Impact of Transportation System Interventions on Vehicle Operating Cost (VOC)

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Transportation Vehicles - Cost Categories

Vehicle Costs

Fixed Costs
(Costs of Owning the Vehicle)

- Purchase costs, Lease costs
- License & Registration costs
- Insurance costs, etc.

Variable Costs
(Costs of Using the Vehicle)

- Fuel cost etc.

Not influenced by Transportation improvements

Influenced by Transportation improvements

FOCUS OF THIS LECTURE
Transportation Vehicles - Cost Categories

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  etc.

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*Influenced by Transportation improvements*

**FOCUS OF THIS LECTURE**

**Q.1:** Which aspects of the vehicle incurs expenditure due to vehicle usage?

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- Fuel use
- Engine oil
- Tire wear
- Preventive maintenance
- Repair
- Cleaning

- Driver’s wage (for commercial vehicles)
- Inventory cost, etc. (for commercial vehicles only)
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These are the VOC Components
Q. 2: What aspects of the highway makes the road-user spend more on the fuel, oil, etc. (VOC components)?
Q. 2: What aspects of the railway track, runway, or guideway makes the agency/operator spend more on gas, oil, tires, etc. (VOC components)?
What aspects of the guideway makes the road-user spend more on gas, oil, tires, etc.

- Horizontal curves
- Vertical alignment (steep grades)
- Guideway condition (e.g., for highways -> potholes)
- Congestion (as aspects that influence congestion)
- Guideway sections that involve deceleration/acceleration

Etc.

These are the VOC Factors
Today’s Talk

VOC components
## Today’s Talk

### VOC Components

<table>
<thead>
<tr>
<th>Components</th>
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<tbody>
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Today’s Talk

- VOC components
  - Fuel
  - Oil
  - Tire
  - Depreciation
  - Shipping Inventory
  - Etc.

- VOC factors
  - Grade
  - Speed
  - Curve
  - Dela
  - Facility Surface
  - Etc.
Today’s Talk

- VOC components
- VOC factors
- Procedural framework for assessing VOC impacts
- VOC estimation software
VOC Components
<table>
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<tr>
<th>Fuel</th>
<th>Oil</th>
<th>Tire</th>
<th>Depreciation</th>
<th>Shipping Inventory</th>
<th>Etc.</th>
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<th>Dela</th>
<th>Facility Surface</th>
<th>Etc.</th>
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</table>

*VOC Factors*
VOC Components

- Individual items associated with vehicle operation on which expenses are directly incurred.

- Include the costs of ...
  - energy needed to propel the vehicle
  - fluids
  - other light consumables associated with mechanical working of the drive-train
  - occasional replacement of vehicle’s contact surfaces with the guideway
  - vehicle repair and maintenance, and
  - vehicle depreciation.
VOC Components - Fuel

• Is a key component of vehicle operating costs (50-75% of all VOC)

• Factors affecting total fuel cost:
  - amount of fuel used
  - fuel efficiency
  - fuel price (per gallon).

• Vehicle factors affecting fuel efficiency/consumption rate:
  - vehicle class, age, type, speed

• Highway factors affecting fuel consumption rate:
  - highway class
  - steep grades
  - sharp horizontal curves
  - congestion conditions

• Unit costs of fuel:
  - 7 cents per vehicle-mile for autos
  - 21 cents per vehicle-mile for large trucks

• Sources of published data on fuel cost:
  - automobile associations, petroleum institutes, and government energy agencies
VOC Components – Lubricating Oils

- Includes engine oil, transmission fluids, brake fluids, and other oil consumables
- Help smooth/safe operation of vehicle engine and drive-train
- Oil cost is a product of unit price ($/quart) and consumption rates (quarts/mile).
- Oil consumption rate depends on:
  - Amount of usage
  - Traffic characteristics (speed, delay, etc.)
  - Facility characteristics (grade, curves, etc.)
- Oil costs may be reported
  - separately from Fuel costs
  - together with fuel costs combined
- Oil costs range $1.73 to $4.32 per quart (FHWA, 2002).
VOC Components – Wheels

Preservation of the Vehicle-Guideway Contact Surface

- At the points of contact with the guideway, the vehicle’s contact surfaces experience deterioration due to wear and tear.

- Vehicle “contact surface” is
  - For highways and runways: the tire
  - For rail: a steel wheel.

- Tires costs (2005$):
  - $54.71/tire for small autos
  - $86.54 for medium/large autos,
  - $95.38 for 4-tire single unit trucks,
  - $230.10 for 6-tire single unit trucks,
  - $569.74 for 3+ axle single unit trucks,
  - $569.74 for 3 - 4 axles, and
  - $569.74 for combination trucks.

- Following VOC factors mostly affect this VOC component:
  - pavement condition
  - grade
  - curvature, and
  - speed changes (Thoresen and Roper, 1996).
VOC Components – Vehicle Repair & Mtce

- After a certain level of usage, some parts of a vehicle may need:
  - repair
  - replacement or replenishment

- Examples:
  - Major electrical parts (batteries, alternators, etc.)
  - fuel pump
  - air pump
  - tire rims
  - Minor electrical parts (bulbs, fuses, wires, etc.)

- In some VOC estimation methodologies, cost of vehicle R&M is not reported separately but added to other non-fuel costs.

- Cost of vehicle R&M:
  - 4.7 per vehicle-mile for small/medium vehicles
  - 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.
### VOC Components – Vehicle Repair & Mtce

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>M&amp;R Cost (cents/veh-mile)</th>
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<tr>
<td>Small Autos</td>
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<td>Medium Autos</td>
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<td>Large Autos</td>
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<td>Van</td>
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<tr>
<td>Trucks</td>
<td>11.09</td>
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</table>
VOC Components – Vehicle Depreciation

• Is a function of:
  - usage (miles of travel)
  - age (years since manufacture).

• Mileage-based depreciation rates are similar across vehicle types
  - Cars: low cost but short service lives
  - Trucks: high cost but long service lives

• Mileage-based depreciation costs → significant fraction of overall VOC

• In some literature, the cost of vehicle depreciation is reported together with other non-fuel costs.
## VOC Components – Vehicle Depreciation

### Average Depreciation Rates by Vehicle Class

<table>
<thead>
<tr>
<th></th>
<th>Total Depreciation (cents/hr)</th>
<th>Average Travel (Miles/Year)</th>
<th>Mileage-related Depreciation (cents/mile)</th>
<th>Time Related Depreciation (cents/hr)</th>
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<td>4-tire Single Unit Trucks</td>
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<td>6-tire Single Unit Trucks</td>
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<td>10,952</td>
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<tr>
<td>3+ Axle Combination Trucks</td>
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<td>15,025</td>
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<td>3-4 Axle Combination Trucks</td>
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<td>5+ Axle Combination Trucks</td>
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<td>66,710</td>
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<td>232</td>
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</tbody>
</table>

*But these are average values b’cos in reality, ...*
VOC Components – Vehicle Depreciation

Depreciation rates are influenced by:
- geometrics (curves, grade)
- congestion
- speed
- weather, etc.

Transportation improvements often produce:
- smoother pavement
- improved driving conditions
  (through reduced stop-and-go situations)
- increased speed
- thus: reduced depreciation
VOC Components – Vehicle Depreciation

Effect of Increased Speed on Depreciation

![Graph showing the effect of increased speed on vehicle depreciation](image)
VOC Components – Vehicle Inventory

- Applicable only to cargo (freight transportation)
- In transporting perishable or valuable cargo, client incurs holding costs which represent an opportunity cost
  - If at the beginning of the shipment, the client had a cash amount worth the cargo being shipped, such amount would have earned some interest by the time the cargo reaches its destination.
- So by having the cargo transported, client forgoes some benefits.
- Greater the cargo value, higher the inventory costs
- Longer time spent in transporting the goods, higher the inventory costs
- More perishable the cargo, higher the inventory costs
VOC Components – Vehicle Inventory

- Inventory cost computation:
  - Hourly discount rate * average value of shipment
  - Inventory costs of cargo expressed in $/vehicle-mile

- The most significant VOC factors that affect the shipping inventory costs are speed and delay,

- Cargo value and interest rate are also influential.

- For example, shipping $100,000 cargo at 10% interest rate:
  Truck A traveling at 50 mph → 6 cents per mile
  Truck B traveling at 60 mph → 2.5 cents per mile
VOC Factors
VOC Factors

Generally:

\[ \text{Total VOC} = \text{Unit VOC (\$/VMT)} \times \text{Amount of Travel (VMT)} \]
VOC Factors

Generally:

Total VOC = Unit VOC ($/VMT) * Amount of Travel (VMT)

What affects this?

And what affects this?
VOC Factors

Total VOC = Unit VOC ($/VMT) * Amount of Travel (VMT)

Factors that Affect VOC

Factors that affect VOC Rate ($/per veh-mile)

Vehicle/Operator Characteristics

Economic Factors

Fixed Asset Characteristics

Policy/Institutional Factors

Factors that affect VMT

Section Length

Section Traffic Volume

Vehicle Type
Vehicle Age
Fuel Type
Driver

Prices of VOC Components (Fuel, Tires, Repair & Maintenance, Depreciation)

Physical Factors

Facility Type (e.g., Road Class)
Condition/Age of Facility (e.g., Roughness)
Gradient
Curvature

Operational

Average Speed
Average Delay
Nr. of Speed Changes

Speed Limits
Incentives for Non-traditional Fuels

Which of these VOC factors can be influenced by transportation improvements?
VOC Factors – Vehicle Type/Size

- Greater vehicle size
  - Greater consumption of fuel, oil
  - higher VOC

- Newer vehicles
  - improved vehicle technology
  - higher fuel efficiency
  - lower fuel consumption → lower VOC

- “Rudimentary” travel vehicles
  - Bicycle (standard basic bicycle) with basic accessories
    - $100-$500
    - annual maintenance costs of $20-40 (tire repl., tire pumping, security).
VOC Factors – Fuel Type

- Fuel Types: Electric, Gasoline, Diesel, Ethanol, etc.
- Electric cars
  - new battery sets every 20,000-30,000 miles
  - new battery costs $2,000-$3,000
  - Battery usage cost: 6-15¢ per vehicle-mile

- Battery replacements over 4 times higher for electric cars compared to hybrid/conventional cars (VTPI, 2005).

- Traditional fuel prices: diesel 10% higher than regular leaded gasoline.

- For regular leaded gasoline, differences in price across the three standard grades.
VOC Factors – Longitudinal Grade

Which VOC components are most affected in ...

- Uphill movements:
- Downhill trips:
VOC Factors – Longitudinal Grade

• Uphill movements:
  → impose additional loads on vehicle engines
  → require greater consumption of energy compared to downhill or level movements
  → increased oil/fuel use and cost

• Downhill trips:
  → fuel consumption is lower compared to uphill or level trips,
  → but increased brake applications
    → increased wear-and-tear of brake linings
    → increased cost of brake maintenance
VOC Factors – Longitudinal Grade

Impact of Longitudinal Grade on VOC, at Various Speeds

- Generally, VOCs lowest for gentle downward slopes (0 to -4 %).
- For other vehicle classes, HERS manual (FHWA, 2002) provides equations to describe effect of longitudinal grade on
  - fuel consumption
  - oil
  - tire wear
  - other VOC components
- Thus, impact of grade-reducing transportation improvements can be quantified
Example

A 2.15-mile section of road on rolling terrain received major vertical realignment.

The average grade of the section was reduced from 3.2% to 2.5%.

Traffic volume, composition, and speed (50 mph) were the same after the improvement.

Assume that traffic stream has a 50-50 directional split and is composed primarily of medium automobiles; traffic volume is 43,340 veh/day.

What is the first-year user benefit in terms of VOC?

Before improvement:

For uphill traffic, VOC at +3.2% grade = $275/1000VMT
For downhill traffic, VOC at -3.2% grade = $190/1000VMT
Average = $232.5/1000 VMT

After improvement:

For uphill traffic, VOC at +2.5% grade = $260/1000VMT
For downhill traffic, VOC at -2.5% grade = $200/1000VMT
Average = $230/1000 VMT

Change in unit costs, VOC\text{}_{\text{before}} - VOC\text{}_{\text{after}}

or \( U_1 - U_2 = $2.5/1000VMT = $0.0025/VMT \)

First year user benefits = \( 0.5 \times (U_1 - U_2) \times (VMT_1 + VMT_2) \)
= \( 0.5 \times (0.0025) \times (2)(43,340 \times 2.15 \times 365) = $85,028 \).
VOC Factors – Speed

• Is a dominant factor in determining VOC (Bennet, 1991; Thoresen and Roper, 1996; Bennet and Greenwood, 2001; FHWA, 2002).

• Transportation improvements influence travel speeds and therefore affect the VOC of vehicles.

• As a VOC factor, speed, in turn, is affected by:
  - speed limits (set by policy)
  - traffic conditions (which vary by time-of-day: peak vs. non-peak).

• Speed affects all VOC components, especially:
  - fuel
  - shipping inventory costs.
VOC Factors – Speed

Impact of Speed on Fuel Use

• Fuel consumption (and overall cost) decreases with increasing speed

• But after a certain point, there is no change (or sometimes, an increase) in fuel consumption with increasing speed.
VOC Factors – Speed

Impact of Speed on Shipping Inventory

\[ U_{IC} = 100 \times \frac{r}{365 \times 24} \times \frac{1}{S} \times R \]

\( U_{IC} \) = user inventory costs (cents per vehicle-mile),
\( r \) = annual interest rate,
\( R \) = value of the cargo, in dollars,
\( S \) = speed of the vehicle, in miles per hour.

Example
Due to a new speed limit policy, the average truck operating speed on a certain interstate freeway increased from 56.5 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 vpd.
On the average, each truck hauls an average of $1.5 million worth of goods daily.
Assume an 8% interest rate.

Solution

Daily changes in inventory costs per truck due to the change in travel speed =

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

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

$$= 1.86 \, \text{¢/veh-mi}$$

Number of trucks per year = 0.22 \times 82,500 \times 365 = 6,624,750
Total reduction in inventory cost for all trucks per year = $0.0186 \times 6,624,750 = $123,220.35/mile.
VOC Factors – Speed

Impact of Speed on Total VOC (All Components Combined)
VOC Factors – Speed and Veh. Class

The Hepburn Model
Impact of Speed and Veh. Class on 5 VOC Components
VOC Factors – Speed and Veh. Class

The Hepburn Model

(Impact of Speed and Veh. Class on 5 VOC Components)

For “low” average travel speeds (< 50 mph):

\[ VOC = C + \frac{D}{S} \]

For “high” average travel speeds (> 50 mph):

\[ VOC = a_0 + a_1 S + a_2 S^2 \]

*VOC* is in cents/vehicle-mile, *S* is speed (mph) and *C*, *D*, *a_0*, *a_1*, and *a_2* are coefficients that are functions of vehicle type.

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th><em>C</em></th>
<th><em>D</em></th>
<th><em>a_0</em></th>
<th><em>a_1</em></th>
<th><em>a_2</em></th>
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<tbody>
<tr>
<td>Small automobile</td>
<td>24.8</td>
<td>45.5</td>
<td>27.2</td>
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<td>Large automobile</td>
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<td>163.4</td>
<td>38.1</td>
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<td>0.00033</td>
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</table>
VOC Factors – Speed and Veh. Class
The Hepburn Model
(Impact of Speed and Veh. Class on 5 VOC Components)

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

Solution: $VOC_1 = C + \frac{D}{S}$
` = 28.5 + (95.3/35)
 = 31.22 cents/vehicle-mile
VOC Factors – Speed, Grade, and Veh. Class

The Zanieswki Model

(Impact of Speed, Grade, and Veh. Class on 5 VOC Components)
## VOC Factors – Speed, Grade, and Veh. Class

### The Zaniewski Model

#### (Impact of Speed, Grade, and Veh. Class on 5 VOC Components)

### VOC by Vehicle Speed and Roadway Grade ($/1000 VMT, for Medium Autos) (in 2005 Dollars)

<table>
<thead>
<tr>
<th>Grade (%)</th>
<th>Speed (mph)</th>
<th>5</th>
<th>10</th>
<th>15</th>
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<th>25</th>
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<td>249</td>
<td>228</td>
<td>209</td>
<td>197</td>
<td>191</td>
<td>212</td>
<td>213</td>
<td>225</td>
<td>235</td>
<td>250</td>
<td>270</td>
<td>477</td>
</tr>
<tr>
<td>-4</td>
<td>422</td>
<td>376</td>
<td>322</td>
<td>273</td>
<td>250</td>
<td>227</td>
<td>212</td>
<td>202</td>
<td>195</td>
<td>190</td>
<td>217</td>
<td>225</td>
<td>239</td>
<td>255</td>
<td>477</td>
</tr>
<tr>
<td>-5</td>
<td>461</td>
<td>407</td>
<td>350</td>
<td>301</td>
<td>276</td>
<td>249</td>
<td>231</td>
<td>217</td>
<td>212</td>
<td>205</td>
<td>204</td>
<td>197</td>
<td>228</td>
<td>243</td>
<td>477</td>
</tr>
<tr>
<td>-6</td>
<td>499</td>
<td>439</td>
<td>379</td>
<td>327</td>
<td>301</td>
<td>273</td>
<td>250</td>
<td>235</td>
<td>228</td>
<td>223</td>
<td>231</td>
<td>213</td>
<td>210</td>
<td>228</td>
<td>477</td>
</tr>
<tr>
<td>-7</td>
<td>537</td>
<td>470</td>
<td>406</td>
<td>352</td>
<td>325</td>
<td>299</td>
<td>273</td>
<td>255</td>
<td>247</td>
<td>237</td>
<td>232</td>
<td>227</td>
<td>223</td>
<td>219</td>
<td>477</td>
</tr>
<tr>
<td>-8</td>
<td>914</td>
<td>503</td>
<td>437</td>
<td>379</td>
<td>350</td>
<td>324</td>
<td>297</td>
<td>279</td>
<td>265</td>
<td>255</td>
<td>249</td>
<td>239</td>
<td>235</td>
<td>228</td>
<td>477</td>
</tr>
</tbody>
</table>
VOC Factors – Speed, Grade, and Veh. Class

Example.
A highway section consists of two segments A and B that have the following characteristics:

<table>
<thead>
<tr>
<th></th>
<th>Segment A</th>
<th>Segment B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Volume (ADT)</td>
<td>5,320</td>
<td>8,580</td>
</tr>
<tr>
<td>Average Grade (%)</td>
<td>$+4.0$</td>
<td>$+1.5$</td>
</tr>
<tr>
<td>Speed (mph)</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Length (miles)</td>
<td>5.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Directional Split</td>
<td>68% on upward slope</td>
<td>45% on upward slope</td>
</tr>
<tr>
<td></td>
<td>32% on downward slope</td>
<td>55% on downward slope</td>
</tr>
</tbody>
</table>

Determine the total vehicle operating costs for each segment. Assume all vehicles are medium automobiles, and further assume that the values in the Zaniewski Table (on previous slide) reflect current fuel consumptions rates.
VOC Factors – Speed, Grade, and Veh. Class

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

**Segment A:**

Unit VOC = (319 * 0.68 + 227 * 0.32) = $289.56 per 1000VMT  
VMT = 5.7 * 5,320 = 30,324 vehicle-miles daily  
Therefore, overall VOC = $289.56 * 30,324 = $8,781/day

**Segment B:**

Unit VOC = (292 * 0.45 + 232 * 0.55) = $259 per 1000VMT  
VMT = 2.6 * 8,580 = 22,308 vehicle-miles daily  
Overall vehicle operating cost = 259 * 22,308 = $5,778/day
VOC Factors – Delay

Nodes and links in the networks of various transportation modes may often experience delay

Travel Delay
- higher vehicle operating costs
- user inconvenience
- frustration

Higher delay, higher cost of some VOC components (fuel and shipping inventory)

How does it happen?
- decelerating to a stop
- idling
- accelerating from a stopped position (stop-and-go traffic, etc.)

Lead to additional strain on vehicle
Higher strain ->
Greater use of fuel & oil
VOC Factors – Delay

How to Estimate “Delay” Impacts on Fuel VOC

The impacts of travel delay on fuel cost can be estimated using AASHTO (2003) methodology.

Find delay with and without the transportation intervention using field measurements (for the existing situation), simulation, or analytical delay models.

Change in delay = delay without intervention - delay with intervention

Total cost of delay = Change in delay * fuel consumption rates * Unit price of fuel

Repeat for each vehicle class.

Example calculations on next slide
## VOC Factors – Delay

### Table 7-5

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

<table>
<thead>
<tr>
<th>Free Flow Speed</th>
<th>Small Automobile</th>
<th>Large Automobile</th>
<th>SUV</th>
<th>2-Axle Single Unit Truck</th>
<th>3-Axle Single Unit Truck</th>
<th>Multiple Unit Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.011</td>
<td>0.022</td>
<td>0.023</td>
<td>0.074</td>
<td>0.102</td>
<td>0.198</td>
</tr>
<tr>
<td>25</td>
<td>0.013</td>
<td>0.026</td>
<td>0.027</td>
<td>0.097</td>
<td>0.133</td>
<td>0.242</td>
</tr>
<tr>
<td>30</td>
<td>0.015</td>
<td>0.030</td>
<td>0.032</td>
<td>0.122</td>
<td>0.167</td>
<td>0.284</td>
</tr>
<tr>
<td>35</td>
<td>0.018</td>
<td>0.034</td>
<td>0.037</td>
<td>0.149</td>
<td>0.203</td>
<td>0.327</td>
</tr>
<tr>
<td>40</td>
<td>0.021</td>
<td>0.038</td>
<td>0.043</td>
<td>0.177</td>
<td>0.241</td>
<td>0.369</td>
</tr>
<tr>
<td>45</td>
<td>0.025</td>
<td>0.043</td>
<td>0.049</td>
<td>0.206</td>
<td>0.280</td>
<td>0.411</td>
</tr>
<tr>
<td>50</td>
<td>0.028</td>
<td>0.048</td>
<td>0.057</td>
<td>0.235</td>
<td>0.321</td>
<td>0.453</td>
</tr>
<tr>
<td>55</td>
<td>0.032</td>
<td>0.054</td>
<td>0.065</td>
<td>0.266</td>
<td>0.362</td>
<td>0.495</td>
</tr>
<tr>
<td>60</td>
<td>0.037</td>
<td>0.060</td>
<td>0.073</td>
<td>0.297</td>
<td>0.404</td>
<td>0.537</td>
</tr>
<tr>
<td>65</td>
<td>0.042</td>
<td>0.066</td>
<td>0.083</td>
<td>0.328</td>
<td>0.447</td>
<td>0.578</td>
</tr>
<tr>
<td>70</td>
<td>0.047</td>
<td>0.073</td>
<td>0.094</td>
<td>0.360</td>
<td>0.490</td>
<td>0.620</td>
</tr>
<tr>
<td>75</td>
<td>0.053</td>
<td>0.080</td>
<td>0.105</td>
<td>0.392</td>
<td>0.534</td>
<td>0.661</td>
</tr>
</tbody>
</table>
VOC Factors – Delay

Example for Fuel Costs

<table>
<thead>
<tr>
<th>Traffic Volume (vpd)</th>
<th>Small Auto</th>
<th>Large Auto</th>
<th>SUV</th>
<th>2-Axle Single Unit Truck</th>
<th>3-Axle Single Unit Truck</th>
<th>Multiple Unit Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>1075</td>
<td>1290</td>
<td>1075</td>
<td>430</td>
<td>215</td>
<td>215</td>
</tr>
<tr>
<td>Fuel Consumption Rate (gals/min)</td>
<td>(b)</td>
<td>0.025</td>
<td>0.043</td>
<td>0.049</td>
<td>0.206</td>
<td>0.280</td>
</tr>
<tr>
<td>(c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Price ($/gal)</td>
<td>(c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$2.2</td>
</tr>
<tr>
<td>Change in Delay due to the Improvement ($D_b - D_h$)</td>
<td>(d)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9 minutes</td>
</tr>
<tr>
<td>Change in Fuel Consumption Costs</td>
<td>(e)</td>
<td>$532</td>
<td>$1098</td>
<td>$1043</td>
<td>$1754</td>
<td>$1192</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$7369</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Therefore, fuel savings due to the transportation improvement = $7,369 per day
VOC Factors – Delay

Calculation Methods for Inventory Costs

- If \( \Delta D \) = Change in delay (in minutes),
- And if \( I(D) \) = inventory costs (cents per vehicle-minute)

\[
= 100 \times \frac{r}{365 \times 24 \times 60} \times P
\]

- Therefore, for each shipping vehicle:
  Change in inventory cost due to a change in delay
  \[
  = I(D) \times \Delta D
  \]

- For \( N \) shipping vehicles per day:
  Change in inventory cost due to a change in delay
  \[
  = I(D) \times \Delta D \times N \text{ per day}
  \]

\( r \) = interest rate (per annum)
\( P \) = dollar value of cargo being transported by the shipping vehicle
VOC Factors – Delay

Example
A freeway project led to a 45-minute reduction in travel delay per trip for shippers involved in transporting goods across the city.

The traffic stream consists of 82,500 vpd of which 22% are trucks.

The average value of cargo is $265,000 per truck and the interest rate is 6%.

Determine:
(i) the reduction in shipping inventory costs due to the improvement
(ii) the user benefits accrued to shippers after the improvement project compared to the before improvement conditions.

Assume that there was 10% increase in traffic of similar trucks due to induced demand.
VOC Factors – Delay

\[ I(D) = 100 \times \frac{r}{365 \times 24 \times 60} \times P = 100 \cdot \frac{0.06}{365(24)60} \cdot 265,000 = 3.025 \text{ c/veh-mile} \]

\[ \Delta D = 45 \text{ minutes} \]
Change in inventory costs = \( I(D) \times \Delta D = 3.025 \times (45) = 136.13 \text{ c/veh} \)

(ii) Number of trucks per year = \( 0.22 \times 82,500 \times 365 = 6,624,750 \)

Therefore, \( \text{VMT}_1 = 6,624,750 \times \text{length of freeway} \);

\( \text{VMT}_2 = 1.1 \times 6,624,750 \times \text{length of freeway} \)

User benefits per year = \( 0.5(U_1 - U_2)(VMT_1 + VMT_2) \)

\[ = 0.5(136.13/100)(2.1 \times 6,624,750) \]

\[ = $9,469,185.78 \text{ per mile} \]
VOC Factors – Speed Changes

- Vehicle speed changes due to geometric & traffic conditions.
- Vehicles slow down or pickup speed → experience additional strain → higher use of fuel and oil.
- Higher frequency of speed changes → higher VOC (fuel).
- Transportation interventions that smoothen traffic flow by reducing the frequency and intensity of speed changes ultimately yield reduced costs of vehicle operation.
- Extremes
  - City Driving: greater frequency of speed changes
  - Highway Driving: lower frequency of speed changes
VOC Factors – Speed Changes

Models to Estimate VOC due to Speed Change Frequency

(1) The Barnes and Longworthy Model

(Percent Decrease in VOC from City to Highway Driving Conditions)

<table>
<thead>
<tr>
<th>VOC Component</th>
<th>Automobile</th>
<th>Pick-up/Van/SUV</th>
<th>Commercial Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>29%</td>
<td>23%</td>
<td>24%</td>
</tr>
<tr>
<td>Maintenance/Repair</td>
<td>16%</td>
<td>14%</td>
<td>13%</td>
</tr>
<tr>
<td>Tires</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Depreciation</td>
<td>16%</td>
<td>14%</td>
<td>13%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>20%</strong></td>
<td><strong>17%</strong></td>
<td><strong>18%</strong></td>
</tr>
</tbody>
</table>
VOC Factors – Speed Changes

Models to Estimate VOC due to Speed Change Frequency

(2) FHWA’S HERS Model

- Provides equations to estimate VOC due to speed-change (Appendix 7-1)
- Equations are for each VOC component
- Equations are also for vehicle class
- VOC here covers five VOC components (fuel, oil, tires, maintenance and repair, and vehicle depreciation).
- Template for computations at Table 7-7.
VOC Factors – Horizontal Curves

- Vehicle negotiating horizontal curve requires extra energy to counter centrifugal forces to stay in radial rather than tangential path.
- Also, side friction increases tire wear-and-tear and frequency and cost of maintenance and replacement.
- VOC due to curve negotiation \(\rightarrow\) fuel, tire, and maintenance/repair,
- Expressed as:

\[
\text{Rate of consumption of component } i \times \text{unit price of component } i
\]

- VOC due to curves a function of vehicle type and average speed.
- In HERS methodology:
  - High speed sections (> 55mph): VOC calculated using the rate of consumption of VOC component for curve sections, by vehicle class, the unit prices of VOC components, adjustment factor for VOC component.
VOC Factors – Road Surface Condition

- **Pavement condition**
  - often overlooked as a VOC factor
  - Often measured in terms of Present Serviceability Rating (PSR), or International Roughness Index (IRI)

- **Motion of vehicle tires on a poor pavement surface is associated with:**
  - bumpy ride which leads to increased vibration and wear-and-tear of vehicle parts
  - greater resistance to movement → leads to higher levels of fuel consumption compared to smooth surface
  - drivers being forced to drive at lower speeds leading to higher fuel consumption.

- **Pavement condition therefore affects the following VOC components**
  - maintenance and repair
  - depreciation
  - fuel

- **Transportation projects such as resurfacing that improve pavement surfaces**
  → reductions in VOCs caused by pavement roughness
VOC Factors – Road Surface Condition

Some Prominent Research Studies:

- The Texas Research and Development Foundation (1982) study
- New Zealand study (Opus, 1999)
- Recent studies by Papagiannakis and Delwar (2001)
- Barnes and Langworthy (2003)
VOC Factors – Road Surface Condition

VOC Adjustments for Pavement Roughness Levels

\[ m = 0.001((\text{IRI}-80)/10)^2 + 0.018((\text{IRI}-80)/10) + 0.9991 \]
VOC Factors – Road Surface Condition

The Barnes and Langworthy (2003) Model

Percent Decrease in VOC from Poor to Good Pavement Condition

<table>
<thead>
<tr>
<th>VOC Component</th>
<th>Automobile</th>
<th>Pick-up/Van/SUV</th>
<th>Commercial Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Maintenance/Repair</td>
<td>20%</td>
<td>21%</td>
<td>20%</td>
</tr>
<tr>
<td>Tires</td>
<td>18%</td>
<td>17%</td>
<td>20%</td>
</tr>
<tr>
<td>Depreciation</td>
<td>21%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>15%</td>
<td>13%</td>
<td>11%</td>
</tr>
</tbody>
</table>

*Good pavement – PSI = 3.5 or above, that is, IRI = 85 or below*
*Poor Pavement – 2.5 or below, that is, IRI = 170 or above*
*Highway driving (not city driving) assumed for both cases.*
VOC Factors – Road Surface Condition

Example

A highway pavement section had 2.5 PSI and a total VOC of $152/1000VMT for automobiles. After a resurfacing project, the pavement PSI increased to 3.7.

Estimate the new VOC for automobiles only.

Solution

From the Table (7.7), the average adjustment in VOC upon pavement improvement from poor to good condition is a 15% reduction.

That is, due to the pavement improvement, the new VOC is $0.85\times152 = $129.2$ for every 1,000VMT.
PROCEDURAL FRAMEWORK FOR ASSESSING VOC IMPACTS
PROCEDURAL FRAMEWORK FOR ASSESSING VOC IMPACTS

The framework for assessing VOC impacts of transportation interventions revolves around three tasks:

- estimating the unit VOC rates (i.e., $/veh-mile) with and without the intervention
- estimating the amounts of travel (VMT) before and after the intervention
- calculating the user VOC benefits of the intervention

Expanded framework (diagram) is provided in next slide.
PROCEDURAL FRAMEWORK

**VOC Impacts**

1. Define the Analysis Area
2. Consider the Base Case Scenario
3. Describe the Transp. Intervention

**Step 7**
- Determine Section Length

**Step 8**
- Estimate Travel Demand (AADT) (see Chapter 3)

**Step 9**
- Estimate VMT for the Project Section
  \[
  VMT = \text{Length} \times \text{AADT}
  \]

**Step 4**
- Estimate/Predict “Base Case” Values of Average Speeds, Grades, Facility Condition, and other relevant VOC Factors

**Step 5**
- Select Appropriate Models or Look-up Tables for unit VOC rates
  \[
  \text{Unit VOC} = f(\text{Average Speed, Grade, Curve, Speed Change, Pavement Condition, etc.})
  \]

**Step 6**
- Establish Unit VOC Rates, VOC ($ per vehicle-mile)

**Step 10**
- Repeat Steps 4-9 for the Improvement Scenario, thereby establishing:
  - Unit VOC Rate with and without improvement: \(U_1, U_2\)
  - VMT before and after improvement: \(VMT_1, VMT_2\)

**Step 11**
- Determine Overall VOC Benefits due to the Intervention
  \[
  0.5 \times (\text{VOC}_1 - \text{VOC}_2) \times (VMT_2 + VMT_1)
  \]
What have we seen?

- VOC Components are many
- VOC Factors are many
- Analysis must be done for each of many vehicle classes
- Thus VOC Estimation can be cumbersome
  - Use of software is helpful
VOC Estimation Software

- HERS Package – National and State Versions
- HDM-4 Road User Effects (HDM-RUE)
- STEAM (Surface Transportation Efficiency Analysis Model)
- Other Models that Include a VOC Estimation Component
  - Model Cal-B/C
  - MicroBENCOST
Questions?