Basic Freeway Segments Worksheet
Level of Service (LOS)

Speed-Flow and Density Curves (see Exhibit 23-3 and Equation 23-4)
The functions defined here are only used to plot the Free-Flow Speed and Density curves of Exhibit 23-3. These curves are shown at the end of the worksheet.

Function to evaluate the Average Passenger-Car Speed \((SS)\) for different free-flow speeds. The arguments of the function are the flow rate \((vp)\) and the free-flow speed \((ffs)\). This function uses the equations shown in the notes of Exhibit 23-3.

\[
SS(vp, ffs) := \begin{cases} 
    ffs & \text{if } 0 \leq vp \leq (3400 - 30 \cdot ffs) \\
    ffs - \left( \frac{ffs - 160}{3} \right) \cdot \left( \frac{vp + 30 \cdot ffs - 3400}{30 \cdot ffs - 1000} \right)^{2.6} & \text{if } (3400 - 30 \cdot ffs) \leq vp \leq 2400 \\
    ffs & \text{otherwise} \\
    ffs - \left( \frac{1}{9} \cdot (7 \cdot ffs - 340) \cdot \left( \frac{vp + 30 \cdot ffs - 3400}{40 \cdot ffs - 1700} \right)^{2.6} \right) & \text{if } (3400 - 30 \cdot ffs) \leq vp \leq (1700 + 10 \cdot ffs)
\end{cases}
\]

Function to evaluate the Average Passenger-Car Speed \((ss)\) for different densities. The arguments of the function are the flow rate \((vp)\) and the density \((DD)\). This function uses the Equation 23-4.

\[
ss(vp, DD) := \frac{vp}{DD}
\]

Units definition
Definition of new units. In this case the unit for liters (L) is used, but any other units could be used.

\[
veh := \frac{L}{L} \quad pc := \frac{L}{L} \quad ln := \frac{L}{L} \quad l := \frac{L}{L}
\]

General Information
- Analyst: 
- Agency or Company: 
- Date Performed: 
- Analysis Time Period: 
- Type of analysis:  

Site Information
- Highway/Direction of Travel: 
- From/To: 
- Jurisdiction: 
- Analysis Year: 
- Freeway segment area:  

Flow Inputs
- Volume: \(V := 2000 \frac{veh}{hr}\) 
- Peak-hour factor: \(PHF := 0.92\)
The $ET$ matrices are the transpose of Exhibit 23-9. This is done in order to match the data of the matrices with the vector of percentage of trucks and buses (PTB).

Variables used in this section and not defined in HCM

- $ER23$: matrix of $E_R$ values for upgrades between 2% and 3%
- $ER34$: matrix of $E_R$ values for upgrades between 3% and 4%
- $ER45$: matrix of $E_R$ values for upgrades between 4% and 5%
- $ER5$: matrix of $E_R$ values for upgrades greater than 5%
- $ET23$: matrix of $E_T$ values for upgrades between 2% and 3%
- $ET34$: matrix of $E_T$ values for upgrades between 3% and 4%
- $ET45$: matrix of $E_T$ values for upgrades between 4% and 5%
- $ET46$: matrix of $E_T$ values for downgrades greater than 4%
- $ET56$: matrix of $E_T$ values for upgrades between 5% and 6%
- $ET6$: matrix of $E_T$ values for upgrades greater than 6%
- $Gt$: defines the type of terrain of the freeway
- $Grade$: defines whether a specific grade exists or not
- $Length$: length of freeway grade
- $PRB$: vector of percentage of RVs
- $PT$: vector of percentage of trucks of Exhibit 23-11
- $PTB$: vector of percentage of trucks and buses of Exhibit 23-9
- $UpDown$: freeway grade

**Passenger-Car equivalents for trucks and buses on upgrades (see Exhibit 23-9)**

The $E_T$ matrices are the transpose of Exhibit 23-9. This is done in order to match the data of the matrices with the vector of percentage of trucks and buses (PTB).
Passenger-Car equivalents for trucks and buses on downgrades (see Exhibit 23-11)

The first two rows of Exhibit 23-11 are not used, because all the values are the same and therefore the $E_T$ value is the same for any % of trucks (see below for calculation of $E_T$ for downgrades).

The $E_T$ matrix is the transpose of Exhibit 23-11. This is done in order to match the data of the matrix with the vector of percentage of trucks (PT).

\[
PT := \begin{pmatrix}
5 \\
10 \\
15 \\
20
\end{pmatrix}
\]

Passenger-Car equivalents of Trucks and Buses (see Exhibit 23-8, Exhibit 23-9 and Exhibit 23-11)

If no specific grade exists (Grade = 1), the first row of Exhibit 23-8 is used to define the $E_T$ value. If specific upgrades exists (Grade = 2), the Exhibit 23-9 is used and if specific downgrades exists (Grade = 3), the Exhibit 23-11 is used.
The value of $E_T$ is calculated using a linear interpolation of the % trucks and buses ($P_T$) at the vector PTB and the matrix ET. The grade defines which matrix ET must be used, and the length of the grade defines which column of that matrix must be used in the interpolation.
linterp(PTB, ET56 \( \cdot \), \( P_T \)) if 0.75mi < Length ≤ 1mi
linterp(PTB, ET56 \( \cdot \), \( P_T \)) if Length > 1mi

if UpDown > 6%
  linterp(PTB, ET6 \( \cdot \), \( P_T \)) if 0mi ≤ Length ≤ 0.25mi
  linterp(PTB, ET6 \( \cdot \), \( P_T \)) if 0.25mi < Length ≤ 0.3mi
  linterp(PTB, ET6 \( \cdot \), \( P_T \)) if 0.3mi < Length ≤ 0.5mi
  linterp(PTB, ET6 \( \cdot \), \( P_T \)) if 0.5mi < Length ≤ 0.75mi
  linterp(PTB, ET6 \( \cdot \), \( P_T \)) if 0.75mi < Length ≤ 1mi
linterp(PTB, ET6 \( \cdot \), \( P_T \)) if Length > 1mi

if Grade = 3

1.5 if (UpDown < 4%)
1.5 if (4% ≤ UpDown ≤ 5%) \( \wedge \) Length ≤ 4mi
linterp(PT, ET46 \( \cdot \), \( P_T \)) if (4% ≤ UpDown ≤ 5%) \( \wedge \) Length > 4mi
1.5 if (5% < UpDown ≤ 6%) \( \wedge \) Length ≤ 4mi
linterp(PT, ET46 \( \cdot \), \( P_T \)) if (5% < UpDown ≤ 6%) \( \wedge \) Length > 4mi
1.5 if UpDown > 6% \( \wedge \) Length ≤ 4mi
linterp(PT, ET46 \( \cdot \), \( P_T \)) if UpDown > 6% \( \wedge \) Length > 4mi

The value of \( E_T \) is calculated linear interpolation of the % truck and buses (\( P_T \)) at the vector \( I \) in the interpolation column of the matrix ET46. The downgrade length of the grade defines which column of that matrix must be used in the interpolation.

Passenger-Car equivalents for RVs on upgrades (see Exhibit 23-10)

The \( E_T \) matrices are the transpose of Exhibit 23-10. This is done in order to match the data of the matrices with the vector of percentage of RVs (PRV)

\[
\begin{array}{cccc}
2 & 1.2 & 1.2 & 1.5 \\
4 & 1.2 & 1.5 & 1.2 & 2.5 & 2.5 & 4 & 4.5 \\
5 & 1.2 & 1.5 & 1.2 & 2.5 & 2.5 & 3 & 3.5 \\
6 & 1.2 & 1.5 & 1.2 & 2.5 & 2.5 & 2 & 3 & 3 & 2.5 & 4 & 4 \\
8 & 1.2 & 1.5 & 1.2 & 2 & 2 & 1.5 & 2.5 & 3 & 2.5 & 3 & 4 \\
10 & 1.2 & 1.5 & 1.2 & 2 & 2 & 1.5 & 2.5 & 2.5 & 2 & 3 & 3 \\
15 & 1.2 & 1.2 & 1.2 & 1.5 & 2 & 1.5 & 2 & 2.5 & 2 & 2.5 & 3 \\
20 & 1.2 & 1.2 & 1.2 & 1.5 & 1.5 & 1.5 & 2 & 2 & 2 & 2.5 & 2.5 \\
25 & 1.2 & 1.2 & 1.2 & 1.5 & 1.5 & 1.5 & 2 & 2 & 2 & 1.5 & 2 & 2 \\
\end{array}
\]

PRV := 8
ER23 := 1.2 1.5
ER34 := 1.2 2 2
ER45 := 1.5 2.5 3
ER5 := 2.5 3 3.5

Passenger-Car equivalents of RVs (see Exhibit 23-8 and Exhibit 23-10)

If no specific grade exists (Grade = 1), the second row of Exhibit 23-8 is used to define the \( E_R \) value. If specific upgrades exists (Grade = 2), the Exhibit 23-10 is used, and if specific downgrades exists (Grade = 3), the grade is treated as level terrain (see Page 23-11)
The value of $E_R$ is calculated using a linear interpolation of the % RVs ($P_R$) at the vector PRV and the matrix ER. The grade defines which matrix ET must be used and the length of the grade defines which column of that matrix must be used in the interpolation.

% of trucks and buses and % of RVs

Convert the % values to decimal values in order to use them in the equations

$$P_T := \frac{P_T}{100}$$

$$P_R := \frac{P_R}{100}$$

Calculate Flow Adjustments

Driver population factor: $f_p := 1$

Passenger-car equivalents for truck/buses: $E_T = 2.5$

Passenger-car equivalents for RVs: $E_R = 2$

Heavy-vehicle adjustment factor: $f_{HV} := \frac{1}{1 + P_T \cdot (E_T - 1) + P_R \cdot (E_R - 1)} \Rightarrow f_{HV} = 0.93$
**Speed Inputs**

- **Lane width**\( L_w := 11 \text{ft} \)
- **Rt.-shoulder lateral clearance**\( R_{slc} := 2 \text{ft} \)
- **Interchange density**\( I_d := 1 \frac{1}{\text{mi}} \)
- **Number of lanes**\( N := 2 \)
- **Free-flow speed (measured)**\( FFS := 0 \text{mph} \)
- **Base free-flow speed**\( BFFS := 75 \text{mph} \)

**Variables used in this section and not defined in HCM**

- \( FID: \) vector of adjustments for interchange density
- \( FLC: \) matrix of adjustments for right-shoulder lateral clearance
- \( FLW: \) vector of adjustments for lane width
- \( FN: \) vector of adjustments for number of lanes
- \( FSA: \) freeway segment area, 1 for rural areas and 2 for urban areas.
- \( IPM: \) vector of interchanges per mile
- \( LW: \) vector of lane widths
- \( NL: \) vector of number of lanes
- \( RSLC: \) vector of right-shoulder lateral clearance

**Adjustment for lane width (see Exhibit 23-4)**

Two vectors are created, one of lanes widths and one of adjustments for lane width. In order to use the interpolation function \((\text{linterp}(vx,vy,x))\) of MathCad, the \( vx \) vector must be in ascending order. That is the reason why the data is in inverse order as it appears in Exhibit 23-4.

\[
\begin{align*}
LW := &\begin{pmatrix}
10 \\
11 \\
12 \\
\end{pmatrix} \text{ ft} \\
FLW := &\begin{pmatrix}
6.6 \\
1.9 \\
0.0 \\
\end{pmatrix} \text{ mph}
\end{align*}
\]

If there is no FFS measured \((FFS = 0 \text{mph})\), \( f_{LW} \) is calculated interpolating the lane width \((L_w)\) at the vector \( LW \) and \( FLW \). Otherwise \( f_{LW} \) is not calculated.

\[
f_{LW} := \begin{cases} 
\text{linterp}(LW,FLW,L_w) & \text{if } FFS = 0 \text{mph} \\
0 \text{mph} & \text{otherwise}
\end{cases}
\]

**Adjustment for right-shoulder lateral clearance (see Exhibit 23-5)**

A vector of right-shoulder lateral clearance and a matrix of adjustments for right-shoulder lateral clearance are created. In order to use the interpolation function \((\text{linterp}(vx,vy,x))\) of MathCad, the \( vx \) vector must be in ascending order. That is the reason why the data is in inverse order as it appears in Exhibit 23-5.

\[
\begin{align*}
RSLC := &\begin{pmatrix}
0 \\
1 \\
2 \\
3 \text{ ft} \\
4 \\
5 \\
6 \\
\end{pmatrix} \\
FLC := &\begin{pmatrix}
3.6 & 2.4 & 1.2 & 0.6 \\
3.0 & 2.0 & 1.0 & 0.5 \\
2.4 & 1.6 & 0.8 & 0.4 \\
1.8 & 1.2 & 0.6 & 0.3 \\
1.2 & 0.8 & 0.4 & 0.2 \\
0.6 & 0.4 & 0.2 & 0.1 \\
0.0 & 0.0 & 0.0 & 0.0 \\
\end{pmatrix} \text{ mph}
\end{align*}
\]
If there is no FFS measured (FFS = 0mph), \( f_{LC} \) is calculated interpolating the Rt.-shoulder lateral clearance (Rslc) at the vector RSLC and matrix FLC. Otherwise \( f_{LC} \) is not calculated.

If the number of lanes in one direction is greater than 5 (\( N > 5 \)), the last column of the matrix FLC is used for the interpolation.

If Rslc is greater than 6, the first row of the matrix FLC is used. All the elements of that row are 0, therefore for any Rslc greater than 6, \( f_{LC} \) is 0 (0.0mph otherwise)

\[
f_{LC} := \begin{cases} 
\text{linterp}(RSLC,FLC_{N-2},Rslc) & \text{if } 2 \leq N \leq 5 \\
\text{linterp}(RSLC,FLC_{N},Rslc) & \text{if } N > 5 \\
0.0\text{mph} & \text{otherwise}
\end{cases}
\]

Adjustments for interchange density (see Exhibit 23-7)

Two vectors are created, one of interchanges per mile and one of adjustments for interchange density.

\[
\text{IPM} := \begin{pmatrix} 
0.50 \\
0.75 \\
1.00 \\
1.25 \\
1.50 \\
1.75 \\
2.00 
\end{pmatrix} \quad \text{FID} := \begin{pmatrix} 
0.0 \\
1.3 \\
2.5 \\
3.7 \\
5.0 \\
6.3 \\
7.5 
\end{pmatrix} \quad \text{mph}
\]

If there is no FFS measured (FFS = 0mph), \( f_{ID} \) is calculated interpolating the interchange density (Id) at the vector IPM and FID. Otherwise \( f_{ID} \) is not calculated.

\[
f_{ID} := \text{linterp(IPM,FID,Id)} \quad \text{if } FFS = 0\text{mph} \\
0\text{mph} \quad \text{otherwise}
\]

Adjustment for number of lanes (see Exhibit 23-6)

Two vectors are created, one of number of lanes and one of adjustments for number of lanes. In order to use the interpolation function (\( \text{linterp}(vx,vy,x) \)) of MathCad, the x vector \( (vx) \) must be in ascending order. That is the reason why the data is in inverse order as it appears in Exhibit 23-6.

\[
\text{FN} := \begin{pmatrix} 
4.5 \\
3.0 \\
1.5 \\
0.0 
\end{pmatrix} \quad \text{mph} \quad \text{NL} := \begin{pmatrix} 
2 \\
3 \\
4 \\
5 
\end{pmatrix}
\]

\( f_{N} \) is calculated only if FFS is not measured (FFS = 0mph), otherwise \( f_{N} \) is 0. \( f_{N} \) is 0 for rural freeway segments (FSA = 1). For urban areas (FSA = 2), \( f_{N} \) is calculated interpolating the number of lanes (N) at the vector NL and FN.
\[ f_N := \begin{cases} \text{if } \text{FFS} = 0 \text{mph} \\
\quad 0 \text{mph if } \text{FSA} = 1 \\
\quad \text{if } \text{FSA} = 2 \\
\quad \text{interp} (NL, FN, N) \text{ if } 2 \leq N \leq 5 \\
\quad 0 \text{mph otherwise} \end{cases} \]

**Free-flow speed (see Equation 23-1)**

FFS is calculated only if there is no FFS measured (\( \text{FFS} = 0 \text{mph} \)), otherwise FFS is the value measured.

\[ \text{FFS} := \begin{cases} \text{BFFS} - f_{\text{LW}} - f_{\text{LC}} - f_{\text{ID}} - f_N \text{ if } \text{FFS} = 0 \text{mph} \\
\quad \text{FFS otherwise} \end{cases} \]

**Calculate Speed Adjustments and FFS**

Adjustment for Lane Width (Exhibit 23-4):

\[ f_{\text{LW}} = 1.9 \text{ mph} \]

Adjustment for Right-Shoulder Lateral Clearance (Exhibit 23-5):

\[ f_{\text{LC}} = 2.4 \text{ mph} \]

Adjustment for Interchange Density (Exhibit 23-7):

\[ f_{\text{ID}} = 2.5 \text{ mph} \]

Adjustment for Number of Lanes (Exhibit 23-6):

\[ f_N = 0 \text{ mph} \]

\[ \text{FSS} = \text{BFFS} - f_{\text{LW}} - f_{\text{LC}} - f_{\text{ID}} - f_N \]

\[ \text{FSS} = 68.2 \text{ mph} \]

**15-min passenger-car equivalent flow rate (see Equation 23-2)**

If the annual avg. daily traffic is not provided (\( \text{ADDT} = 0 \)), \( v_p \) is computed using the hourly volume (\( V \)). Otherwise \( v_p \) is computed using the directional design-hour volume (DDHV), which is computed in the Flow Input section of the worksheet.

\[ v_p := \begin{cases} \frac{V}{\text{PHF} \cdot N \cdot f_{\text{HV}} \cdot f_p} \text{ if } \text{ADDT} = 0 \\
\quad \frac{\text{DDHV}}{\text{PHF} \cdot N \cdot f_{\text{HV}} \cdot f_p} \text{ otherwise} \end{cases} \]

**Average passenger-car speed (see Exhibit 23-3)**

S is computed using the equations presented in the note of Exhibit 23-3. Units have been added to the ranges of values of \( v_p \) and FFS. These ranges define when each of the equations is applicable.

The units of \( v_p \) and FFS are removed to perform the computations.

\[ S := \begin{cases} \text{if } 70 \text{mph} < \text{FFS} \leq 75 \text{mph} \\
\quad \text{FFS if } 0 < \frac{\text{pc}}{\text{hr} \cdot \text{ln}} \leq V_p \leq \left( \frac{3400 \cdot \text{pc}}{\text{hr} \cdot \text{ln}} - 30 \cdot \frac{\text{pc}}{\text{mi} \cdot \text{ln}} \cdot \text{FFS} \right)^{2.6} \\
\quad \left( \text{FFS - } \frac{160}{\text{mph}} \right) \cdot \frac{V_p}{1 \cdot \frac{\text{pc}}{\text{hr} \cdot \text{ln}}} + \frac{30 \cdot \text{FFS}}{1 \text{mph}} - 3400 \right)^{2.6} \text{ otherwise} \end{cases} \]

\[ \text{if } \left( 3400 \cdot \frac{\text{pc}}{\text{hr} \cdot \text{ln}} - 30 \cdot \frac{\text{pc}}{\text{mi} \cdot \text{ln}} \cdot \text{FFS} \right) < V_p \leq 2 \]
Density (see Equation 23-4)

\[ D := \frac{V_p}{S} \text{ if } S \neq 0 \text{ mph} \]
\[ 0 \text{ mph otherwise} \]

Level of service (see Page 23-3)

If \( v_p \) is greater than 2400 pc/hr/ln the LOS is "Oversaturated"

\[ \text{LOS} := \begin{cases} \text{"A"} & \text{if } 0 \frac{\text{pc}}{\text{hr} \cdot \text{ln}} \leq V_p \leq 11 \frac{\text{pc}}{\text{mi} \cdot \text{ln}} \\ \text{"B"} & \text{if } 11 \frac{\text{pc}}{\text{mi} \cdot \text{ln}} < D \leq 18 \frac{\text{pc}}{\text{mi} \cdot \text{ln}} \\ \text{"C"} & \text{if } 18 \frac{\text{pc}}{\text{mi} \cdot \text{ln}} < D \leq 26 \frac{\text{pc}}{\text{mi} \cdot \text{ln}} \\ \text{"D"} & \text{if } 26 \frac{\text{pc}}{\text{mi} \cdot \text{ln}} < D \leq 35 \frac{\text{pc}}{\text{mi} \cdot \text{ln}} \\ \text{"E"} & \text{if } 35 \frac{\text{pc}}{\text{mi} \cdot \text{ln}} < D \leq 45 \frac{\text{pc}}{\text{mi} \cdot \text{ln}} \\ \text{"F"} & \text{if } D > 45 \frac{\text{pc}}{\text{mi} \cdot \text{ln}} \end{cases} \]
\[ "\text{Oversaturated}" \text{ otherwise} \]

Coordinates

Create the coordinates of the point corresponding to the characteristics of the freeway segment. The \( x \) coordinate is the Flow Rate and the \( y \) coordinate is Average Passenger-Car Speed. The units are removed.

\[ x := V_p \cdot \frac{\text{hr} \cdot \text{ln}}{\text{pc}} \]
\[ y := S \cdot \frac{1}{\text{mph}} \]
**LOS and Performance Measures**

Flow rate: \( V_p = \frac{V_{or}DHV}{PHF \cdot N \cdot f_{HV} \cdot f_p} \)  \( V_p = 1168 \frac{pc}{hr \cdot ln} \)

Average passenger-car speed: \( S = 68.2 \text{ mph} \)

Density: \( D = \frac{V_p}{S} \)  \( D = 17.1 \frac{pc}{mi \cdot ln} \)

Level of service: LOS = "B"

**Note:** to see all annotations, right-click on the graph and choose "Send to Back"