.0577SG$
$-1.5 \leq G < 0$ and $S \leq 25$, or $G < 0$ and $-12.2G + 4 \leq S$ and $25 < S < 55$	$\text{CSMR} = 45.19 + 0.00584S^2 + 0.229S + 0.0562SG$
$G < -1.5$ and $S \leq 25$, or $G < 0$ and $-12.2G + 4 > S$ and $25 < S < 55$	$\text{CSMR} = -6.67 - 0.018S^2 - 23.4G$
$-0.14S + 3.6 < G < 0$ and $S \geq 55$	$\text{CSMR} = 72.46 + 0.01373S^2 - 0.7081S + 0.05597SG$
Otherwise	$\text{CSMR} = -5.415 - 0.01912S^2 - 23.51G$
(c) Four-Tire Truck	
$G \geq 0$	$\text{CSMR} = 49.2 + 0.00881S^2 + 0.0545SG$
$-1.5 \leq G < 0$ and $S \leq 20$, or $G < 0$ and $20 < S < 55$ and $S \geq -10G + 6$	$\text{CSMR} = 46.0 + 0.00595S^2 + 0.231S + 0.0531SG$
$G < -1.5$ and $S \leq 20$, or $G < 0$ and $20 < S < 55$ and $S < -10G + 6$	$\text{CSMR} = -12.43 - 0.019S^2 - 23.5G$
$G < 0$ and $S \geq 55$ and $G > -0.1S + 0.75$, or $G < 0$ and $S > 70$	$\text{CSMR} = 72.36 + 0.01373S^2 - 0.6841S + 0.0532SG$
Otherwise	$\text{CSMR} = -13.83 - 0.0197S^2 - 24.01G$
(d) Six-Tire Truck	
$-4 \leq G \leq -1$ and $S > -1.6667G^3 - 17.5G^2 - 70.833G - 45$ and $S < -1.6667G^3 - 17.5G^2 - 70.833G - 40$	$\text{CSMR} = 1/(0.96223 + 2.3017 \times 10^{-6}S^3 - 0.33129\exp(S/44.4878) + 0.48203/G - 0.00029083\exp(-G))$
$G \geq -1$, or $G < -1$ and $S \geq -1.6667G^3 - 17.5G^2 - 70.833G - 40)$	$\text{CSMR} = 44.2 + 0.01147S^2 + 0.1462SG$
Otherwise	$\text{CSMR} = -0.722 - 0.00697S^2 - 15.9G$
(e) 3+ Axle Single-Unit Truck	
$-4 \leq G \leq -1$ and $S > -1.6667G^3 - 17.5G^2 - 75.833G - 45)$ and $S < -1.6667G^3 - 17.5G^2 - 75.833G - 40)$	$\text{CSMR} = 1046.8 - 499.21\ln(S) + 106.76[\ln(S)]^2 + 601.98G + 154.36G^2 + 15.039G^3$
$G \geq -1$, or $G < -1$ and $S \geq -1.6667G^3 - 17.5G^2 - 75.833G - 40$	$\text{CSMR} = 46 + 0.008S^2 + 0.146SG$
Otherwise	$\text{CSMR} = 1.6996 + 0.094776S - 0.016324S^2 + 0.00037673S^3 - 4.0767 \times 10^{-6}S^4 + 1.4984 \times 10^{-8}S^5 - 14.684G$
(f) 3–4 Axle Combination-Unit Truck	
$-3 \leq G \leq -1$ and $S \geq (-7.5G^2 - 52.5G - 25)$ and $S < -7.5G^2 - 52.5G - 20$	$\text{CSMR} = 169.6 + 6.4867S + 333.98G + 48.825G^2$

(*continued overleaf*)

Table A7.1.4 (*continued*)

$G > -1$, or $G < -1$ and $G \geq -3$ and $S \geq -7.5G^2 - 52.5G - 20$	$\text{CSMR} = 46 + 0.008S^2 + 0.146SG$
Otherwise	$\text{CSMR} = 2.44881 - 0.0404901S^{1.5} - 15.8112G$
(g) 5+ Axle Combination-Unit Truck	
$G \geq 0$	$\text{CSMR} = 44.9 + 0.01148S^2 + 0.254SG$
$G < 0$ and $S > 25$ and $S \geq -40G - 15$	$\text{CSMR} = 78.7 + 1.545S - 20.6\ln(S) + 0.254SG$
Otherwise	$\text{CSMR} = 0.996 - 0.00149S^2 - 15.8G$

Table A7.1.5 VOC for Depreciation at Constant Speed (CSVD)

(a) Small Automobile	
$\text{CSVD} = 2.2 + 0.001596S - 0.38\ln(S)$	
(b) Medium-Sized/Large Automobile	
$\text{CSVD} = 1.725 + 0.001892S - 0.311\ln(S)$	
(c) Four-Tire Truck	
$\text{CSVD} = 0.742 + 0.000589S - 0.1307\ln(S)$	
(d) Six-Tire Truck	
$S < 55$	$\text{CSVD} = 1.126 + 0.0028S - 0.247\ln(S)$
$S \geq 55$	$\text{CSVD} = 0.2006 + 4.936/S$
(e) 3 + Axle Single-Unit Truck	
$S < 55$	$\text{CSVD} = 1.126 + 0.00279S - 0.247\ln(S)$
Otherwise	$\text{CSVD} = 0.2006 + 4.936/S$
(f) 3–4 Axle Combination-Unit Truck	
$S < 55$	$\text{CSVD} = 0.354 + 0.000974S - 0.0806\ln(S)$
Otherwise	$\text{CSVD} = 0.05657 + 1.598/S$
(g) 5+ Axle Combination-Unit Truck	
$S < 55$	$\text{CSVD} = 0.395 + 0.001215S - 0.0941\ln(S)$
Otherwise	$\text{CSVD} = 0.05657 + 1.598/S$

Table A7.1.6 VOC for Excess Fuel Consumption at Curved Sections (CFC)

(a) Small Automobiles	
$S \geq 1/(0.001147 + 0.008062D^{0.5} + 0.008862/D$	$\text{CFC} = \max(0, 18387.7115(1/(1 + (D/39.459)^{-3.0419}))$ $(1)/(1 + (S/104.38)^{-6.2768}))$
$D \geq 6$ and $S > 10$ and $S \leq -0.6807D + 30.944$	$\text{CFC} = \max(0, -0.046905 + 0.95904\ln(D) - 0.02218S$ $- 0.17662[\ln(D)]^2 + 0.000957S^2 - 0.021388S\ln(D))$
$D \geq 6$ and $S > 10$, or $D < 6$ and $S \leq 25$	$\text{CFC} = \max(0, -1.9503 + 1.0112\ln(D) + 0.31328S$ $-0.16763[\ln(D)]^2 - 0.012903S^2 - 0.031507S\ln(D))$
Otherwise	$\text{CFC} = 0$
(b) Medium-Sized/Large Automobile	
$D \leq 5$ and $S \leq 1/(-0.0137 + 0.0123D^{0.5}$ $+0.0299/D^{0.5})$	$\text{CFC} = \max(0, -0.34211 + 0.28291D + 0.014828S$ $-0.016971D^2 - 0.00024465S^2 - 0.0047869DS)$
$D > 5$ and $S \leq 1/(-0.0137 + 0.0123D^{0.5}$ $+0.0299/D^{0.5})$	$\text{CFC} = \max(0, -0.79434 + 1.1403\ln(D) + 0.052408S$ $-0.1933[\ln(D)]^2 - 0.00060403S^2 - 0.028889S\ln(D))$
$S > 1/(-0.0137 + 0.0123D^{0.5} + 0.0299/D^{0.5})$	$\text{CFC} = \max(0, \exp(-18.864 - 0.02183D^{1.5}$ $+ 2.6113D^{0.5} + 1.80792S^{0.5}))$

Table A7.1.6 (*continued*)

(c) Four-Tire Truck	
$D < 6$ and $S \geq -0.5682D^2 + 0.75D + 55.818$, or $D \geq 6$ and $S \geq -0.0055D^2 - 0.7634D + 43.597$	$\text{CFC} = \max(0, \exp(779.63 - 1.2743D + 3.1889D^{0.5}\ln(D) - 2.9306D^{0.5} - 25.106S^{0.5} - 10{,}108.5/S^{0.5} + 10{,}588.5\ln(S)/S))$
$D \geq 10$ and $S \leq 57.993 + 1.1162D - 13.963D^{0.5}$, or $8 \leq D < 10$ and $S \leq 25$	$\text{CFC} = \max(0, -0.45381 + 0.98231\ln(D) + 0.10049S - 0.15[\ln(D)]^2 - 0.0011603S^2 - 0.046122S\ln(D))$
$4 \leq D < 8$ and $S \leq -2.5D + 45$	$\text{CFC} = \max(0, -2.0296 + 2.4402\ln(D) + 0.087398S - 0.50234[\ln(D)]^2 - 0.0012841S^2 - 0.036879S\ln(D))$
$2 \leq D < 4$ and $S \leq 35$, or $D < 2$ and $S \leq 2.5D + 30$	$\text{CFC} = \max(0, \exp(0.0010091 - 5.4673/D^2 - 0.082805S + 0.011991S^2 - 0.0018375S^{2.5}))$
Otherwise	$\text{CFC} = 0$
(d) Six-Tire Truck	
$D \geq 10$ and $S \geq 27.9 - 0.0144D^2 + 300/D^2$, or $2 \leq D < 10$ and $S \geq 1/(0.0127 + 0.00484D - 0.000675D^2 + 3.97 \times 10^{-5}D^3)$, or $D < 2$ and $S \geq 1/(0.0286 + 0.00429D - 0.00429D^2)$	$\text{CFC} = \max(0, \exp(-50.349 - 0.98363D - 0.05974D^2 + 59.476\exp(D/31.649) - 90.158/S^{0.5}))$
$D \geq 5$ and $S \leq 27.9 - 0.0144D^2 + 300/D^2$	$\text{CFC} = \max(0, -9.7649 + 7.88\ln(D) + 6.036\ln(S) - 1.0423[\ln(D)]^2 - 1.053[\ln(S)]^2 - 1.464\ln(D)\ln(S))$
$1 < D < 5$ and $S \leq 30 + 70/D - 100/D^2$	$\text{CFC} = \max(0, \exp(1.604 - 4.6423/D^{1.5} - 0.000062414S^3))$
Otherwise	$\text{CFC} = 0$
(e) 3+ Axle Single-Unit Truck	
$D \geq 6$ and $S \geq 44.375 - 1.8236D + 0.02044D^2 + 0.0018571D^2 - 0.000053954D^2$ or $6 > D \geq 2$ and $S \geq 39.5 + 4.1667D - 0.83333D^2$	$\text{CFC} = \exp(371.346 + 5.1878\ln(D) + 10.1521/D^{0.5} - 12.1424S^{0.5} - 4915.79/S^{0.5} + 5093.19\ln(S)/S))$
$D < 2$ and $S \geq 24.5 - 10D + 10D^2$	$\text{CFC} = \max(0, 1.3873 + 8.977\exp(-0.5(((D - 2.2124)/1.071)^2 + ((S - 102.44)/16.633)^2)))$
$2 \leq D \leq 16$ and $S < 10$	$\text{CFC} = \max(0, -4.0824 + 1.833D - 0.15946D^2 + 0.0044245D^3 + 0.56919S - 0.038513S^2 + 0.00079158S^3)$
$D \leq 1$ and $S < 25$	$\text{CFC} = 0$
Otherwise	$\text{CFC} = \max(0, -8.9743 - 0.099969D + 16.366\ln(S) + 0.0052265D^2 - 3.6805(\ln(S))^2 - 0.11371D\ln(S))$
(f) 3–4 Axle Combination-Unit Truck	
$D < 6$ and $S \leq 20$	$\text{CFC} = \max(0, (-0.069855 + 0.4852\ln(D) + 0.029223\ln(S))/(1 - 0.30752\ln(D) + 0.10364(\ln(D))^2 - 0.52169\ln(S) + 0.10545(\ln(S))^2))$
$20 < S \leq 64 + 0.93749D - 13.928D^{0.5}$ and $D < 6$	$\text{CFC} = \max(0, -36.549 + 8.3919D + 19.444\ln(S) - 0.19172\text{DCA}^2 - 2.6623[\ln(S)]^2 - 1.9932D\ln(S))$
$20 < S \leq 64 + 0.93749D - 13.928D^{0.5}$ and $D \geq 6$	$\text{CFC} = \max(0, -44.639 + 15.079\ln(D) + 31.738\ln(S) - 1.734[\ln(D)]^2 - 5.305[\ln(S)]^2 - 3.6061\ln(D)\ln(S))$
$D > 1$ and $S \geq 67 + 0.93749D - 13.928D^{0.5}$	$\text{CFC} = \max(0, \exp(948{,}774.18 + 1.056802(\ln(D))^2 + 11{,}715.15S^{0.5}\ln(S) + 54{,}041.58(\ln(S))^2 - 133{,}443.12S^{0.5} - 268{,}395.66\ln(S) + 309{,}522.12/\ln(S) - 1{,}311{,}374.33/(S^{0.5})))$
$D \leq 1$ and $S \geq 67 + 0.93749D - 13.928D^{0.5}$	$\text{CFC} = \max(0, (-13.559 - 1.1956D + 0.37772\text{DCA}^2 + 3.5166\ln(S))/(1 - 0.37771D + 0.1152\text{DCA}^2 - 0.1529\ln(S)))$
Otherwise	$\text{CFC} = 0$

(*continued overleaf*)

Table A7.1.6 (*continued*)

(g) 5 + Axle Combination-Unit Truck	
$D < 6$ and $S \leq 20$	$CFC = \max(0, \exp(4.892 - 5.8015/D^2 - 0.070341S - 6.612/S^{0.5}))$
$20 < S \leq 64 + 0.93749D - 13.928D^{0.5}$ and $D < 6$	$CFC = \max(0, -0.76579 + 9.3637\ln(D) + 0.025171S - 0.75491[\ln(D)]^2 + 0.00010068S^2 - 0.22116S\ln(\mathrm{D}))$
$\mathrm{S} \leq 64 + 0.93749D - 13.928D^{0.5}$ and $D \geq 6$	$CFC = \max(0, -44.672 + 15.308\ln(D) + 31.804\ln(S) - 1.8472[\ln(D)]^2 - 5.3075[\ln(S)]^2 - 3.5085\ln(\mathrm{D}) * \ln(S))$
$D > 1$ and $S \geq 67 + 0.93749D - 13.928D^{0.5}$	$CFC = \max(0, \exp(-37.185 - 0.0034062D^2 + 1.262(\ln(D))^2 - 0.00000046205S^3 + 8.9915\ln(S)))$
$D \leq 1$ and $S \geq 67 + 0.93749D - 13.928 * D^{0.5}$	$CFC = \max(0, -3.3518 + 58.52/((1 + ((D - 3.8448)/3.142)^2)(1 + ((S - 99.792)/14.486)^2)))$
Otherwise	$CFC = 0$

Table A7.1.7 VOC for Excess Tire Wear at Curved Sections (CTW)

(a) Small Automobile	
$D \geq 16$ and $S \geq -0.031746D^2 + 0.74603D + 21.19$, or $16 \geq D \geq 6$ and $S \geq 45 - 1.9167D + 0.041667D^2$, or $D < 6$ and $S \geq (-442.3 + 2959.4/D^{0.5} - 6735.1/D + 6810.6/D^{1.5} - 2582.5/D^2$	$CTW = \max(0, 351{,}887\exp(-\exp(-(D - 51.408)/19.756) - (D - 51.408)/19.756 + 1) \times \exp(-\exp(-(S - 122.22)/38.201) - (S - 122.22)/38.201 + 1))$
$D \geq 16$ and $S < -0.031746D^2 + 0.74603D + 21.19$, or $16 > D \geq 8$ and $S < 45 - 1.9167D + 0.041667D^2$	$CTW = \max(0, -21.508 + 13.474\ln(D) + 19.67\ln(S) - 1.5206(\ln(D))^2 - 3.5315[\ln(S)]^2 - 0.6298\ln(D)\ln(S))$
$8 > D \geq 6$ and $S < 45 - 1.9167D + 0.041667D^2$, or $D < 6$ and $S < -442.3 + 2959.4/D^{0.5} - 6735.1/D + 6810.6/D^{1.5} - 2582.5/D^2$	$CTW = \max(0, -3.3578 + 3.5095D + 0.080638S - 0.18665D^2 - 0.00054297S^2 - 0.061173DS)$
(b) Medium-Sized-Large Automobile	
$D \geq 16$ and $S \geq -0.031746D^2 + 0.74603D + 21.19$, or $6 \leq D < 16$ and $S \geq 45 - 1.9167D + 0.041667D^2$, or $D < 6$ and $S \geq -442.3 + 2959.4/D^{0.5} - 6735.1/D + 6810.6/D^{1.5} - 2582.5/D^2$	$CTW = \max(0, 519{,}464\exp(-\exp(-(D - 48.665)/18.647) - (D - 48.665)/18.647 + 1) \times \exp(-\exp(-(S - 127.84)/39.862) - (S - 127.84)/39.862 + 1))$
$D \geq 16$ and $S < -0.031746D^2 + 0.74603D + 21.19$, or $6 \leq D < 16$ and $S < 45 - 1.9167D + 0.041667D^2$	$CTW = \max(0, -31.7 + 20.767\ln(D) + 22.783\ln(S) - 2.5841[\ln(D)]^2 - 3.9522[\ln(S)]^2 - 4.4831\ln(D)\ln(S))$
$D < 6$ and $S < -442.3 + 2959.4/D^{0.5} - 6735.1/D + 6810.6/D^{1.5} - 2582.5/D^2$	$CTW = \max(0, -4.4955 + 4.542D + 0.088792S - 0.27253D^2 - 0.00042329S^2 - 0.07399DS)$
(c) Four-Tire Truck	
$D \geq 16$ and $S \geq 0.02381D^2 - 1.4524D + 42.143$, or $6 \leq D < 16$ and $S \geq 35 - 125/D + 750/D^2$, or $(D < 6$ and $S \geq 23.334 + 112.5/D - 150.83/D^2 + 25/D^3$	$CTW = \max(0, 450{,}515\exp(-\exp((D - 49.07)/18.816) -(D - 49.07)/18.816 + 1) \times \exp(-\exp(-(S - 124.84)/38.88) -(S - 124.84)/38.89 + 1))$
$D \leq 16$ and $S < 0.02381D^2 - 1.4524D + 42.143$	$CTW = \max(0, -13.126 + 79.095/D + 254.26/S - 39.567/D^2 - 694.97/S^2 - 217.62/DS)$
$6 \leq D < 16$ and $S < 35 - 125/D + 750/D^2$, or $D < 6$ and $S < 23.334 + 112.5/D - 150.83/D^2 + 25/D^3$	$CTW = \max(0, -2.743 + 3.5215D + 0.077273S - 0.16376D^2 - 0.00069592S^2 - 0.064592DS$
(d) Six-Tire Truck	
$D \geq 16$ and $S \geq 0.02381D^2 - 1.4524D + 42.143$, or $6 \leq D < 16$ and $S \geq 35 - 125/D + 750/D^2$, or $D < 6$ and $S \geq 23.334 + 112.5/D - 150.83/D^2 + 25/D^3$	$CTW = \max(0, 377{,}675\exp(-\exp(-(D - 51.703)/19.791) - (D - 51.703)/19.791 + 1) \exp(-\exp(-(S - 120.93)/37.611) - (S - 120.93)/37.611 + 1))$

Table A7.1.7 (*continued*)

$D \geq 16$ and $S < 0.02381D^2 - 1.4524D + 42.143$, or $6 \leq D < 16$ and $S < 35 - 125/D + 750/D^2$	$\text{CTW} = \max(0, -26.586 + 17.42\ln(D) + 19.303\ln(S) - 2.1482[\ln(D)]^2 - 3.3487[\ln(S)]^2 - 3.81\ln(D)\ln(S))$
$D < 6$ and $S < 23.334 + 112.5/D - 150.83/D^2 + 25/D^3$	$\text{CTW} = \max(0, -4.0066 + 3.8372D + 0.11043S - 0.2262D^2 - 0.0011358S^2 - 0.064529DS)$
(e) 3+ Axle Single-Unit Truck	
$D \geq 16$ and $S \geq 0.02381D^2 - 1.4524D + 42.143$, or $16 > D \geq 6$ and $S \geq 35 - 125/D + 750/D^2$, or $D < 6$ and $S \geq 23.334 + 112.5/D -150.83/D^2 + 25/D^2$	$\text{CTW} = \max(0, 707{,}192\exp(-\exp(-(D - 44.524)/16.77) - (D - 44.524)/16.77 + 1) \times \exp(-\exp(-(S - 132.23)/40.729) - (S - 132.23)/40.729 + 1))$
$D \geq 16$ and $S < 0.02381D^2 - 1.4524D + 42.143$, or $16 > D \geq 6$ and $S < (35 - 125/D + 750/D^2$	$\text{CTW} = \max(0, 7.4369 + 29.473/D + 6.5816 * \ln(S) - 541.46/D^2 - 3.8133[\ln(S)]^2 + 45.797(\ln(S))/D)$
$D < 6$ and $S < 23.334 + 112.5/D - 150.83/D^2 + 25/D^3$	$\text{CTW} = \max(0, -4.6194 + 4.5401D + 0.10837S - 0.26588D^2 - 0.00099725S^2 - 0.076619DS)$
(f) 3–4 Axle Combination-Unit Truck	
$D \geq 16$ and $S \geq (0.02381D^2 - 1.4524D + 42.143$, or $16 > D \geq 6$ and $S \geq 35 - 125/D + 750/D^2$, or $D < 6$ and $S \geq 23.334 + 112.5/D - 150.83/D^2 + 25/D^3$	$\text{CTW} = \max(0, 578{,}653\exp(-\exp(-(D - 54.618)/20.44) - (D - 54.618)/20.44 + 1) \times \exp(-\exp(-(S - 120.41)/37.427) - (S - 120.41)/37.427 + 1))$
$D \geq 16$ and $S < 0.02381D^2 - 1.4524D + 42.143$, or $(16 > D \geq 6$ and $S < 35 - 125/D + 750/D^2$	$\text{CTW} = \max(0, -26.305 + 16.264\ln(D) + 20.114\ln(S) - 1.7217[\ln(D)]^2 - 3.4077[\ln(S)]^2 - 4.0945\ln(D)\ln(S))$
$D < 6$ and $S < 23.334 + 112.5/D - 150.83/D^2 + 25/D^3$	$\text{CTW} = \max(0, -3.8937 + 3.8291D + 0.092128S - 0.22412D^2 - 0.00082522S^2 - 0.064764DS)$
(g) 5+ Axle Combination-Unit Truck	
$D \geq 16$ and $S \geq 0.02381D^2 - 1.4524D + 42.143$, or $16 > D \geq 6$ and $S \geq 35 - 125/D + 750/D^2$, or $1 \leq D < 6$ and $S \geq (23.334 + 112.5/D - 150.83/D^2 + 25/D^3$	$\text{CTW} = \max(0, \exp(-40.193 + 14.371\exp(D/ - 53.803) + 1.2303(\ln(D))^2 - 1.8886S/\ln(S) + 7.0737S^{0.5}))$
$D < 1$ and $S \geq 23.334 + 112.5/D - 150.83/D^2 + 25/D^3$	$\text{CTW} = \max(0, 1/(1.1442 - 0.015388D^3 - 9704.3/S^{1.5} +27{,}917\ln(S)/S^2 - 42{,}372/S^2))$
$D \geq 16$ and $S < 0.02381D^2 - 1.4524D + 42.143$, or $16 > D \geq 6$ and $S < 35 - 125/D + 750/D^2$	$\text{CTW} = \max(0, -27.686 + 18.235\ln(D) + 24.103\ln(S) - 2.2305[\ln(D)]^2 - 4.3932[\ln(S)]^2 - 4.4593\ln(D)\ln(S))$
$D < 6$ and $S < (23.334 + 112.5/D - 150.83/D^2 + 25/D^3)$	$\text{CTW} = \max(0, -4.9124 + 4.8372D + 0.12051S - 0.2845D^2 - 0.0011691S^2 - 0.08169DS)$

Table A7.1.8 VOC for Excess Maintenance and Repair at Curved Sections (CMR)

(a) Small Automobile	
$D > 10$ and $S \geq -0.65D + 34.5$, or $D < 10$ and $S \geq -2.4444D + 52.444$	$\text{CMR} = \max(0, \exp(-19.624 - 1.0614D^{0.5}\ln(D) + 6.4853D^{0.5} + 0.033374S^{1.5} - 0.00046284S^2\ln(S)))$
$5 \leq D \leq 10$ and $(-1D + 20) \leq S \leq (-1D + 25)$	$\text{CMR} = 0.1$
Otherwise	$\text{CMR} = 0$
(b) Medium-sizes/Large Automobile	
$D > 12$ and $S \geq -0.5D + 30$, or $D < 12$ and $S \geq -2.3636D + 52.364$	$\text{CMR} = \max(0, \exp(-37.927 + 3.2935\ln(D) + 1.8096/D + 7.8477\ln(S)))$

(*continued overleaf*)

Table A7.1.8 (*continued*)

(c) Four-Tire Truck	
$5 \le D \le 10$ and $-1D + 20 \le S \le -1D - 25$	CMR $= 0.1$
Otherwise	CMR $= 0$
$D \ge 12$ and $S \ge -0.45D + 30.4$, or $D < 12$ and $S \ge -2.2727D + 52.273$	CMR $= \max(0, \exp(594.56 - 0.021279D^{1.5} + 2.6656D^{(0.5)} -19.444S^{0.5} - 7777/S^{0.5} + 8121.8\ln(S)/S))$
$3.5 < D < 8.5$ and $17.5 \le S < 22.5$, or $4.5 < D < 10.5$ and $12.5 \le S \le 17.5$, or $7.5 < D < 12.5$ and $7.5 < S \le 12.5$	CMR $= 0.1$
Otherwise	CMR $= 0$
(d) Six-Tire Truck	
$D \ge 8$ and $S \ge -0.0038D^2 - 0.3106D + 27.272$	CMR $= \max(0, \exp(9.6157 + 0.12975D - 157.95/D^2 + 7095.5\exp(-D) - 106.49\ln(S)/S))$
$D < 8$ and $S \ge -0.625D^2 + 3.125D + 40$,	CMR $= \max(0, \exp(-314.6 + 2.5973D\ln(D) - 1.4569D^2 + 0.30227D^{2.5} + 2642/\ln(S) - 2565.9/S^{0.5}))$
$1 \le D \le 3$ and $-10D + 37.5 \le S \le 10D + 2.5$, or $3 < D \le 5$ and $S < 32.5$, or $5 < D < 8$ and $S < 0.8333D^2 - 14.167D + 85$ or $D \ge 8$ and $S < -0.0038D^2 - 0.3106D + 24.5$	CMR $= 0.1$
$D > 4.5$ and $12.5 < S < -0.35D^2 + 3.85D + 12$	CMR $=$ CMR $+ 0.1$
Otherwise	CMR $= 0$
The fourth equation for six-tire truck excess maintenance and repair due to curves is incremental; the condition is true when certain other conditions are true and the equations adds value to the existing CMR value.	
(e) 3+ Axle Single-Unit Truck	
$D \ge 10$ and $S \ge -0.75D + 40$, or $10 > D \ge 2$ and $S \ge -2.1875D + 54.375$ or $D < 2$ and $S \ge (5D^2 - 2.5D + 35$	CMR $= \max(0, \exp -50.038 + 0.71092[\ln(D)]^2 + 0.50522\ln(D) - 0.08522S + 13.02\ln(S)))$
$1 \le D \le 3$ and $10D + 2.5 \ge S \ge -10D + 37.5$, or $3 < D \le 5$ and $S \le 32.5$, or $D \ge 14$ and $S \le -0.3125D + 21.875$, or $5 < D < 14$ and $S \le -1.66667D + 40.8333$	CMR $= 0.1$
$4.5 \le D \le 10.5$ and $S > 39.3 - 13.497D + 2.215D^2 - 0.11833D^3$ and $S < 17.5 + 5/(1 + \exp(-((D - 7.0222)/ - 0.07845))))$	CMR $=$ CMR $+ 0.1$
Otherwise	CMR $= 0$
The third equation for 3+ axle single-unit truck excess maintenance and repair due to curves is used to increment the value for CMR derived from the second equation under certain conditions. The conditions for this may be true when the condition for the second equation is true.	
(f) 3–4 Axle Combination-Unit Truck	
$D \ge 17.5$ and $S \ge -0.4D + 29.5$, or $17.5 > D \ge 2.5$ and $S \ge -1.5D + 48.75$, or $D < 2.5$ and $S \ge 4D + 35$	CMR $= \max(0, \exp(304.96 - 0.90108D + 2.0321D^{0.5}\ln(D) - 0.70003\ln(D) - 41.773\ln(S) - 1312.1/S^{0.5} + 2080.7/S))$
$D \le 3$ and $-6.667D^2 + 38.33D + -22.5 \ge S \ge 6.667D^2 - 38.33D + 62.5$, or $3 < D \le 6$ and $S \le 32.5$, or $6 < D < 10$ and $S \le -2.5D + 47.5$, or $D \ge 10$ and $S \le -0.5D + 27.5$	CMR $= 0.1$
$3.5 < D < 6.5$ and $12.5 < S < 22.5$, or $5.5 < D < 12.5$ and $7.5 < S < 17.5$	CMR $=$ CMR $+ 0.1$
Otherwise	CMR $= 0$

Table A7.1.8 (*continued*)

The third equation for 3–4 axle combination-unit truck excess maintenance and repair due to curves is, under certain conditions, used to increment the CMR value derived from the second equation. Under some circumstances, the conditions for both the second and third and equations will be true.

(g) 5+ Axle Combination-Unit Truck

$D \geq 10$ and $S \geq (-0.5D + 32.5)$, or $10 > D > 3$ and $S \geq -2.8571D + 56.071$, or $D < 3$ and $S \geq 6.6667D + 27.5$	$\text{CMR} = \exp(703.2 + 0.75135[\ln(D)]^2 - 1.3433/D^{0.5} - 62.464\ln(S) - 2045.3/\ln(S) + 3128.1/S))$
$1.5 \leq D \leq 3$ and $5D + 22.5 > S > -5D + 17.5$, or $16 \leq D \leq 25$ and $S \leq 17.5$, or $D > 25$ and $S \leq -1D + 42.5$, or $3 < D < 16$ and $S \leq -1.5385D + 42.115$	$\text{CMR} = 0.1$
$2.5 \leq D \leq 6.5$ and $12.5 \leq S \leq 27.5$, or $3.5 \leq D \leq 10.5$ and $7.5 \leq S \leq 22.5$, or $9.5 \leq D \leq 15$ and $2.5 < S \leq 17.5$, or $15 \leq D \leq 17$ and $7.5 \leq S \leq 17.5$ or $17 \leq D < 22.5$ and $7.5 \leq S \leq 12.5$	$\text{CMR} = \text{CMR} + 0.1$
$3.5 < D < 6.5$ and $17.5 \leq S < 22.5$, or $4.5 < D < 10.5$ and $12.5 \leq S \leq 17.5$, or $(7.5 < D < 10.5$ and $7.5 < S \leq 12.5)$	$\text{CMR} = \text{CMR} + 0.1$
Otherwise	$\text{CMR} = 0$

The third and fourth equations for 5+ axle combination-unit truck excess maintenance and repair due to curves are, under certain conditions, used to increment the CMR value derived from the second equation. These conditions for one or both of these equations may be true when the condition for the second equation is true.

Table A7.1.9 Excess VOC for Fuel Consumption due to Speed Variability (SCCFC)

(a) Small Automobile	
CSMAX < 5	$\text{SCCFC} = 0.00424\text{CSMAX}^3$
CSMAX ≥ 5	$\text{SCCFC} = 0.04547 + 0.08559\text{CSMAX} + 3677 \times 10^{-8}\text{CSMAX}^3$
(b) Medium-Sized/Large Automobile	
CSMAX < 5	$\text{SCCFC} = 0.008\text{CSMAX}^3$
CSMAX ≥ 5	$\text{SCCFC} = 0.03401 + 0.1902\text{CSMAX} + 4491 \times 10^{-8}\text{CSMAX}^3$
(c) Four-Tire Truck	
CSMAX < 5	$\text{SCCFC} = 0.00904\text{CSMAX}^3$
CSMAX ≥ 5	$\text{SCCFC} = 0.8137 + 0.1576\text{CSMAX} + 7327 \times 10^{-8}\text{CSMAX}^3$
(d) Six-Tire Truck	
CSMAX < 5	$\text{SCCFC} = 0.1184\text{CSMAX}^2$
CSMAX ≥ 5	$\text{SCCFC} = 3.09 + 0.02843\text{CSMAX}^2$
(e) 3+ Axle Single-Unit Truck	
CSMAX < 5	$\text{SCCFC} = 0.174\text{CSMAX}^2$
CSMAX ≥ 5	$\text{SCCFC} = 4.477 + 0.03862\text{CSMAX}^2$
(f) 3–4 Axle Combination-Unit Truck	
CSMAX < 5	$\text{SCCFC} = 0.324\text{CSMAX}^2$
CSMAX ≥ 5	$\text{SCCFC} = 6.342 + 0.5855\text{CSMAX} + 0.03191\text{CSMAX}^2$
(g) 5+ Axle Combination-Unit Truck	
CSMAX < 5	$\text{SCCFC} = 0.3584\text{CSMAX}^2$
CSMAX ≥ 5	$\text{SCCFC} = 2.052 + 1.167\text{CSMAX} + 0.03292\text{CSMAX}^2$

Table A7.1.10 Excess VOC for Oil Consumption due to Speed Variability (SCCFC)

(a) Small Automobile	
CSMAX < 5	$SCCOC = 0.00004CSMAX^3$
CSMAX ≥ 5	$SCCOC = 0.000879 + 0.000934CSMAX - 1612 \times 10^{-8}CSMAX^2 + 193 \times 10^{-9}CSMAX^3$
(b) Medium-sized/Large Automobile	
CSMAX < 5	$SCCOC = 0.00004{*}CSMAX^3$
CSMAX ≥ 5	$SCCOC = 0.000801 + 0.000869CSMAX - 1617 \times 10^{-8}CSMAX^2 + 197 \times 10^{-8}CSMAX^3$
(c) Four-Tire Truck	
CSMAX < 5	$SCCOC = 0.0002CSMAX^2$
CSMAX ≥ 5	$SCCOC = \exp(-6.242 + 0.5935\ln(CSMAX) + 0.000131CSMAX^2)$
(d) Six-Tire Truck	
CSMAX < 5	$SCCOC = 0.00068{*}CSMAX^2$
CSMAX ≥ 5	$SCCOC = \exp(-5.069 + 0.6392\ln(CSMAX) + 0.000169CSMAX^2)$
(e) 3+ Axle Single-Unit Truck	
CSMAX < 5	$SCCOC = 0.00136{*}CSMAX^2$
CSMAX ≥ 5	$SCCOC = \exp(-4.408 + 0.6632\ln(CSMAX) + 0.000148CSMAX^2)$
(f) 3–4 Axle Combination-Unit Truck	
CSMAX < 5	$SCCOC = 0.00136{*}CSMAX^2$
CSMAX ≥ 5	$SCCOC = \exp(-4.408 + 0.6632\ln(CSMAX) + 0.000148CSMAX^2)$
(g) 5+ Axle Combination-Unit Truck	
CSMAX < 5	$SCCOC = 0.0028{*}CSMAX^2$
CSMAX ≥ 5	$SCCOC = \exp(-3.735 + 0.6849\ln(CSMAX) + 0.000112CSMAX^2)$

Table A7.1.11 Excess VOC for Tire Wear due to Speed Variability (SCCFC)

(a) Small Automobile	
CSMAX < 5	$SCCTW = 0.0008CSMAX^2$
CSMAX ≥ 5	$SCCTW = \exp(-7.112 + 1.999\ln(CSMAX) - 8384 \times 10^{-8}CSMAX^2)$
(b) Medium-Sized/Large Automobile	
CSMAX < 5	$SCCTW = 0.0012CSMAX^2$
CSMAX ≥ 5	$SCCTW = \exp(-6.64 + 1.947\ln(CSMAX) - 9909 \times 10^{-8}CSMAX^2)$
(c) Four-Tire Truck	
CSMAX < 5	$SCCTW = 0.0012CSMAX^2$
CSMAX ≥ 5	$SCCTW = \exp(-6.568 + 1.906\ln(CSMAX) - 7502 \times 10^{-8}CSMAX^2)$
(d) Six-Tire Truck	
CSMAX < 5	$SCCTW = 0.0016CSMAX^2$
CSMAX ≥ 5	$SCCTW = \exp(-6.387 + 1.984\ln(CSMAX) - 988 \times 10^{-7}CSMAX^2)$
(e) 3+ Axle Single-Unit Truck	
CSMAX < 5	$SCCTW = 0.0012CSMAX^2$
CSMAX ≥ 5	$SCCTW = \exp(-6.595 + 1.918\ln(CSMAX) - 6855 \times 10^{-8}CSMAX^2)$
(f) 3–4 Axle Combination-Unit Truck	
CSMAX < 5	$SCCTW = 0.0008CSMAX^2$
CSMAX ≥ 5	$SCCTW = \exp(-7.111 + 2.0276\ln(CSMAX) - 0.000102CSMAX^2)$
(g) 5+ Axle Combination-Unit Truck	
CSMAX < 5	$SCCTW = 0.0012CSMAX^2$
CSMAX ≥ 5	$SCCTW = \exp(-6.643 + 1.947\ln(CSMAX) - 721 \times 10^{-7}CSMAX^2)$

Table A7.1.12 Excess VOC for Maintenance and Repair due to Speed Variability (SCCFC)

(a) Small Automobile	
$CSMAX < 5$	$SCCMR = 0.0016CSMAX^2$
$CSMAX \geq 5$	$SCCMR = \exp(-6.284 + 0.006889CSMAX + 1.881\ln(CSMAX) - 7388 \times 10^{-8}CSMAX^2)$
(b) Medium-Sized/Large Automobile	
$CSMAX < 5$	$SCCMR = 0.0016CSMAX^2$
$CSMAX \geq 5$	$SCCMR = \exp(-6.277 + 0.007347CSMAX + 1.876\ln(CSMAX) - 7275 \times 10^{-8}CSMAX^2)$
(c) 4-Tire Truck	
$CSMAX < 5$	$SCCMR = 0.0016CSMAX^2$
$CSMAX \geq 5$	$SCCMR = \exp(-6.39 + 1.958\ln(CSMAX) - 1781 \times 10^{-8}CSMAX^2)$
(d) 6-Tire Truck	
$CSMAX \leq 5$	$SCCMR = 0.0012CSMAX^2$
$CSMAX > 5$	$SCCMR = \exp(-6.427 + 0.01826CSMAX + 1.758\ln(CSMAX) - 0.000103CSMAX^2)$
(e) 3+ Axle Single-Unit Truck	
$CSMAX < 5$	$SCCMR = 0.0008CSMAX^2$
$CSMAX \geq 5$	$SCCMR = \exp(-7.446 - 0.005514CSMAX + 2.212\ln(CSMAX) + 5075 \times 10^{-8}CSMAX^2)$
(f) 3–4 Axle Combination-Unit Truck	
$CSMAX < 5$	$SCCMR = 0.0012CSMAX^2$
$CSMAX \geq 5$	$SCCMR = \exp(-6.639 + 0.006003CSMAX + 1.912\ln(CSMAX))$
(g) 5+ Axle Combination-Unit Truck	
$CSMAX < 5$	$SCCMR = 0.0012CSMAX^2$
$CSMAX \geq 5$	$SCCMR = \exp(-6.705 + 0.008136CSMAX + 1.94\ln(CSMAX))$

Table A7.1.13 Excess VOC for Depreciation due to Speed Variability (SCCD)

(a) Small Automobile	
$CSMAX < 60$	$SCCD = 0.0004CSMAX$
$CSMAX \geq 60$	$SCCD = \exp(-4.327 + 0.000168CSMAX^2)$
(b) Medium-Sized/Large Automobile	
$CSMAX < 5$	$SCCD = 0.0004CSMAX$
$5 \leq CSMAX < 50$	$SCCD = 0.001 + 0.0002CSMAX$
$CSMAX \geq 50$	$SCCD = \exp(-4.973 + 0.000228CSMAX^2)$
(c) 4-Tire Truck	
$CSMAX < 60$	$SCCD = 0.0002CSMAX$
$CSMAX \geq 60$	$SCCD = \exp(-5.0007 + 0.000162CSMAX^2)$
(d) 6-Tire Truck	
$CSMAX < 5$	$SCCD = 0.0004CSMAX$
$5 \leq CSMAX < 40$	$SCCD = 0.001429 + 0.000221CSMAX$
$CSMAX \geq 40$	$SCCD = \exp(-4.957 + 0.000294CSMAX^2)$
(e) 3+ Axle Single-Unit Truck	
$CSMAX < 5$	$SCCD = 0.0006CSMAX$
$5 \leq CSMAX < 55$	$SCCD = 0.001 + 0.0004CSMAX$
$CSMAX \geq 55$	$SCCD = \exp(-4.439 + 0.000231CSMAX^2)$

(*continued overleaf*)

Table A7.1.13 (*continued*)

(f) 3–4 Axle Combination-Unit Truck	
CSMAX < 60	SCCD = 0.0002CSMAX
CSMAX ≥ 60	$SCCD = \exp(-5.007 + 0.000162CSMAX^2)$
(g) 5+ Axle Combination-Unit Truck	
CSMAX < 60	SCCD = 0.0002CSMAX
CSMAX ≥ 60	$SCCD = \exp(-5.007 + 0.000162CSMAX^2)$

APPENDIX A7.2: VOC COMPONENT UNIT COSTS

Table A7.2.1 Unit VOC Component Costs in 2005 Dollars

	Fuel ($/gal)	Oil ($/qrt)	Tires ($/tire)	Maintenance and Repair ($/1000 mi)	Depreciation Value ($)
Automobiles					
Small	1.89	4.32	54.71	101.80	21,929
Medium-Sized/Large	1.89	4.32	86.54	123.58	25,865
Trucks					
Single unit, four-tires	1.05	4.32	95.38	157.11	27,873
Single unit, six-tires	1.05	1.73	230.10	294.01	41,650
Single unit, 3+ axles	0.92	1.73	569.74	415.77	91,630
Combination, 3–4 axles	0.92	1.73	569.74	430.66	106,140
Combination, 5+ axles	0.92	1.73	569.74	430.66	115,411

Source: Updated from HERS (FHWA, 2002).

APPENDIX A7.3: PAVEMENT CONDITION ADJUSTMENT FACTORS

Table A7.3.1 Constant-Speed Operating Costs, Pavement Condition Adjustment Factors[a]

(a) General Equation[b]

	Vehicle Class		
		Trucks	
VOC Component	Four-Tire Vehicles	Single-Unit	Combination
Maintenance and repair (PCAFMR)	$3.19 + 0.0967PSR^2 - 0.961PSR$	$1.724 + 0.00830PSR^2 - 0.661 \ln(PSR)$	$2.075 + 0.273PSR - 1.622 \ln(PSR)$
Depreciation (PCAFVD)	$1.136 - 0.106 \ln(PSR)$	$1.332 - 0.262 \ln(PSR)$	$1.32 - 0.254 \ln(PSR)$
Oil consumption (PCAFOC)	$2.64 + 0.0729PSR^2 - 0.722PSR$	$1.176 - 0.1348 \ln(PSR)$	
Tire wear (PCAFTW)	$2.40 - 1.111 \ln(PSR)$	$1.668 + 0.001372PSR^3 - 0.581 \ln(PSR)$	

Source: FHWA (2002).

Table A7.3.1 (*continued*)

(b) Specific Values

	Oil Consumption (PCAFOC)		Tire Wear (PCAFTW)		Maintenance and Repair (PCAFMR)			Depreciation (PCAFVD)		
PSR	Four-Tire Vehicle	Truck	Four-Tire Vehicle	Truck	Four-Tire Vehicle	Single-Unit Truck	Combination Truck	Four-Tire Vehicle	Single-Unit Truck	Combination Truck
5.0	0.85	0.96	0.61	0.90	0.80	0.87	0.83	0.97	0.91	0.91
4.0	0.92	0.99	0.86	0.95	0.89	0.94	0.92	0.99	0.97	0.97
3.0	1.13	1.03	1.18	1.07	1.18	1.07	1.11	1.02	1.04	1.04
2.0	1.49	1.08	1.63	1.28	1.65	1.30	1.50	1.06	1.15	1.14
1.0	1.99	1.18	2.40	1.67	2.33	1.73	2.35	1.14	1.33	1.32
0.0	2.64	—	—	—	3.19	—	—	—	—	—

Source: FHWA (2002).

[a]PCAFOC, pavement condition adjustment factor for oil consumption; PCAFTW, pavement condition adjustment factor for tire wear; PCAFMR, pavement condition adjustment factor for maintenance and repair; PCAFVD, pavement adjustment factor for depreciation expenses.

[b]PSR $= 5e^{-0.26\text{IRI}}$ when IRI is in mm/m, or $= 5e^{-0.0041\text{IRI}}$ when IRI is in in/mi (Al-Omari and Darter, 1994).

APPENDIX A7.4: FUEL EFFICIENCY AND OTHER COMPONENT ADJUSTMENT FACTORS

Table A7.4.1 Fuel Efficiency Adjustment Factors

Vehicle Class	Factor
Automobiles (All Sizes)	1.536
4-Tire Trucks	1.596
6-Tire Trucks	1.207
3+ Axle and Combination Trucks	1.167

Source: FHWA (2002).

Table A7.4.2 Adjustment Factors for Other VOC Components

VOC Component	Factor
Fuel (FEAF)	1.536
Oil (OCAF)	1.050
Tire (TWAF)	1.000
Maintenance and Repair (MRAF)	1.000
Depreciation (VDAF)	1.300

Source: FHWA (2002).