5 TRANSPORTATION

5.1 Traffic Engineering (Capacity Analysis and Transportation Planning)

5.1.1 Uninterrupted Flow (e.g., Level of Service, Capacity)

5.1.1.1 Traffic Flow, Density, Headway, and Speed Relationships

Traffic flow:

$$q = \frac{n}{t}$$

where

q = traffic flow in vehicles per unit time

n = number of vehicles passing some designated roadway point during time t

t = duration of time interval

Traffic flow is the equivalent hourly rate at which vehicles pass a point on a highway during a period less than 1 hour:

$$q = \frac{n(3,600)}{T}$$

where

n = number of vehicles passing a point in the roadway in T sec

q = equivalent hourly flow

Traffic density is defined as

$$k = \frac{n}{l}$$

where

k = traffic density in vehicles per unit distance

n = number of vehicles occupying some length of roadway at some specified time

l = length of roadway

Headway

$$t = \sum_{i=1}^{n} h_i$$

where

t = duration of time interval

h_i = time headway of the ith vehicle (time transpired between arrivals of vehicle i and $i - 1$)

n = number of measured vehicle time headways at some designated roadway point

$$q = \frac{n}{\sum_{i=1}^{n} h_i}$$

$$q = \frac{1}{\bar{h}}$$

where $\bar{h}$ = average time headway, $\frac{\sum h_i}{n}$, in unit time per vehicle

5.1.1.2 Space Mean Speed

$$u_s = \frac{q}{k} = \frac{\text{flow}}{\text{density}}$$

$$u_s = \frac{nL}{\sum_{i=1}^{n} t_i}$$

where

u_s = space mean speed (mph)

n = number of vehicles

L = length of section of highway (miles)

t_i = time it takes the ith vehicle to travel across a section of highway

q = equivalent hourly flow (vph)

flow = density × space mean speed

$$q = k \times u_s$$

5.1.1.3 Lane Occupancy Used in Freeway Surveillance

$$R = \frac{\text{sum of length of vehicles}}{\text{length of roadway section}} = \frac{\sum L_i}{D}$$

where R can be divided by the average length of a vehicle to get an estimate of density k.

Source: Khisty-Lall. *Transportation Engineering: An Introduction*. 3rd ed. New York: Pearson Prentice Hall, 2003, p. 123.

5.1.1.4 Greenshields Maximum Flow Rate Relationship

$$q_{\max} = \frac{k_j u_f}{4}$$

where

$q_{\max}$ = maximum flow rate for Greenshields relationship (vph)

k_j = jam density (veh/mi)

u_f = mean free speed (mph)

Source: Garber, Nicholas J. and Lester A. Hoel. *Traffic & Highway Engineering*. 5th ed. 2014. Cengage Learning, Inc. Reproduced by permission. www.cengage.com/permissions.

5.1.2 Street Segment Interrupted Flow (e.g., Level of Service, Running Time, Travel Speed)

5.1.2.1 Speed-Density Model

$$u_s = u_f\left(1 - \frac{k}{k_j}\right)$$

where

u_f = free-flow speed (mph)

k = density (veh/mi)

k_j = jam density (veh/mi)

5.1.2.2 Flow-Density Model

$$q = u_f\left(k - \frac{k^2}{k_j}\right)$$

where

$$q_{\text{cap}} = u_{\text{cap}} \times k_{\text{cap}}$$

$$k_{\text{cap}} = \frac{k_j}{2}$$

$$u_{\text{cap}} = \frac{u_f}{2}$$

$$q_{\text{cap}} = u_f \frac{k_j}{4}$$

where

q_{cap} = flow at capacity

k_{cap} = density at the capacity flow rate

5.1.2.3 Speed-Flow Model

$$k = k_j\left(1 - \frac{u_s}{u_f}\right)$$

$$q = k_j\left(u_s - \frac{u_s^2}{u_f}\right)$$

5.1.2.4 Time Mean Speed

The TMS $\overline{u_t}$ is computed as the arithmetic average of individual vehicle speeds.

$$\overline{u_t} = \frac{\sum_{i}^{t} u_i}{n}$$

where

$\overline{u_t}$ = time mean speed in unit distance per unit time

u_i = spot speed of the *i*th vehicle

n = number of measured vehicle spot speeds

Source: Mannering, Fred L. and Scott S. Washburn. *Principles of Highway Engineering and Traffic Analysis*. 6th ed. Hoboken, NJ: John Wiley and Sons, 2016.

5.1.2.5 Average Speed (Mean Speed)

$$\overline{x} = \frac{\sum n_i S_i}{N}$$

where

$\overline{x}$ = average or mean speed (mph)

n_i = frequency of observations in group i

S_i = middle speed of group i (mph)

N = total number of individual speed observations

Source: Roess, Roger, William McShane, and Elena Prassas. *Traffic Engineering*. 2nd ed. New York: Pearson, 1998, p. 161.

5.1.2.6 Segment Running Time Simplified

The *Highway Capacity Manual*, v. 6, 2016, equation 18-7, p. 18-31, which "is used to compute segment running time on the basis of consideration of through movement control at the boundary intersection, free-flow speed, vehicle proximity, and various midsegment delay sources" may be simplified to the following equation if all of the lost time and boundary control delays are accounted for or given as part of the through movement average travel speed.

Average running time = Segment length / Average travel speed

5.1.3 Traffic Analysis (e.g., Volume Studies, Peak Hour Factor, Speed Studies, Modal Split)

5.1.3.1 Average Annual Daily Traffic Estimation

Average annual daily traffic (AADT)

$$\text{AADT} = V_{24ij} \times DF_i \times MF_j$$

where

AADT = average annual daily traffic (vpd)

V_{24ij} = 24-hour volume for day i in month j (vehicles)

DF_i = daily adjustment factor for day i

MF_j = monthly adjustment factor for month j

$$DF = \frac{V_{\text{avg}}}{V_{\text{day}}}$$

where

V_{avg} = average daily count for all days of the week (vehicles)

V_{day} = average daily count for each day of the week (vehicles)

$$MF_i = \frac{\text{AADT}}{\text{ADT}_i}$$

where

MF_i = monthly adjustment factor for month i

AADT = average annual daily traffic (vehicles/day) (estimated as the average of 12 monthly ADTs)

ADT_i = average daily traffic for month i (vehicles/day)

5.1.3.2 Estimating Annual Vehicle-Miles Traveled

$$VMT_{365} = \text{AADT} \times L \times 365$$

where

VMT_{365} = annual vehicle-miles traveled over the segment

AADT = vehicles per day for the segment

L = length of the segment

The AAWT is computed as the total weekday volume divided by 260 days, or:

$$\text{AAWT} = \frac{\text{total weekday traffic}}{260}$$

Sources: McShane, William, Roger Roess, and Elena Prassas. *Traffic Engineering*. 4th ed. New York: Pearson, 2011 & Mannering, Fred L. and Scott S. Washburn. *Principles of Highway Engineering and Traffic Analysis*. 6th ed. Hoboken, NJ: John Wiley and Sons, 2016.

5.1.3.3 Peak-Hour Factor

$$v = \frac{V}{PHF} \qquad PHF = \frac{V}{V_{15} \times 4}$$

where

v = rate of flow for a peak 15-min period (vph)

PHF = peak-hour factor

V = hourly volume for hour of analysis

V_{15} = maximum 15-min flow rate within peak hour

4 = number of 15-min periods per hour

5.1.4 Accident Analysis (e.g., Conflict Analysis, Accident Rates, Collision Diagrams)

5.1.4.1 Acceleration

Acceleration Assumed Constant

When the acceleration of the vehicle is assumed to be constant:

$$a = \frac{dS}{dt} = \frac{d^2x}{dt^2}$$

where

$dS = a\,dt$

$S = at + S_0$

S_0 = initial speed

$$S = at + S_0 = \frac{dx}{dt}$$
$$dx = (at + S_0)dt$$
$$x = \frac{1}{2}at^2 + S_0 t + x_0$$

where x_0 = initial position

Source: Khisty-Lall. *Transportation Engineering: An Introduction*. 3rd ed. New York: Pearson Prentice Hall, 2003, p. 100-110.

5.1.4.2 Acceleration Characteristics of Typical Car Versus Typical Truck on Level Terrain

Vehicle Acceleration Rates

Speed Range (mph)	Acceleration Rate (ft/sec^2) for:	
	Typical Car (30 lb/hp)	Typical Truck (200 lb/hp)
0–20	7.5	1.6
20–30	6.5	1.3
30–40	5.9	0.7
40–50	5.2	0.7
50–60	4.6	0.3

Source: McShane, William, Roger Roess, and Elena Prassas. *Traffic Engineering*. 4th ed. New York: Pearson, 2011, Table 2.5, p. 30.

5.1.4.3 Estimating Speed of Vehicle from Skid Marks

The following equation is used to find the initial speed, v_1, of the vehicle based on the known or estimated final speed, v_2:

$$d_b = \frac{v_1^2 - v_2^2}{30(f \pm G)}$$

$$v_1 = \sqrt{d_b(30)(f \pm G) + (v_2)^2}$$

where

d_b = horizontal distance traveled (ft) in reducing speed of vehicle from v_1 to v_2 during braking maneuvers

v_1 = vehicle speed when brakes are applied (initial speed) (mph)

v_2 = vehicle speed at end of travel (final speed) (mph)

$f = \frac{a}{g}$ = coefficient of friction (unitless) between tires and road pavement

a = deceleration of vehicle when brakes are applied (ft/sec^2)

g = acceleration due to gravity (32.2 ft/sec^2)

G = grade of roadway (decimal form; negative if downhill)

Source: McShane, William, Roger Roess, and Elena Prassas. *Traffic Engineering*. 4th ed. New York: Pearson, 2011, p. 30.

5.1.5 Traffic Forecast

The gravity model is based on the gravitational modeling principles covered in physics (the gravitational forces of planets) where the likelihood of a trip going to a destination is a function of the distance from the trip origin and some measure of attractiveness (the equivalent of mass in gravitational theory) of the destination.

$$T'_{ab} = T'_a \frac{A_b f_{ab} K_{ab}}{\sum_{\forall b} A_b f_{ab} K_{ab}}$$

where

T'_{ab} = total number of trips from traffic analysis zone (TAZ) *a* to TAZ *b*

T'_a = total number of trips from TAZ *a*

A_b = total number of trips attracted to TAZ *b*

f_{ab} = distance/travel cost "friction factor"

K_{ab} = estimated parameter to ensure results balance

Source: Mannering, Fred L. and Scott S. Washburn. *Principles of Highway Engineering and Traffic Analysis*. 6th ed. Hoboken, NJ: John Wiley and Sons, 2016.

5.1.6 Design Traffic

Use expected cumulative Equivalent Single Axle Loads (ESAL) to calculate design traffic by direction and lanes.

$$ESAL_{DL} = D_D \times D_L \times ESAL$$

where

$ESAL_{DL}$ = ESAL in the design lane

ESAL = cumulative two-directional 18-kip Equivalent Single Axle Loads units predicted during the analysis period

D_D = directional distribution factor, expressed as a ratio, that accounts for the distribution of ESAL units by direction

D_L = lane distribution factor, expressed as a ratio, that accounts for distribution of traffic when two or more lanes are available in one direction. If no other information is provided, the following table may be used as a guide:

Number of Lanes in Each Direction	Percent ESAL in Design Lane
1	100
2	80–100
3	60–80
4	50–75

Source: Based on information from AASHTO Guide for Design of Pavement Structures, 1993, published by the American Association of State Highway and Transportation Officials, Washington, D.C.

5.1.7 Predicting Truck Traffic Volumes

The Average Annual Daily Truck Traffic for vehicles class *c* ($AADTT_c$) is obtained from:

$$AADTT_c = \frac{1}{7}\sum_{i=1}^{7}\left[\frac{1}{12}\sum_{j=1}^{12}\left(\frac{1}{n}\sum_{k=1}^{n} AADTT_{ijkc}\right)\right]$$

where

$AADTT_{ijkc}$ = average daily traffic volume for vehicle class *c*, for day *k*, for day of the week (DOW) *i*, and for month *j*

i = DOW, ranging from 1 to 7 for Monday to Sunday, respectively

j = month of the year, ranging from 1 to 12 for January to December, respectively

n = number of times data from a particular DOW is available for computing the average in a given month (i.e., 1, 2, 3, 4, or 5)

5.1.8 Monthly Adjustment Factor

$$MAF_j = \frac{AADTT_c}{VOL_{cj}}$$

where

MAF_j = monthly adjustment factor for month *j*

$AADTT_c$ = average annual daily truck traffic volume for vehicle class *c*

VOL_{cj} = average annual daily truck traffic volume for vehicle class *c* and month *j* that can be obtained from automatic vehicle classification data

General equation for the accumulation ESAL (Equivalent Single Axle Load) for each category of axle load is:

$$ESAL_i = f_d \times G_{rn} \times AADT_i \times 365 \times N_i \times F_{Ei}$$

where

$ESAL_i$ = equivalent accumulated 18,000-lb (80 kN) single-axle load for the axle category i

f_d = design lane factor

G_{rn} = growth factor for a given growth rate r and design period n

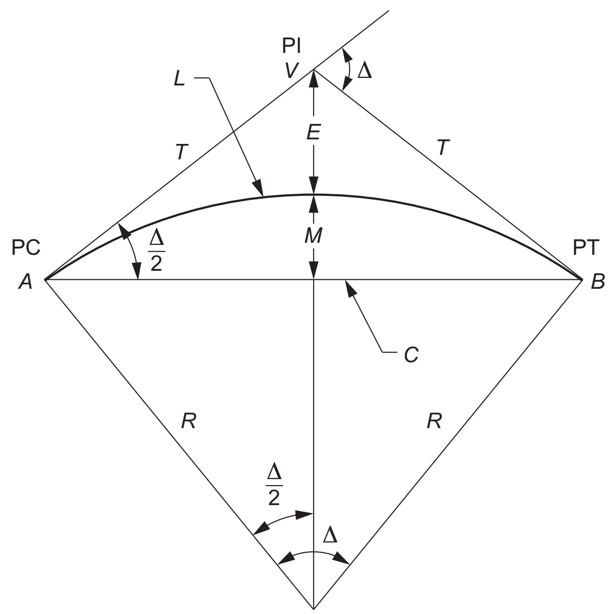
$AADT_i$ = first year annual average daily traffic for axle category i

N_i = number of axles on each vehicle in category i

F_{Ei} = load equivalency factor for axle category i

5.2 Horizontal Design

5.2.1 Basic Curve Elements (e.g., Middle Ordinate, Length, Chord, Radius)



Parts of a Circular Curve

R = radius of circular curve

T = tangent length

Δ = intersection angle/central angle/deflection angle (degrees)

M = middle ordinate

PC = point of curve

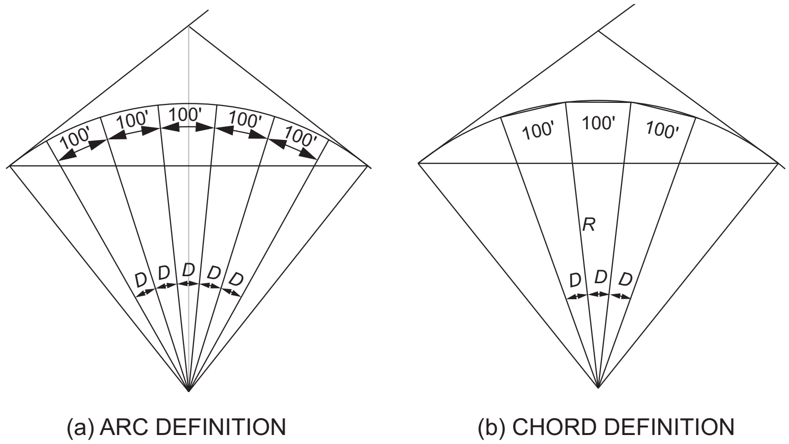
PT = point of tangent

PI = point of intersection

E = external distance

Line $AB = C$ = chord length

L = arc length = curve length measured along the arc from PC to PT

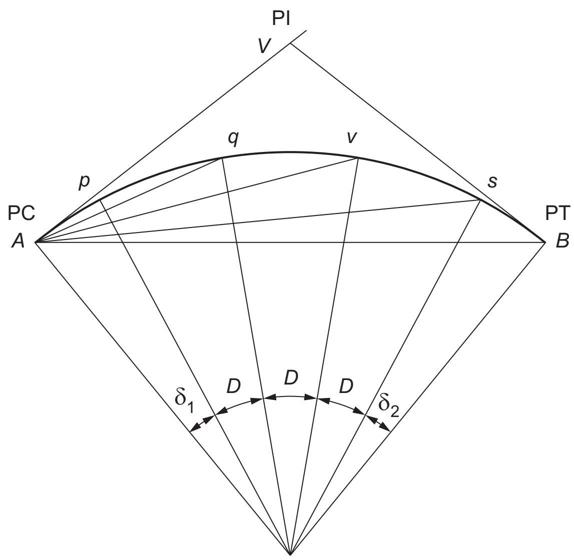


Arc and Chord Definitions for a Circular Curve

where

D_a = degree of curvature by arc definition

D_c = degree of curvature by chord definition



Deflection Angles on a Simple Circular Curve

where

$$R = \frac{5{,}729.6}{D_a}$$

$$D_a = \frac{100\left(\frac{180}{\pi}\right)}{R} = \frac{18{,}000}{\pi R}$$

$$R = \frac{50}{\sin \frac{D_c}{2}}$$

$$T = R \tan \frac{\Delta}{2}$$

$$C = 2R \sin \frac{\Delta}{2}$$

$$E = R \sec \frac{\Delta}{2} - R = T\left(\tan \frac{\Delta}{4}\right) = R\left(\frac{1}{\cos \frac{\Delta}{2}} - 1\right)$$

$$M = R - R \cos \frac{\Delta}{2}$$

$$= R\left(1 - \cos \frac{\Delta}{2}\right)$$

$$L = \frac{R\Delta\pi}{180}$$

$$l_1 = \frac{R\delta_1 \pi}{180}$$

$$\frac{\delta_1}{\Delta} = \frac{l_1}{L}$$

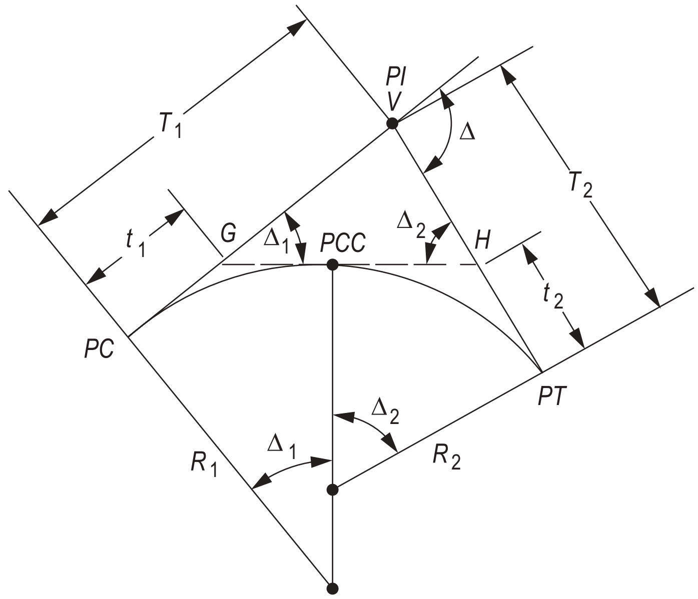
$$L = 100\frac{\Delta}{D_a}$$

where

l_1 = length of curve from PC to point p subtended by central angle δ_1

$C_1 = 2R \sin \frac{\delta_1}{2}$ = chord length from PC to point p

5.2.2 Layout of Two-Centered Compound Curves



Two-Centered Compound Curve

where

R_1, R_2 = radii of simple curves forming compound curve

Δ_1, Δ_2 = deflection angles of simple curves

Δ = deflection angle of compound curve

$= \Delta_1 + \Delta_2$

t_1, t_2 = tangent lengths of simple curves

T_1, T_2 = tangent lengths of compound curves

PCC = point of compound curve

PI = point of intersection

PC = point of curve

PT = point of tangent

$$\frac{\overline{VG}}{\sin \Delta_2} = \frac{\overline{VH}}{\sin \Delta_1} = \frac{t_1 + t_2}{\sin(180 - \Delta)} = \frac{t_1 + t_2}{\sin \Delta}$$

where

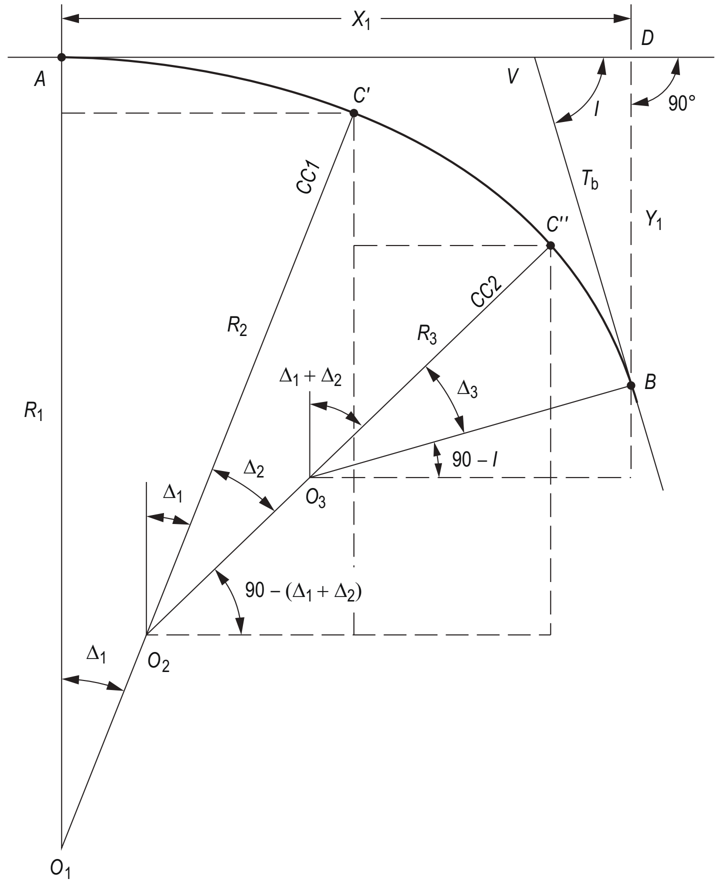
$$T_1 = \overline{VG} + t_1$$

$$t_1 = R_1 \tan \frac{\Delta_1}{2}$$

$$t_2 = R_2 \tan \frac{\Delta_2}{2}$$

$$T_2 = \overline{VH} + t_2$$

5.2.3 Layout of Three-Centered Compound Curves



Three-Centered Compound Curve

Source: Hickerson, Thomas. *Route Location and Design*. 5th ed. 1967, Fig. 47, p. 131.

A three-centered compound curve has centers at O_1, O_2, and O_3 with central angles equal to Δ_1, Δ_2, and Δ_3.

I = total central angle = $\Delta_1 + \Delta_2 + \Delta_3$

Proceeding from flatter to sharper curve, the radii are R_1, R_2, and R_3.

The first PCC is at C', the second at C''.

T_a = AV = long tangent

T_b = VB = short tangent

PCC = point of compound curve

X_1, Y_1 equals the coordinates of point B with reference to A as origin and AV as X axis, where X_1 = AD and Y_1 = DB. Then,

$$Y_1 = T_b \times \sin I$$

$$X_1 = T_a + T_b \times \cos I$$

$$T_b = \frac{Y_1}{\sin I}$$

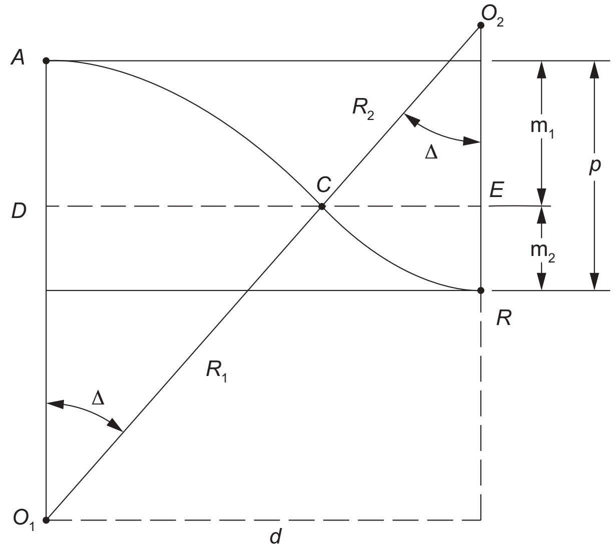
$$T_a = X_1 - T_b \times \cos I$$

$$X_1 = R_1 \sin \Delta_1 + R_2 \sin\left(\Delta_1 + \Delta_2\right) - R_2 \sin \Delta_1 + R_3 \sin I - R_3 \sin\left(\Delta_1 + \Delta_2\right)$$

OR

$$X_1 = \left(R_1 - R_2\right) \sin \Delta_1 + \left(R_2 - R_3\right) \sin\left(\Delta_1 + \Delta_2\right) + R_3 \sin I$$

5.2.4 Layout of Reverse Horizontal Curves Between Parallel Tangents



Reverse Horizontal Curves Between Parallel Tangents

Source: Hickerson, Thomas. *Route Location and Design*. 5th ed. 1967, Fig. 56, p. 142.

where

$d = DE = DC + CE$

$p = m_1 + m_2$ = distance between parallel tracks

Then radii R_1 and R_2 may be equal or unequal.

If equal:

$$R_1 = R_2 = R$$

$$DC = CE = \frac{d}{2} \text{ and } m_1 = m_2 = \frac{p}{2}$$

$$d = R_1 \sin\Delta + R_2 \sin\Delta = (R_1 + R_2)\sin\Delta$$

$$p = R_1(1 - \cos\Delta) + R_2(1 - \cos\Delta) = (R_1 + R_2)(1 - \cos\Delta)$$

If any three are given, the other two may be found.

5.2.5 Method of Designating Directions

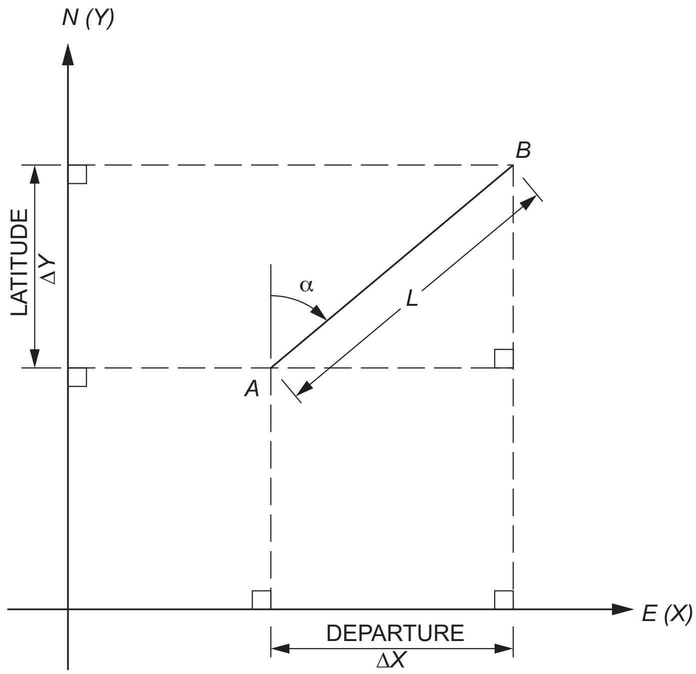
The direction of a line is expressed as the angle between a meridian and the line. The meridian may be a *true meridian*, which is a great circle of the earth passing through the poles, a *magnetic meridian*, the direction of which is defined by a compass needle, or a *grid meridian*, which is established for a plane coordinate system.

The direction of a line may be expressed as its *bearing* or its *azimuth*.

- The bearing of a line is the horizontal acute angle between the meridian and the line
- Because the bearing of a line cannot exceed 90°, the full horizontal circle is divided into four quadrants: northeast, southeast, southwest, and northwest.

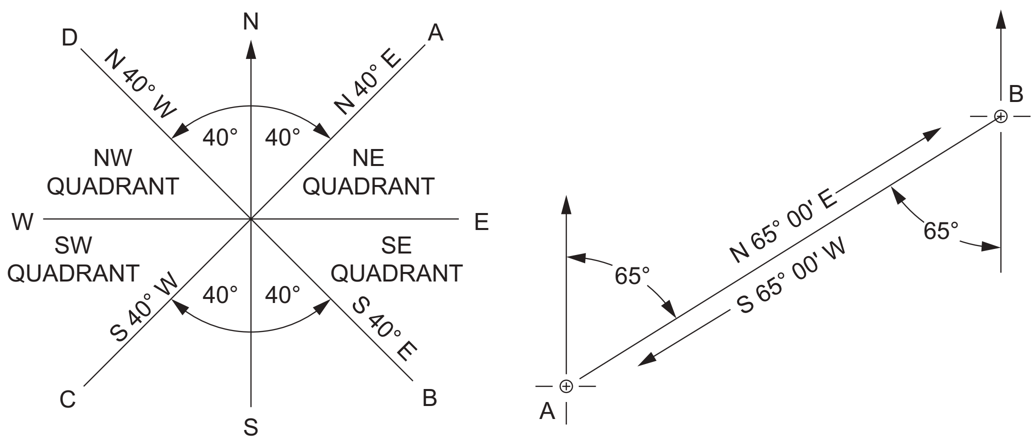
  Northing = latitude = Y = distance × cos (bearing)

  Easting = departure = X = distance × sin (bearing)



Relationship of Latitude and Departure

Ghilani, Charles D. *Elementary Surveying: An Introduction To Geomatics*. 15th ed. 2018. Reprinted by permission of Pearson Education, Inc.



Example Bearings

Example Directions for Lines in the Four Quadrants

Quadrant	Formulas for Computing Bearing Angles from Azimuths
I (NE)	bearing = azimuth
II (SE)	bearing = 180° – azimuth
III (SW)	bearing = azimuth – 180°
IV (NW)	bearing = 360° – azimuth

Source: Ghilani, Charles D. *Elementary Surveying: An Introduction To Geomatics*. 15th ed. 2018. Reprinted by permission of Pearson Education, Inc.

5.3 Vertical Design

5.3.1 Symmetrical Vertical Curve Formula

$$y = ax^2$$
$$A = |g_2 - g_1|$$
$$a = \frac{g_2 - g_1}{2L}$$
$$E = a\left(\frac{L}{2}\right)^2$$
$$E = \frac{AL}{8}$$
$$r = \frac{g_2 - g_1}{L}$$
$$K = \frac{L}{A}$$
$$x_m = -\frac{g_1}{2a} = \frac{g_1 L}{g_1 - g_2}$$

Vertical Curve Formulas

$$\text{Tangent elevation} = Y_{PVC} + g_1 x = Y_{PVI} + g_2\left(x - \frac{L}{2}\right)$$

$$\text{Curve elevation} = Y_{PVC} + g_1 x + ax^2 = Y_{PVC} + g_1 x + x^2\left(\frac{g_2 - g_1}{2L}\right)$$

where

PVC = point of vertical curvature, or beginning of curve

PVI = point of vertical intersection, or vertex

PVT = point of vertical tangency, or end of curve

A = algebraic difference in grades

a = parabola constant

E = tangent offset at PVI

g_1 = grade of back tangent

g_2 = grade of forward tangent

K = rate of vertical curvature

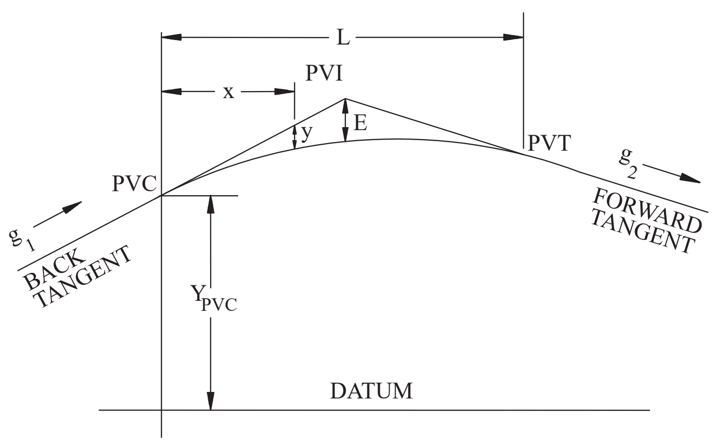
L = length of curve

r = rate of change of grade

x = horizontal distance from PVC to point on curve

x_m = horizontal distance to min/max elevation on curve

y = tangent offset

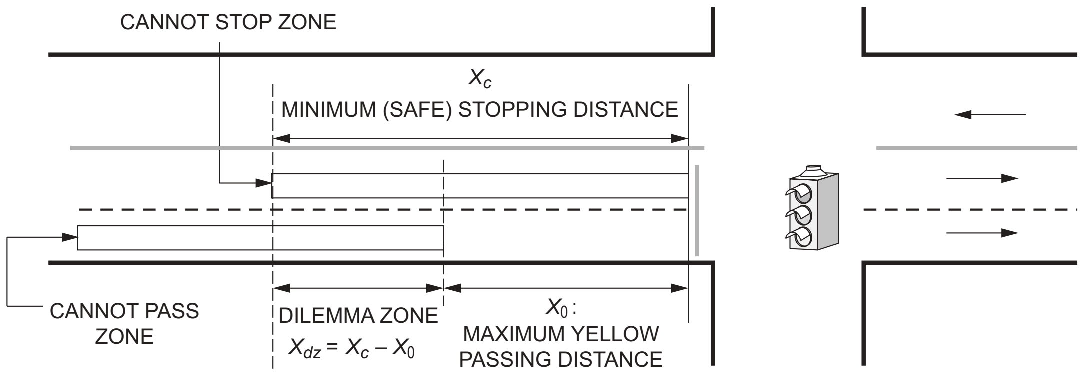


Vertical Curve

5.4 Signal Design

5.4.1 Dilemma Zones

A *dilemma zone* is defined as a zone within which a driver can neither bring his/her vehicle to a stop safely nor go through the signal-controlled intersection before the signal turns red. The formation of a dilemma zone is depicted below:



Dilemma Zone Formation

Sources: Adapted from Mannering, Fred L. and Scott S. Washburn. *Principles of Highway Engineering and Traffic Analysis*. 5th ed. Hoboken, NJ: John Wiley and Sons, 2012, Fig. 7.12, p. 251 & Garber, Nicholas J. and Lester A. Hoel, *Traffic & Highway Engineering*, 5th ed., 2014, Boston, MA: Cengage Learning, Inc., 2015, Fig. 8.16, p. 393.

The physical zone between X_c and X_0, when $X_c > X_0$, is the dilemma zone. In this situation, the word "dilemma" exactly represents such a circumstance, although the driver may not be aware of it.

$$X_c = 1.47V(t_{\text{stop}}) + 1.075\frac{V^2}{a_2}$$

$$X_0 = 1.47VY - W + \frac{1}{2}a_1(Y - t_{\text{passing}})^2$$

where

V = vehicle approach speed (mph)

t_{stop} = driver perception time for safe stopping (sec)

t_{passing} = driver perception time for safe passing (sec)

a_2 = maximum vehicle deceleration rate to stop (ft/sec^2)

a_1 = constant vehicle acceleration rate (ft/sec^2)

W = summation of intersection width and vehicle length (ft)

Y = yellow interval (sec)

5.4.2 Offsets

The time difference between a common reference point in the coordinated phases at adjacent signalized intersections is referred to as the *offset.* Assuming a moving platoon, the offset is calculated as:

$$offset = \frac{d_o}{V}$$

where

offset = start of green phase for downstream intersection relative to upstream intersection, for the same traffic movement (sec)

d_o = distance between upstream and downstream for offset calculation (ft)

V = travel speed between upstream and downstream intersection (ft/sec)

Assuming a standing platoon:

$$offset = l_1 + \frac{d_o}{V}$$

With vehicles queued downstream:

$$offset_{\text{adj}} = \frac{d_o}{V} - \left(Qh + l_1\right)$$

where

Q = number of vehicles queued per lane (vehicles)

h = discharge headway of queued vehicles (sec/vehicle)

l_1 = startup lost time (sec)

For good progression in both directions, the cycle length (for both intersections) needs to be twice the travel time from Intersection 1 to Intersection 2:

$$C_{\text{prog}} = \frac{d_o}{V} \times 2$$

where C_{prog} = cycle length necessary for ideal two-way progression (sec)

Sources: Mannering, Fred L. and Scott S. Washburn. *Principles of Highway Engineering and Traffic Analysis*. 5th ed. Hoboken, NJ: John Wiley and Sons, 2012, p. 262 & Garber, Nicholas J. and Lester A. Hoel, *Traffic & Highway Engineering*, 5th ed., 2014, Boston, MA: Cengage Learning, Inc., 2015, p. 250-264.

5.4.3 Interval Timing

ITE *Traffic Engineering Handbook*, 6th edition, included the following recommendations for the timing of yellow and red intervals.

5.4.3.1 Yellow Change Interval

ITE provides the following formula for determining the appropriate yellow time for an approach:

$$Y = t + \frac{v}{2a + 2Gg}$$

where

Y = calculated yellow time

t = reaction time (typically 1 second if no other information is provided)

v = design speed (ft/sec)

a = deceleration rate (typically 10 ft/sec^2 if no other information is provided)

g = acceleration due to gravity

G = grade of approach

5.4.3.2 Red Clearance Interval

ITE provides the following formula for determining the appropriate timing for an optional interval where the approach signal is red and no conflicting traffic is moving.

$$R = \frac{w + L}{v}$$

where

R = calculated red clearance interval time

w = width of intersection measured from near-side stop line to far side point of clearance

L = length of vehicle (typically 20 ft if no other information is provided)

v = design speed (ft/sec)

Source: Adapted from *Traffic Engineering Handbook*, 6th ed., Institute of Transportation Engineers, 2009, pp. 412–413.

5.5 Geotechnical and Pavement

5.5.1 Relative Soil Density

The relative density, usually given as a percentage

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}}$$

where

D_r = relative density, usually given as percentage

e = in situ void ratio of the soil

$e_{\max}$ = void ratio of the soil in the loosest condition

$e_{\min}$ = void ratio of the soil in the densest condition

Using the definition of dry unit weight, relative density in terms of maximum and minimum dry unit weights can be expressed as:

$$D_r = \frac{\left[\frac{1}{\gamma_{d(\min)}}\right] - \left[\frac{1}{\gamma_d}\right]}{\left[\frac{1}{\gamma_{d(\min)}}\right] - \left[\frac{1}{\gamma_{d(\max)}}\right]} = \left[\frac{\gamma_d - \gamma_{d(\min)}}{\gamma_{d(\max)} - \gamma_{d(\min)}}\right]\left[\frac{\gamma_{d(\max)}}{\gamma_d}\right]$$

where

$\gamma_{d(\min)}$ = dry unit weight in the loosest condition

γ_d = in situ dry unit weight

$\gamma_{d(\max)}$ = dry unit weight in the densest condition

Source: Das, Braja M. and Nagaratnam Sivakugan. *Fundamentals of Geotechnical Engineering*. 5th ed. Boston, MA: Cengage Learning, Inc., 2017, p. 70.

5.5.2 Plasticity Index

A one-point method for estimation of liquid limit using the fall cone device is:

$$LL = \frac{w}{0.65 + 0.0175d}$$

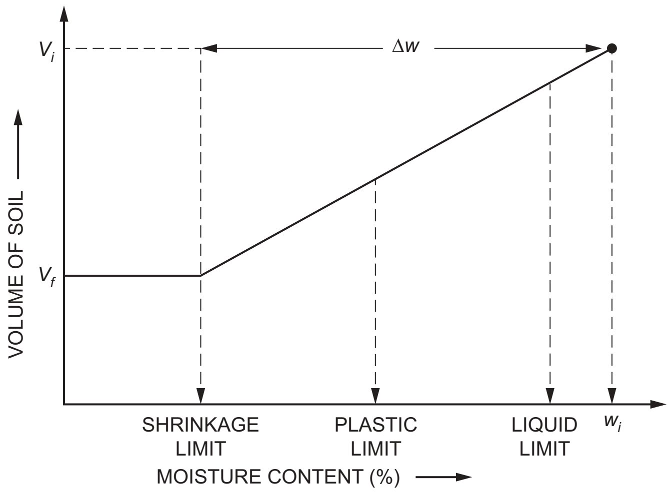
where w = moisture content for 17 mm ≤ d ≤ 23 mm

Qualitative Descriptions of Granular Soil Deposits

Relative Density (%)	Description of Soil Deposit
0–15	Very loose
15–35	Loose
35–65	Medium dense
65–85	Dense
85–100	Very dense

Source: Das, Braja M. and Nagaratnam Sivakugan, *Fundamentals of Geotechnical Engineering*, 5th ed., 2017, Cengage Learning, Inc. Reproduced by permission. www.cengage.com/permissions.

5.5.3 Shrinkage of Soil Mass



Shrinkage Limits

Source: Das, Braja M. and Nagaratnam Sivakugan, *Fundamentals of Geotechnical Engineering*, 5th ed., 2017, Cengage Learning, Inc. Reproduced by permission. www.cengage.com/permissions.

The moisture content at which the volume change of the soil mass ceases is defined as the shrinkage limit. The shrinkage limit is determined by the equation:

$$SL = w_i - \Delta w$$

where

SL = shrinkage limit

w_i = initial moisture content when the soil is placed in the shrinkage limit dish (%)

Δw = change in moisture content (%)

However,

$$w_i(\%) = \frac{m_1 - m_2}{m_2} \times 100$$

where

m_1 = mass of the wet soil pat in the dish at the beginning of the test

m_2 = mass of the dry soil pat

$$\Delta w(\%) = \frac{(V_i - V_f)\rho_w}{m_2} \times 100$$

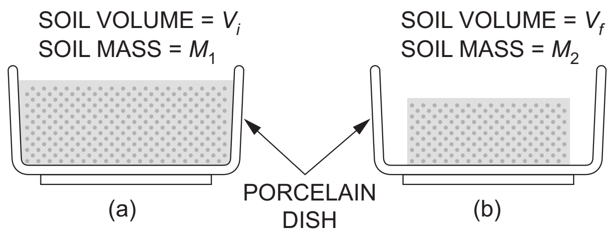
where

V_i = initial volume of the wet soil pat

V_f = volume of the oven-dried soil pat

ρ_w = density of water

$$SL = \left(\frac{m_1 - m_2}{m_2}\right)(100) - \left[\frac{(V_i - V_f)\rho_w}{m_2}\right](100)$$



Shrinkage Limit Test
(a) Soil pat before drying;
(b) Soil pat after drying

Source: Das, Braja M. and Nagaratnam Sivakugan, *Fundamentals of Geotechnical Engineering*, 5th ed., 2017, Cengage Learning, Inc. Reproduced by permission. www.cengage.com/permissions.

5.5.4 Soil Compaction

Compaction – General Principles

Compaction may be measured in terms of dry unit weight.

Water acts as a softening agent during compaction.

The dry unit weight at $w = w_1$ is:

$$\gamma_{d(w=w_1)} = \gamma_{d(w=0)} + \Delta\gamma_d$$

The dry unit weight increases initially as water is added.

After a certain point, $(w = w_2)$, the dry unit weight decreases as the moisture content increases.

The moisture content at maximum dry weight is the *optimum moisture content*.

5.5.5 Asphalt Mixture Design

5.5.5.1 Specific Gravity, Bulk Specific Gravity, Bulk Specific Gravity-Saturated Surface Dry

Determined by ASTM C127 and ASTM C128. Both are based on Archimedes' Principle.

5.5.5.2 Specific Gravity of Aggregates

Apparent specific gravity: ratio of the weight of dry aggregate to the weight of water having a volume equal to the solid volume of aggregate (excluding permeable pores) = $\dfrac{A}{A-C}$

Bulk specific gravity: ratio of the weight of dry aggregate to the weight of water having a volume equal to the volume of the aggregate, including permeable and impermeable pores = $\dfrac{A}{B-C}$

Bulk specific gravity-saturated, surface dry (SSD): ratio of the weight of the aggregate, including the weight of water in its permeable voids, to the weight of an equal volume of water = $\dfrac{B}{B-C}$

$$\text{Water absorption}(\%) = \frac{B-A}{A}(100)$$

where

A = weight of oven-dry sample of aggregate in air

B = weight of saturated, surface-dry sample in air

C = weight of saturated sample in water

5.5.5.3 Specific Gravity of Fine Aggregates

Apparent specific gravity = $\dfrac{A}{B+A-C}$

Bulk specific gravity = $\dfrac{A}{B+D-C}$

Bulk specific gravity (SSD) = $\dfrac{D}{B+D-C}$

Adsorption = $\dfrac{D-A}{A}(100)$

where

A = weight of oven-dry specimen in air

B = weight of pycnometer filled with water

C = weight of pycnometer with specimen and water to calibration mark

D = weight of saturated surface-dry specimen

The percentage of combined aggregate passing a given sieve size (P) is calculated as

$$P = Aa + Bb + Cc + ...$$

where

A, B, C … = percentages of each aggregate that pass a given sieve size

a, b, c … = proportions of each aggregate needed to meet the requirements for material passing the given sieve (given that $a + b + c$ … = 100)

The combined specific gravity, G, and absorption are calculated using

$$\text{Combined specific gravity } G = \frac{1}{\dfrac{a}{100G_A} + \dfrac{b}{100G_B} + ...} ...$$

Combined absorption = a Absorption$_A$ + b Absorption$_B$ + …

$$\text{Moisture content} = \frac{(\text{mass wet sand} - \text{mass dry sand})}{\text{mass dry sand}}$$

Saturated surface-dry weight of sand = SSD = Absorption × dry weight + dry weight

Source: Papagiannakis, A. T., and E. A. Masad. *Pavement Design and Materials*. Hobokon, NJ: John Wiley and Sons, 2008, p. 84-86.

5.5.6 Structural Design of Flexible Pavement

5.5.6.1 Asphalt Mixture Volumetrics

Effective specific gravity of aggregate:

$$G_{se} = \frac{100 - P_b}{\dfrac{100}{G_{mm}} - \dfrac{P_b}{G_b}}$$

Maximum specific gravity of the paving mixture:

$$G_{mm} = \frac{100}{\dfrac{P_s}{G_{se}} + \dfrac{P_b}{G_b}}$$

Asphalt absorption:

$$P_{ba} = 100G_b \frac{G_{se} - G_{sb}}{G_{sb}G_{se}}$$

Effective asphalt content:

$$P_{be} = P_b - \frac{P_{ba}}{100} P_s$$

Percent voids in compacted mineral aggregates:

$$VMA = 100 - \frac{G_{mb}P_s}{G_{sb}}$$

Percent air voids in compacted mixture:

$$P_a = \frac{G_{mm} - G_{mb}}{G_{mm}} \times 100$$

where

G_{se} = effective specific gravity of the aggregates

G_{mm} = maximum specific gravity of paving mixture (no air voids)

P_b = asphalt percent by total weight of paving mixture (thus, 100 – P_b is the percent by weight of the base mixture that is not asphalt)

G_b = specific gravity of the asphalt

P_s = percent by weight of aggregates in paving mixture

P_{ba} = amount of asphalt absorbed as a percentage of the total weight of aggregates

G_{sb} = bulk specific gravity of the aggregates

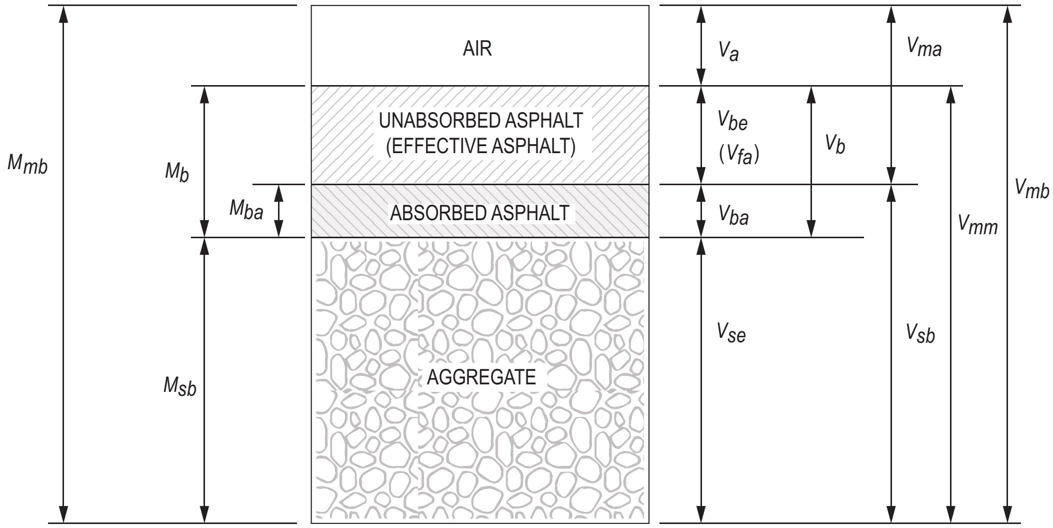
P_{be} = effective asphalt content in paving mixture (percent by weight)

VMA = percent voids in compacted mineral aggregates (percent of bulk volume)

P_a = percent air voids in compacted paving mixture

G_{mb} = bulk specific gravity of the compacted paving mixture

5.5.6.2 Asphalt Concrete Volumetric Terms and Definitions Using Phase Diagram



Phase Diagram

Source: Asphalt Institute. *MS2 Asphalt Mix Design Methods*. 7th ed. Lexington, KY: Asphalt Institute, 2015.

Asphalt Concrete Volumetric Terms

Term	Read as	Defined as
M_{mb}	Bulk mass of mixture	Total mass of component materials (asphalt and aggregate)
M_{sb}	Bulk mass of aggregate	Total mass of combined aggregate in asphalt concrete mixture
M_b	Mass of binder	Total mass of asphalt cement in asphalt concrete mixture
M_{ba}	Mass of absorbed binder	Mass of asphalt cement that is absorbed into the aggregate
V_{sb}	Bulk volume of aggregate	Volume of solid aggregate + total volume of void space in aggregate particle
V_{se}	Effective volume of aggregate	Volume of solid aggregate + total volume of void space in aggregate particle – volume of void space in aggregate particle containing asphalt
V_{sa}	Apparent volume of aggregate	Volume of solid aggregate only (not shown in diagram; $V_{sa} < V_{se} < V_{sb}$)
V_b	Volume of asphalt binder	Total volume of asphalt cement in asphalt concrete mixture
V_{ba}	Volume of absorbed binder	Volume of asphalt absorbed into aggregate
V_{be}	Effective volume of binder	Volume of asphalt binder in mixture that is not absorbed by the aggregate (Note that V_{be} is equal to V_{fa}.)
V_a	Volume of air	Volume of air in asphalt concrete mixture
V_{ma}	Volume of voids in mineral aggregate	Volume of void space between aggregate particles, interparticulate void spaces (does not include void spaces within the individual aggregate particles). This quantity is very similar to the %Voids quantity calculated from the DRUW test.
V_{fa}	Volume of V_{ma} filled with asphalt	Volume of total interparticulate void space that is filled with asphalt cement
V_{mm}	Voidless mix volume	Absolute volume occupied by only aggregate and asphalt cement (does not include volume occupied by air)
V_{mb}	Bulk volume	Total volume occupied by asphalt concrete mixture

Source: Asphalt Institute. *MS2 Asphalt Mix Design Methods*. 7th ed. Lexington, KY: Asphalt Institute, 2015.

Defined Quantities from Volumetric Values

Specific Gravities				
G_{se}	=	Effective specific gravity	=	$\dfrac{M_{sb}}{V_{se} \times \rho_{H_2O}}$
G_{sb}	=	Bulk specific gravity (same as G_s(DRY))	=	$\dfrac{M_{sb}}{V_{sb} \times \rho_{H_2O}}$
G_{mb}	=	Bulk specific gravity	=	$\dfrac{M_{mb}}{V_{mb} \times \rho_{H_2O}}$
G_{mm}	=	Maximum specific gravity	=	$\dfrac{M_{mb}}{V_{mm} \times \rho_{H_2O}}$
Volumetric Indices				
VMA	=	Voids in mineral aggregate	=	$\dfrac{V_{ma}}{V_{mb}} \times 100$
VFA	=	Voids filled with asphalt	=	$\dfrac{V_{fa}}{V_{ma}} \times 100$
VTM (% Air)	=	Air voids	=	$\dfrac{V_a}{V_{mb}} \times 100 = \left(1 - \dfrac{G_{mb}}{G_{mm}}\right) \times 100$
Other				
% Absorption	=	Absorbed asphalt content	=	$\dfrac{M_{ba}}{M_{sb}} \times 100$

Source: Asphalt Institute. *MS2 Asphalt Mix Design Methods*. 7th ed. Lexington, KY: Asphalt Institute, 2015.

Structural Layer Coefficients (a's)

Pavement Component	Coefficient
Wearing Surface	
Sand-mix asphaltic concrete	0.35
Hot-mix asphaltic concrete	0.44
Base	
Crushed stone	0.14
Dense-graded crushed stone	0.18
Soil cement	0.20
Emulsion/aggregate-bituminous	0.30
Portland-cement/aggregate	0.40
Lime-pozzolan/aggregate	0.40
Hot-mix asphaltic concrete	0.40
Subbase	
Crushed stone	0.11

Source: Mannering, Fred L. and Scott S. Washburn. *Principles of Highway Engineering and Traffic Analysis*. 6th ed. Hoboken, NJ: John Wiley and Sons, 2016, p.128.