Chapter 1

Introduction to Highway Engineering and Traffic Analysis

Highways:

- Influence is economic, social and political
- Studied as a cultural, political and economic phenomenon.
Highway trends:

- Emphasis shifting from the construction of the mid-20th century (e.g., US Interstate system, the greatest Civil Engineering project of all time)

- Current focus:
  - Infrastructure maintenance and rehabilitation,
  - Improvements in operational efficiency,
  - Various traffic-congestion relief measures,
  - Energy conservation,
  - Improved safety and
  - Environmental mitigation.
1.2 Highways and the Economy

- 15% of household income spent on vehicles
- 16 million new vehicles sold in the US annually
- Vehicle industry $400 billion in vehicle sales
- 5 million jobs related to vehicle production and maintenance
- Highways strongly influence economic development
Elements of Highway Transportation

1.5.1 Passenger Transportation Modes and Traffic Congestion

- In the last 50 years, the percentage of trips taken in private vehicles has risen from slightly less than 70 percent to over 90 percent (public transit and other modes make up the balance)

- Over this same period, the average private-vehicle occupancy has dropped from 1.22 to 1.09 persons per vehicle

- Result: Massive traffic congestion that is difficult to manage
1.5.2 Highway Safety

- Highway safety involves technical and behavioral components and the complexities of the human/machine interface.

Vehicle Technologies

- Foreign competition and changing consumer tastes have propelled technological advances:
  - Supplemental restraint systems,
  - Anti-lock brake systems,
  - Traction control systems,
  - Electronic stability control
Such technologies directly influence highway design and traffic operations, and are critical considerations in providing high levels of mobility and safety.
1.6.3 Traffic Control Technologies

- New advances in traffic signal timing and traffic signal coordination

- New traffic signal controls, numerous safety, navigational, and congestion-mitigation technologies are now reaching the market under the broad heading of Intelligent Transportation Systems (ITS)

- Obstacles associated with ITS implementation include system reliability, human response and the human/machine interface
HIERARCHY IN TRANSPORTATION SYSTEMS

EXTERNALITIES:
- CONGESTION
- POLLUTION
- CONSTRUCTION
- ACCIDENTS

TRANSPORTATION MODES
Chapter 2

Road Vehicle Performance

Why is vehicle performance important?

- Determines all highway design and traffic operations
- Defines how transportation engineers must react to advancing vehicle technologies
- The single most important factor in defining the tradeoff between mobility (speed) and safety
2.2 TRACTIVE EFFORT AND RESISTANCE

- Tractive effort – force available to perform work (engine-generated)

- Resistance:

  - Aerodynamic
    - Drag, shape of vehicle, etc.

  - Rolling resistance
    - Tire, roadway surface

  - Grade (gravitational) resistance
Figure 2.1 Forces acting on a road vehicle.
2.3 AERODYNAMIC RESISTANCE

- Sources:
  - Turbulence around the body (85%)
  - Air friction (12%)
  - Air flow through components (3%)
Basic Formula:

\[ R_a = \frac{\rho}{2} C_D A_f V^2 \]  \hspace{1cm} (2.3)

Where:

- \( R_a \) = aerodynamic resistance in lb (N),
- \( \rho \) = air density in slugs/ft\(^3\) (kg/m\(^3\)),
- \( C_D \) = coefficient of drag and is unitless,
- \( A_f \) = frontal area of the vehicle (projected area of the vehicle in the direction of travel) in ft\(^2\) (m\(^2\)), and
- \( V \) = speed of the vehicle in ft/s (m/s).
Figure 2.2 Effect of operational factors on the drag coefficient of an automobile.
Power required to overcome air resistance:

**US Customary**

\[ hp_{Ra} = \frac{\rho C_D A_f V^3}{1100} \]

**Metric**

\[ P_{Ra} = \frac{\rho}{2} C_D A_f V^3 \]  \hspace{1cm} (2.4)

Where:

- \( hp_{Ra} \) = horsepower required to overcome aerodynamic resistance (1 horsepower equals 550 ft-lb/s),

- \( P_{Ra} \) = power required to overcome aerodynamic resistance in Nm/s (watts), and Other terms as defined previously.
2.4 ROLLING RESISTANCE

- Sources:
  - Tire deformation (90%)
  - Pavement penetration (4%)
  - Friction, other sources (6%)

- Factors influencing sources:
  - Tire inflation, temperature, speed
- Coefficient of rolling resistance:

\[
\begin{align*}
\text{US Customary} & : f_{rl} = 0.01\left(1 + \frac{V}{147}\right) \\
\text{Metric} & : f_{rl} = 0.01\left(1 + \frac{V}{44.73}\right) \quad (2.5)
\end{align*}
\]

Where:

\[f_{rl} = \text{coefficient of rolling resistance and is unit less, and}\]
\[V = \text{vehicle speed in ft/s (m/s)}.\]

- Rolling resistance, in lb (N), is coefficient of rolling resistance multiplied by \(W \cos \theta_s\), with small \(\theta_s\), \(\cos \theta_s = 1\):

\[
R_{rl} = f_{rl} \ W \quad (2.6)
\]
power required to overcome rolling resistance is:

\[
\text{US Customary} \quad \text{hp}_{\text{rl}} = \frac{f_{\text{rl}}WV}{550} \\
\text{Metric} \quad P_{R_{rl}} = f_{rl}WV \quad (2.7)
\]

Where:

\( \text{hp}_{\text{rl}} \) = horsepower required to overcome rolling resistance (1 horsepower equals 550 ft-lb/s),

\( P_{R_{rl}} \) = power required to overcome rolling resistance in Nm/s (watts), and

\( W \) = total vehicle weight in lb (N).
2.5 GRADE RESISTANCE

• From in Fig. 2.1, the resistance \((R_g)\) is

\[
R_g = W \sin \theta_g \quad (2.8)
\]

• With small highway grades \(\sin \theta_g \cong \tan \theta_g\). So,

\[
R_g \cong W \tan \theta_g = WG \quad (2.9)
\]

Where:

\(G = \) grade defined as the vertical rise per some specified horizontal distance in ft/ft (m/m).
2.6 AVAILABLE TRACTIVE EFFORT

- Force available to overcome resistance will be governed by engine or tire/pavement interface:

2.6.1 **Maximum Tractive Effort** – Tire/pavement interface

*Figure 2.3  Vehicle forces and moment-generating distances.*
In this figure,

\( F_f \) = available tractive effort of the front tires in lb (N),
\( F_r \) = available tractive effort of the rear tires in lb (N),
\( W \) = total vehicle weight in lb (N),
\( W_f \) = weight of the vehicle on the front axle in lb (N),
\( W_r \) = weight of the vehicle on the rear axle in lb (N),
\( \theta_g \) = angle of the grade in degrees,
\( m \) = vehicle mass in slugs (kg),
\( a \) = rate of acceleration in ft/s\(^2\) (m/s\(^2\)),
\( L \) = length of wheelbase,
\( h \) = height of the center of gravity above the roadway surface,
\( l_f \) = distance from the front axle to the center of gravity,
and
\( l_r \) = distance from the rear axle to the center of gravity.
- Summing moments gives, for Rear wheel drive:

\[ F_{\text{max}} = \frac{\mu W (l_f - f_{rl} h) / L}{1 - \mu h / L} \]  

(2.14)

- Summing moments gives, for Front wheel drive:

\[ F_{\text{max}} = \frac{\mu W (l_r + f_{rl} h) / L}{1 + \mu h / L} \]  

(2.15)

- \( \mu = \) coefficient of road adhesion
2.6.2 Engine Generated Tractive Effort

US Customary

\[ hp_e = \frac{2\pi M_e n_e}{550} \]

Metric

\[ P_e = \frac{2\pi M_e n_e}{1000} \]  \hspace{1cm} (2.16)

Where:

- \( hp_e \) = engine-generated horsepower (1 horsepower equals 550 ft-lb/s),
- \( P_e \) = engine-generated power in kW,
- \( M_e \) = engine torque in ft-lb (Nm), and
- \( n_e \) = engine speed in revolutions per second (the speed of the crankshaft).
Engine-generated tractive effort reaching the driving wheels \((F_e)\) is given as

\[
F_e = \frac{M_e \varepsilon_0 \eta_d}{r}
\]

(2.17)

Where:

\(F_e\) = engine-generated tractive effort reaching the driving wheels in lb \((N)\),

\(r\) = radius of the drive wheels in ft \((m)\),

\(M_e\) = engine torque in ft-lb \((Nm)\),

\(\varepsilon_0\) = overall gear reduction ratio, and

\(\eta_d\) = mechanical efficiency of the driveline \((0.75 \text{ to } 0.95)\).
• Relationship between vehicle speed and engine speed is

$$V = \frac{2\pi n_e (1 - i)}{\varepsilon_0}$$  \hspace{1cm} (2.18)

Where:

$V =$ vehicle speed in ft/s (m/s),

$n_e =$ crankshaft revolutions per second,

$i =$ slippage of the driveline, generally taken as 2 to 5% ($i = 0.02$ to 0.05) for passenger cars, and

Other terms as defined previously.
2.7 VEHICLE ACCELERATION

• Basic equation

\[ F - \sum R = \gamma_m ma \]  \hspace{1cm} (2.19)

• where the mass factor (rotational inertia) is approximated as

\[ \gamma_m = 1.04 + 0.0025 \varepsilon_0^2 \]  \hspace{1cm} (2.20)

• the force available to accelerate is

\[ F_{net} = F - \sum R. \]
2.8 FUEL EFFICIENCY

- Factors affecting fuel efficiency
  - Engine design
  - Driveline slippage
  - Driveline efficiency
  - Aerodynamics
  - Frontal area
  - Weight
  - Tire design
2.9 PRINCIPLES OF BRAKING

Figure 2.7 Forces acting on a vehicle during braking with driveline resistance ignored.
2.9.1 Braking Forces

Maximum braking (coefficient of road adhesion, $\mu$),

$$ F_{bf\ max} = \mu W_f $$

$$ = \frac{\mu W}{L} [l_r + h(\mu + f_{rl})] \quad (2.28) $$

and

$$ F_{br\ max} = \mu W_r $$

$$ = \frac{\mu W}{L} [l_f - h(\mu + f_{rl})] \quad (2.29) $$

- Maximum braking forces developed when tires are at the point of an impending slide.
2.9.2 Braking Force Ratio and Efficiency

• Front/rear proportioning of braking forces optimal when deceleration rate equal to $\mu g$.

• Occurs when brake force ratio is $F_{bf\ max}/F_{br\ max}$ or

$$BFR_{fr\ max} = \frac{l_r + h(\mu + f_{rl})}{l_f - h(\mu + f_{rl})} \quad (2.30)$$

• Problem:
  $l_r$ and $l_f$ change depending on deceleration rate.
• Percentage of braking force that the braking system should allocate to the front axle ($PBF_f$) and rear axle ($PBF_r$) for maximum braking is

$$PBF_f = 100 - \frac{100}{1+ BFR_{f/r \ max}}$$ \hspace{1cm} (2.31)

and

$$PBF_r = \frac{100}{1+ BFR_{f/r \ max}}$$ \hspace{1cm} (2.32)

$$\eta_b = \frac{g_{\ max}}{\mu}$$ \hspace{1cm} (2.33)
Where:

$$\eta_b = \text{braking efficiency,}$$

$$\mu = \text{coefficient of road adhesion, and}$$

$$g_{\text{max}} = \text{maximum deceleration in } g\text{-units (with the absolute maximum } = \mu).$$

### 2.9.4 Theoretical Stopping Distance

$$S = \frac{\gamma_b W}{2gK_a} \ln \left[ \frac{\mu W + K_a V_1^2 + f_{rl} W \pm W \sin \theta_g}{\mu W + K_a V_2^2 + f_{rl} W \pm W \sin \theta_g} \right]$$  \hspace{1cm} (2.39)

If the vehicle is assumed to stop ($V_2 = 0$) and including braking efficiency,
\[ S = \frac{\gamma_b W}{2 g K_a} \ln \left[ 1 + \frac{K_a V_1^2}{\eta_b \mu W + f_{rl} W \pm W \sin \theta_g} \right] \]  \hspace{1cm} (2.42)

- If aerodynamic resistance is ignored (due to its comparatively small contribution to braking),

\[ S = \frac{\gamma_b \left( V_1^2 - V_2^2 \right)}{2 g \left( \eta_b \mu + f_{rl} \pm \sin \theta_g \right)} \]  \hspace{1cm} (2.43)
2.9.5 Practical Stopping Distance

• Basic physics 101 equation,

\[ V_2^2 = V_1^2 + 2ad \]  \hspace{1cm} (2.44)

Where:

\[ d = \text{deceleration distance (practical stopping distance) in ft (m),} \]
\[ a = \text{acceleration (negative for deceleration) in ft/s}^2 \text{ (m/s}^2)\), \]
\[ V_1 = \text{initial vehicle speed in ft/s (m/s), and} \]
\[ V_2 = \text{final vehicle speed in ft/s (m/s).} \]
• AASHTO [2001] recommends a deceleration rate of 11.2 ft/s² (3.4 m/s²), so with grade and $V_2 = 0$:

$$d = \frac{V_1^2}{2 \ g \left(\left(\frac{a}{g}\right) \pm G\right)}$$

(2.47)

Where:

$g =$ gravitational constant, 32.2 ft/s² (9.807 m/s²),

$G =$ roadway grade (+ for uphill and – for downhill) in percent/100, and

Other terms as defined previously.

• AASHTO maximum deceleration of 0.35 $g$’s (11.2/32.2 or 3.4/9.807) is used for Eq. 2.47.
2.9.6 Distance Traveled During Driver Perception/Reaction

- In providing a driver sufficient stopping distance, Must consider distance traveled during perception/reaction:

\[ d_r = V_1 \times t_r \]  \hspace{1cm} (2.49)

Where:

- \( V_1 \) = initial vehicle speed in ft/s (m/s), and
- \( t_r \) = time required to perceive and react to the need to stop, in sec.
- Conservative perception/reaction time has been determined to be 2.5 seconds [AASHTO 2001].
- Average drivers have perception/reaction times of approximately 1.0 to 1.5 seconds.
- Total required stopping distance = theoretical or practical plus the distance traveled during perception/reaction,

\[ d_s = d_r + d \]  

(2.50)

Where:
- \( d_s \) = total stopping distance (including perception/reaction) in ft (m),
- \( d \) = distance traveled during braking in ft (m), and
- \( d_r \) = distance traveled during perception/reaction in ft (m).
Chapter 3

Geometric Design of Highways

Objective to design highways that are safe for:

- Wide variety of vehicle performance
- Wide variety of human performance
- Highway positioning defined by distance along a horizontal plane
Stationing - with a station being 100ft or 1km

If a point is 4250ft (1295.3m) from origin, it is station:

- $42 + 50$
- $1 + 295.300$

3.3 VERTICAL ALIGNMENT

- Equal tangent vertical curves
Figure 3.3 Types of vertical curves.
\[ G_1 = \text{initial roadway grade in percent or ft/ft (m/m) (this grade is also referred to as the initial tangent grade, viewing Fig. 3.3 from left to right)}, \]
\[ G_2 = \text{final roadway (tangent) grade in percent or ft/ft (m/m)}, \]
\[ A = \text{absolute value of the difference in grades (initial minus final, usually expressed in percent)}, \]
\[ PVC = \text{point of the vertical curve (the initial point of the curve)}, \]
\[ PVI = \text{point of vertical intersection (intersection of initial and final grades)}, \]
\[ PVT = \text{point of vertical tangent, which is the final point of the vertical curve (the point where the curve returns to the final grade or, equivalently, the final tangent)}, \] and
\[ L = \text{length of the curve in stations or ft (m) measured in a constant-elevation horizontal plane}. \]
At the PVC, \( x = 0 \), so, using Eq. 3.2,

\[
b = \frac{dy}{dx} = G_1
\]  \hspace{1cm} (3.3)

Equating Eqs. 3.4 and 3.5 gives

\[
a = \frac{G_2 - G_1}{2L}
\]  \hspace{1cm} (3.6)

Watch units for "a" and "b"

Additional equations:
Figure 3.4 Offsets for equal tangent vertical curves.

Referring to the elements shown in Fig. 3.4, the properties of an equal tangent parabola can be used to give
\[ Y = \frac{A}{200L} x^2 \]  

(3.7)

Where:
\( A = \) absolute value of the difference in grades (\(|G_1 - G_2|\)) expressed in percent, and

Other terms are as defined in Fig. 3.4.

Note that in this equation, 200 is used in the denominator instead of 2 because \( A \) is expressed in percent instead of ft/ft (m/m) (this division by 100 also applies to Eq. 3.8 and 3.9 below)

3.3.2 Stopping Sight Distance

\[
SSD = \frac{V_i^2}{2g \left( \left( \frac{a}{g} \right) \pm G \right)} + V_i \times t_r
\]

(3.12)

Where:
SSD = stopping sight distance in ft (m),

\[ a = \text{deceleration rate in } \text{ft/s}^2 (\text{m/s}^2), \]

\[ V_1 = \text{initial vehicle speed in } \text{ft/s} (\text{m/s}), \]

\[ g = \text{gravitational constant in } \text{ft/s}^2 (\text{m/s}^2), \]

\[ t_r = \text{perception/reaction time in sec}, \]

\[ G = \text{roadway grade (+ for uphill and – for downhill) in percent/100}. \]

With \( a = 11.2 \text{ ft/s}^2 (3.4 \text{ m/s}^2), \ t_r = 2.5 \text{s}, \) the application of Eq. 3.12 (assuming \( G = 0 \)) produces the stopping sight distances presented in Table 3.1.

### 3.3.3 Stopping Sight Distance and Crest Vertical Curve Design

The case of designing a crest vertical curve for adequate stopping sight distance is illustrated in Fig. 3.6.
Figure 3.6 Stopping sight distance considerations for crest vertical curves.
For $S < L$

$$L_m = \frac{AS^2}{200 \left(\sqrt{H_1} + \sqrt{H_2}\right)^2} \quad (3.13)$$
For \( S > L \)

\[
L_m = 2S - \frac{200(\sqrt{H_1} + \sqrt{H_2})^2}{A}
\]

(3.14)

**Where:**

\( L_m = \) minimum length of vertical curve in ft (m), and

Other terms are as defined in Fig. 3.6.
With $H_1, = 3.5 \text{ ft (1080 mm)}$ and $H_2, = 2.0 \text{ ft (600 mm)}$ (the height of an object to be avoided by stopping before a collision):

<table>
<thead>
<tr>
<th>US Customary</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>For SSD $&lt; L$</td>
<td>For SSD $&gt; L$</td>
</tr>
<tr>
<td>$L_m = \frac{A \times SSD^2}{2158}$</td>
<td>$L_m = \frac{A \times SSD^2}{658}$</td>
</tr>
<tr>
<td>$L_m = 2 \times SSD - \frac{2158}{A}$</td>
<td>$L_m = 2 \times SSD - \frac{658}{A}$</td>
</tr>
</tbody>
</table>

Where:

SSD = stopping sight distance in ft (m), and

$A =$ algebraic difference in grades in percent.
Where:

\[ K = \text{horizontal distance, in ft (m), required to affect a 1\% change in the slope (as in Eq. 3.10), and is defined as} \]

\[ K = \frac{SSD^2}{2158} \quad \text{US Customary} \]

\[ K = \frac{SSD^2}{658} \quad \text{Metric} \]

3.3.4 Stopping Sight Distance and Sag Vertical Curve Design
Figure 3.7 Stopping sight distance considerations for sag vertical curves.
In this figure,

\[ S = \quad \text{sight distance in ft (m)}, \]

\[ H = \quad \text{height of headlight in ft (m)}, \]

\[ \beta = \quad \text{inclined angle of headlight beam in degrees}, \]

\[ PVC = \quad \text{point of the vertical curve (the initial point of the curve)}, \]

\[ PVI = \quad \text{point of vertical intersection (intersection of initial and final grades)}, \]

\[ PVT = \quad \text{point of vertical tangent, which is the final point of the vertical curve (the point where the curve returns to the final grade or, equivalently, the final tangent), and} \]

\[ L = \quad \text{length of the curve in ft (m)}. \]
For $S < L$

$$L_m = \frac{AS^2}{200(H + S \tan \beta)} \quad (3.19)$$

For $S > L$

$$L_m = 2S - \frac{200(H + S \tan \beta)}{A} \quad (3.20)$$

Where:

$L_m =$ minimum length of vertical curve in ft (m), and

Other terms are as defined in Fig. 3.7.
With headlight height of 2.0 ft (600 mm) and an upward angle of 1 degree: