Some motivation…

- For those of us under age 35, driving’s the most **dangerous** thing we do.
- U.S. traffic **crashes claim $200 billion** every year. (Travel **delays claim $100 billion**.)
- U.S. agencies spend **$200 million** every **day** constructing, fixing & improving our roads.
- Roughly **30% of city land** is devoted to serving our vehicles.
- Over an **hour of car travel a day** has become the national norm. (And much of that is delay time.)
- “This isn’t love; it’s **addiction**.” (K. Alvord)

**Pair Up for Introductions!**

Information to present to class…

- **Name**
- **Hometown**
- What you are **most interested in learning** about in this class?
CE367 Lessons 1-5
Intro., Design Vehicles, Drivers, Traffic & Speeds, Sight Distances

KEY NOTATION (1)

• \( v \) & \( u \) = Speed in any units (but must be consistent with units of other variables in eqn.)
• \( V \) = Speed in mi/hr (mph)
• \( G \) = Grade (may be a fraction or a %, + or –; careful with this one!) = \( \tan(\gamma) \)
• \( e \) = Superelevation rate = Cross-slope/banking, as a fraction (unlike grade) = \( \tan(\alpha) \)
• \( t_r \) = Total response time (secs., typically)
• \( S \) = Sight distance needed (may be SSD or PSD…)

KEY NOTATION (2)

• \( HC \) & \( VC \) = Horiz. & Vertical Curves
• \( PI \) = Point of Intersection of 2 HC tangents
• \( PC \) & \( PT \) = Points of Curvature & Tangency
• \( T \) = Tangent lengths (from PC or PT to the PI)
• \( L \) = Length of circular arc
• \( LC \) = Long Chord distance (straight from PC to PT)
• \( \Delta \) = Subtended angle of HC
• \( M \) & \( E \) = Middle ordinate & external distances on HC
KEY NOTATION (3)

- \( L_r \) = Runoff length = Development length (for warping pavement, to develop superelevation)
- \( L_t \) = Runout length (to warp from NC to 0%)
- \( \Delta_{edge} \) = Edge slope of pavement rotation/warping
- \( h_w \) = Adjustment factor for #lanes rotated (to achieve banking)
- \( L_s \) = Spiral length (= \( L_r \) if using this spiral to introduce banked simple curve)

INTRODUCTION

Lesson 1’s Objectives…

- Become familiar with the Course Contents & general requirements.
- Understand the Course Objectives.
- Recognize sources of Standards for Roadway Design.

COURSE OBJECTIVES

- Design of Safe & Efficient roadways.
- Comfort with Computer-Aided Highway Design Software.
SAFETY requires consideration of:

- Driver *response* times,
- Sight distances & stopping/*braking* abilities,
- Sight distances for *passing* on two-lane roads,
- And what else? (Please pair up & list 5-10.)

ROADWAY DESIGN – in a nutshell 😊

<table>
<thead>
<tr>
<th>CRITERIA:</th>
<th>TOPICS:</th>
<th>TOOLS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety*</td>
<td>Sight Distances</td>
<td>Geometry</td>
</tr>
<tr>
<td>Cost*</td>
<td>Horiz Curves</td>
<td>Physics &amp; Calculus</td>
</tr>
<tr>
<td>Speed/Delay</td>
<td>Vertical Curves</td>
<td>Computers &amp; CAD</td>
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<tr>
<td>Comfort</td>
<td>Cross-sections</td>
<td>Experiments,</td>
</tr>
<tr>
<td>Equity</td>
<td>Intersections</td>
<td>Data &amp; Statistics</td>
</tr>
<tr>
<td>Environment</td>
<td>Operations</td>
<td>Eng’g Economy</td>
</tr>
<tr>
<td>Aesthetics …</td>
<td>Other Travelers</td>
<td>Hydraulics …</td>
</tr>
<tr>
<td>* also Topics</td>
<td>Drainage …</td>
<td></td>
</tr>
</tbody>
</table>

Q: What are the *connections* between criteria, topics, & tools?

Safety + EFFICIENCY require…

OPTIMIZATION & TRADE-OFFS

What are some *examples* of such trade-offs?

Design manuals help us make these tradeoffs…
DESIGN GUIDELINES & STANDARDS

The GREEN BOOK
• AASHTO’s A Policy on Geometric Design of Highways & Streets, 2004
• Produced by Committee & augmented by State DOTs

HCM
• The Transportation Research Board’s Highway Capacity Manual, 2000
• Also by Committee

Operation & Service Levels of Roadways

MUTCD
• Institute of Transp. Engineers’ (ITE) Manual on Uniform Traffic Control Devices
• Signage, marking, & signals – appearance & siting

Coming soon: AASHTO’s Highway Safety Manual!

COMPUTER-AIDED HIGHWAY DESIGN

MicroStation:
• Typical CADrafting Software

GEOPAK:
• Highway-Design Software: Runs “on top” of MS
• Coordinate Geometry + Horizontal Alignment
• Vertical Profile & Superelevation Design
• Intersection Design & Truck-Tracking Templates
• D&C Manager → Earthwork & Other Quantities
• 3-D Terrain Mapping → Drive-Through Design

HIGHWAY FUNCTIONS & DESIGN VEHICLES

Lesson 2’s Objectives …
• Classify roadways by movement type & functional class.
• Define critical features of design vehicles.
• Quantify tracking characteristics of turning vehicles.
Network Classification:
6 Movement Types

- **Primary** Movement (freeways & expressways)
- **Transition** (ramps & connectors)
- **Distribution** (minor arterials)
- **Collection** (penetrate neighborhoods)
- **Access** (local streets)
- **Termination** (driveways)

Network Classification:
4 Functional Categories

- Principal **Arterials** (Freeways & major roadways, even Lamar) ≈ 45% VMT
- Minor Arterials (ex: Guadalupe) ≈ 20% VMT
- Major & Minor **Collectors** (ex: Exposition) ≈ 20% VMT
- **Local** Roads & Streets ≈ 15% VMT

** Note the *trade-offs* in speed vs. access. **

**Ch. 2: DESIGN CONTROLS & CRITERIA**

- The “Design Vehicle” Concept
- Driver Performance/Behavior & Abilities
- Traffic Characteristics & Flow Behavior

The “**Design Vehicle**” Concept:

- Design Vehicles = *Hypothetical*, composite vehicles with *critical dimensions, weights, & operating characteristics.*
General Vehicle Classes
(& almost 20 types total):

• Passenger Vehicles ($P = PCs + LDTs$)

• Trucks ($HDTs = SU + WB$)

• Buses ($BUS & A-BUS$), RVs ($MH, P/T, P/B, MH/B$), Tractor ($TR$)

Questions:

?: Are design vehicles larger or smaller than the common vehicle in their class?

?: Are their turning radii larger or smaller?

?: Are their stopping distances longer or shorter?

?: What are ~12+ Critical Measurements for safe design?

→ Critical (Maximum) Height ~ 13.5’

→ Critical Width ~ 8.5’

[& 6.9’ for $P_s$]

Exh. 2-2 to 2-23:

MINIMUM TURNING RADII & PATHS of design vehicles.

Exhibit 2-3:
Passenger Car Design-Vehicle ($P$)
Minimum Turning Paths (cont’d)

- **WB-50** = typical critical vehicle for *local roads*
- “Minimum turn radii” are to *front outside tire*, traveling slowly.

**Recall:** What are the *critical points* on a turning vehicle (i.e., the most outer & inner points)?

---

**Supplementary Topic**

**Heavy-Duty Vehicles (HDVs):**

*Truck safety* is particularly difficult to design for. ...
Truck Offtracking & Swept Path Widths

Source(s): ITE (1992), Adapted from FHWA (1990)

Truck Offtracking for Various Turn Radii & Angles

Source(s): ITE (1992), Adapted from FHWA (1990)

Additional HDV Design Issues:

- **Offtracking**: 2' to 23' for $R = 300'$ to 50'
curves of $\Delta = 60^\circ$-$120^\circ$

- **Rollover**: Common at 0.3g (vs. 1.2g for PCs)
  $\rightarrow$ Much more likely

- **Skid**: More likely than PCs, at same speed.

- **Braking**: ABS reduces needs by ~50% (!)

- Acceleration & Speed Maintenance on Grades
So what is a WB-50?

Vehicle Speeds at impending Skid or Rollover on HCs

Source(s): ITE (1992), Adapted from FHWA (1990)

In Summary: What have we learned?

• What two features (arguably) most distinguish roadway types?

• What key features define design vehicles?

Extra: What sorts of critical situations are sufficiently common that we must design for them?
Every driver differs…

Example: Variation in total stopping distances, for drivers & their vehicles…

ANIMATION!!!
DRIVER RESPONSE TIME

Total Response Time \( t_r \) = \( P + I + J + R \) Times
= ?? + ?? + ?? + ??

Braking Response-Time study results:

Average \( t_r \approx ?? \) secs.,
Max(\( t_r \)) = ?? secs. – when info. expected

vs. ?? secs. – when unexpected

Often design for 85th - 95th worst case:

Design Standards: \( t_r = 2.5 \) s on highways (& adequate for > 90% of drivers) & 1.5 s (urban streets)

Designing for Most Drivers:

• In designing roadways, we typically design for 85th or 95th “worst” case.

• Why don’t we design for 100% of cases?

EXTRA SLIDES: Standard Normal’s Cumulative Probability Function

→ Cumulative Probability Values (\( P \)) Corresponding to Random Value Limit (\( z_p \)) for the Standard Normal Curve

Notes:
1. \( P = \) Prob(\( Z \leq z_p \)), where \( Z \) follows a standard normal distribution; i.e., \( Z \sim N(0,1) \)
2. If \( X \sim N(\mu, \sigma) \), then “\( Z = (X - \mu) / \sigma \) ~ N(0,1)"
3. Prob(\( Z \leq z_p \)) = Prob(\( Z \leq -z_p \)) + T

Example: Prob(\( Z \leq -1.62 \)) = 1 - Prob(Z ≤ 1.62) = 1 - .9474 = 0.0526

Note: 95% of the distribution lies within 2 standard devs. of the mean. 68% lies within 1 std. deviation.
Traffic Control Devices (TCDs)...

... make driving more safe by informing drivers – & thereby moderating behavior.

**Questions:**
- What are at least 9 different TCDs?
- What is the MUTCD, & what does it specify?

Driving is Complicated!

Good design (incl. traffic control devices) is critical.
TRAFFIC: SPEED & FLOW

Lesson 4’s Objectives …
• Recognize the relationship between speed, flow, & density.
• Quantify typical design speeds & capacity values for different highways.

Characterizing Traffic Conditions…
• Speed “v” or “u” or “V” = [mi/hr]
• Flow/Volume “q” = [veh/hr] or [vph]
• Density “k” = [??]
?: What is the trivariate relation between these?

Note: AADT = Average Annualized Daily Traffic (vpd)

Characterizing Speeds…
• Design Speed (v_d) = ?
• BFFS & FFS = ?
• Posted Speed Limit = ?

* Also, one may hear of Running speed, Critical speed, Spot speed, Time-mean speed, Space-mean speed, & Operating speed... (phew!)
Typical Design Speeds ($v_d$)

- 70-75 mph: Principal Arterials
- 50-70 mph: Elevated & depressed Freeways
- 30-60 mph: Minor Arterials

?: Choice of $v_d$ \(\rightarrow\) Affects what sight distance needs?

Characterizing Supply…

- In general, many design so supply > demand.
- Capacity means maximum supply.
- Under ideal conditions, Capacity is approx.:
  - \(？\) pcp/hpl on divided freeways
  - \(？\) pcp/hpl on two-lane highways
  - \(？\) pcp/hpl at signalized intersections

?: If demand exceeds capacity, what happens?
?: What roadway characteristics determine highway capacity? (Lessons 21?)

In Summary… (Lessons 3 & 4)

- Drivers must perform many tasks; some are more capable than others.
- Roadway designers must be very attuned to driver & vehicle abilities.
- Design speeds must be selected carefully.
- Roadway capacity is highly related to design & must be compared to demand.
SIGHT DISTANCES

Lesson 5’s Objectives …

• List different sight distance needs on roadways.
• Compute stopping sight distances for different conditions.
• Determine passing sight distances for different speeds.
• Know table to consult for decision sight distances.

?: Have you ever been in a situation where sight distance was inadequate?

Chapter 3: ELEMENTS OF DESIGN

✓ Sight Distances ← Today’s Topic
✓ Horizontal Alignment (lessons 6-8)
✓ Vertical Alignment (lessons 9 & 10)

?: What sorts of things limit sight distances?
(to solve in pairs)

SAFE SIGHT DISTANCES:
Stopping, Passing, & Decision-making

• Drivers should always be able to see any unexpected & dangerous obstacles in their paths with sufficient time to be able to respond & stop before colliding.
• Two-way two-lane highways also require frequent passing opportunities.
• Complex driving situations require space/time to make decisions.

?: If there’s not enough sight distance, what MUST drivers do to stay safe?
1. Stopping Sight Distance (\(d_{ss}\) or “SSD”)

\[ d_{ss} = \text{Composed of what 2 distances?} \]

\[
d_{ss} = (v_{f,\text{response}}) + \left( v_{f,\text{stop}} + \frac{1}{2}at_{\text{stop}} \right) = v_{f,\text{response}} - \frac{v_f^2}{2a},
\]

if "a" is CONSTANT & units are consistent.

- \(t_{\text{response}} = ??? \) secs. (assumed in AASHTO’s Exh. 3-1)
- Deceleration rate “a” depends on what?

BRAKING DISTANCE: Free-Body Diagram

\[ \sum F_x = mg \sin(\phi) - f mg \cos(\phi) = ma_x \]

Note: \(d_{\text{brake}}\) = measured HORIZONTALLY

REVIEW: TRAVELER TRAJECTORIES

Distance-Speed-Acceleration:
\[
\begin{align*}
x(t) &= \text{location at time } t \\
v(t) &= \text{velocity at time } t \\
a(t) &= \text{acceleration at time } t \\
a(t) &= \ddot{x}(t) = \frac{d^2x}{dt^2} = \dot{v}(t) = v'(t) \\
v(t) &= \frac{dx}{dt} = x'(t) = \dot{x}(t) \\
x(t) &= \int v(x)dx + x_c = \int \int a(x)dx dx + x_c + v_c t
\end{align*}
\]

Take-Home Example Problem 1: If acceleration \([\text{ft/s}^2]\) equals 10 \(t\) \((\text{where } t-[\text{s}])\) & initial speed is 55 mph, what’s the distance traveled in the first 5 s of travel? (Answer: 612 ft.)
Example Problem 2:
How long & how far does it take a car going 70 mph to stop, given it decelerates with \( a(t) = -0.01 + 0.0005t \) [mi/s^2]?

What if acceleration can be assumed constant?

**General Braking Distance Formula:**

\[
d_{\text{b, horizontal}} = \frac{v_i^2 - v_f^2}{2g(f + G)} = \frac{v_i^2 - v_f^2}{2(a_i + gG)}
\]

where \( v_i \) & \( v_f \) = initial & final speeds (horiz.),
\( g \) = gravitational constant [32.2 ft/sec^2],
\( a_i = \) braking deceleration [e.g., +11.2 ft/sec^2]
\( f = \) friction coefficient, &
\( G = \tan(\gamma) = \%\text{grade}/100 \) (can be < 0).

?: Derive this equation (for HW). (*Careful with slope.*)

AASHTO 2004 Stopping Distance Formulae:

\[
d_s = SSD = 1.47V_f t_r + \frac{V_f^2}{30\left(\frac{a_s}{32.2} \pm G\right)} \quad \text{[ENGLISH]}
\]

where \( d = \) [ft], \( V_f = \) [mph], \( a = \) [ft/sec^2];
\( a_s = \) assumed to be +11.2 ft/sec^2 [+3.4 m/sec^2];
\( t_r = \) assumed to be 2.5 sec for braking response.

?: Does this equation assume anything else?
Example Problems:

• What is the total stopping distance needed by someone driving at 35 mph on a downhill grade of 5%, who requires only 1.5 s to react to an emergency & who brakes at an average rate of –13 ft/sec^2?

• What would AASHTO standard design practice call for here?

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Reaction Distance ft</th>
<th>Braking Distance on Level</th>
<th>Stopping Sight Distance Calculated (ft)</th>
<th>Design (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>35.1</td>
<td>21.6</td>
<td>76.7</td>
<td>80</td>
</tr>
<tr>
<td>20</td>
<td>47.0</td>
<td>31.2</td>
<td>111.9</td>
<td>115</td>
</tr>
<tr>
<td>25</td>
<td>59.9</td>
<td>40.6</td>
<td>141.9</td>
<td>155</td>
</tr>
<tr>
<td>30</td>
<td>73.5</td>
<td>50.0</td>
<td>176.5</td>
<td>200</td>
</tr>
<tr>
<td>35</td>
<td>88.1</td>
<td>60.6</td>
<td>211.7</td>
<td>250</td>
</tr>
<tr>
<td>40</td>
<td>103.6</td>
<td>70.3</td>
<td>246.9</td>
<td>305</td>
</tr>
<tr>
<td>45</td>
<td>119.1</td>
<td>80.6</td>
<td>282.7</td>
<td>355</td>
</tr>
<tr>
<td>50</td>
<td>135.7</td>
<td>90.6</td>
<td>318.3</td>
<td>405</td>
</tr>
<tr>
<td>55</td>
<td>152.2</td>
<td>100.0</td>
<td>354.9</td>
<td>455</td>
</tr>
<tr>
<td>60</td>
<td>169.8</td>
<td>110.3</td>
<td>391.5</td>
<td>505</td>
</tr>
<tr>
<td>65</td>
<td>187.4</td>
<td>120.6</td>
<td>429.1</td>
<td>555</td>
</tr>
<tr>
<td>70</td>
<td>205.1</td>
<td>130.6</td>
<td>466.6</td>
<td>605</td>
</tr>
<tr>
<td>75</td>
<td>222.7</td>
<td>140.6</td>
<td>504.2</td>
<td>655</td>
</tr>
<tr>
<td>80</td>
<td>240.4</td>
<td>150.6</td>
<td>541.8</td>
<td>705</td>
</tr>
</tbody>
</table>

Assumes response time of 2.5 secs & deceleration rate of 11.2 ft/s^2.

2. Passing Sight Distance (d_p or “PSD”)

• Without sufficient sight distance for passing, what happens to speeds, flows, & LOS on two-lane facilities?

• Are PSDs longer or shorter than SSDs?

• Must we always provide sufficient PSD?

• What do we do with road markings & signage when PSD does not exist?

• AASHTO d_p’s (Exh. 3-6 & 3-7) assume passing vehicle takes moment to perceive the (nearby) section as clear, travels 10 mph faster than overtaken vehicle, & leaves suitable clearance when returning to lane.
Passing Maneuver Distances (AASHTO 2001, p.119):

![First Phase](image1.png)
![Second Phase](image2.png)

Exhibit 3-4. Elements of Passing Sight Distance for Two-Lane Highways

PSD Components (Exh. 3-6, AASHTO 2001, p. 123):

![Exhibit 3-7](image3.png)

Exhibit 3-7. PSD
For Design of Two-Lane Highways (AASHTO 2001, p.124)

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Passed vehicle speed (mph)</th>
<th>Passing vehicle speed (mph)</th>
<th>Passing sight distance (ft) From Exhibit 3-6</th>
<th>Rounded for design</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>18</td>
<td>28</td>
<td>708</td>
<td>710</td>
</tr>
<tr>
<td>25</td>
<td>22</td>
<td>32</td>
<td>897</td>
<td>900</td>
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<td>30</td>
<td>26</td>
<td>36</td>
<td>1088</td>
<td>1090</td>
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<td>44</td>
<td>1470</td>
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<td>47</td>
<td>1625</td>
<td>1625</td>
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<td>50</td>
<td>41</td>
<td>51</td>
<td>1832</td>
<td>1835</td>
</tr>
<tr>
<td>55</td>
<td>44</td>
<td>54</td>
<td>1984</td>
<td>1985</td>
</tr>
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<td>60</td>
<td>47</td>
<td>57</td>
<td>2133</td>
<td>2135</td>
</tr>
<tr>
<td>65</td>
<td>50</td>
<td>60</td>
<td>2281</td>
<td>2285</td>
</tr>
<tr>
<td>70</td>
<td>54</td>
<td>64</td>
<td>2479</td>
<td>2480</td>
</tr>
</tbody>
</table>
Exh. 3-4: \[ d_p = d_1 + d_2 + d_3 + d_4 = f(v_d) \]

= what + what + what + what?

**Other Questions:**

?: Which of the four distances is longest?

?: Why is \( d_4 \) less than the distance the opposing traffic would traverse during all of \( d_1 \) & \( d_2 \)?

?: What are \( d_p \) & \( d_s \) for \( v_d = 30 \text{ mph} \)?

... And for \( v_d = 70 \text{ mph} \)?

3. Decision Sight Distances (DSDs)

- DSDs allow drivers to respond to complex information & choose a new, safe path or other maneuver.
- DSDs depend on \( v_d \) & the situation.

?: What are some examples of situations for checking DSD?

?: Are DSDs > \( d_s = SSD \)? (See Exhs. 3-3 & 3-1.)

---

**Exhibit 3-3. DSD**

(AASHTO 2004, p.116)

<table>
<thead>
<tr>
<th>Name</th>
<th>DSD (AASHTO 2004, p.116)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>DSD (ft)</td>
</tr>
<tr>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>60</td>
<td>95</td>
</tr>
<tr>
<td>70</td>
<td>115</td>
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<td>120</td>
<td>265</td>
</tr>
<tr>
<td>130</td>
<td>300</td>
</tr>
<tr>
<td>140</td>
<td>330</td>
</tr>
<tr>
<td>150</td>
<td>360</td>
</tr>
</tbody>
</table>

Aviation Maneuver A: Stop on main road—\( v = 20 \text{ mph} \)
Aviation Maneuver B: Stop on side road—\( v = 20 \text{ mph} \)
Aviation Maneuver C: Speed up to direction change on main road—\( v = 20 \text{ mph} \)
Aviation Maneuver D: Speed up to direction change on side road—\( v = 20 \text{ mph} \)
Aviation Maneuver E: Speed up to direction change on urban road—\( v = 20 \text{ mph} \)
**In Summary:** What have we learned?

- **What** sight distances **must** be provided & **where**?

- What are their **magnitudes**?

- What **must** we do **if we don’t provide** sufficient sight distance?