Highway and Railway Design 1 **EXERCISES 1.** (for Lecture 2. of **Dr. A. Timár)**

A. Rolling resistance calculation

The force that resists the motion of a body rolling on a surface is called the rolling resistance or the rolling friction.

The rolling resistance can be expressed as

$$F_r = \mu * W$$

where

- F_r = rolling resistance or rolling friction (N)
- μ= rolling resistance coefficient - dimensionless (coefficient of rolling friction - CRF)
- $W = m * a_g$ = normal force - or weight - of the body (N)
- m = mass of body (kg)
- a_g = acceleration of gravity (9.81 m/s^2)

The rolling resistance can alternatively be expressed as

$$F_r = \mu_l \, W / r$$

where

- μ_l = rolling resistance coefficient – dimension: length (coefficient of rolling friction) (mm)
- **r** = radius of vehicle's wheel (mm)

Examples:

1. The rolling resistance of a car with weight 1500 kg on concrete pavement with rolling friction coefficient 0.015 can be estimated as
   F_r = 0.015*(1500 kg)*(9.81 m/s^2) = **220.7** N

2. The rolling resistance of a truck with weight 6000 kg on asphalt pavement with rolling friction coefficient 0.01 can be estimated as
   F_r = 0.01*(6000 kg)*(9.81 m/s^2) = **588.6** N

3. The rolling resistance of a car with weight 1200 kg on asphalt pavement with rolling friction coefficient 0.02 can be estimated as
   F_r = 0.02*(1200 kg)*(9.81 m/s^2) = **235.4** N

4. The rolling resistance of a truck with weight 12000 kg on compacted gravel road surface with rolling friction coefficient 0.05 can be estimated as
   F_r = 0.05 (12000 kg) (9.81 m/s^2) = 5886 N; i. e. **5.9** kN

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B. Uphill resistance calculation

When the vehicle travels uphill, a component of its weight works in a direction opposite to its motion. If some energy is not supplied to overcome this backward force, then the vehicle would slow down, stall and roll backwards. If the vehicle is trading uphill at a slope of **α**, then the weight of the vehicle, **W** has two components: one perpendicular to the road surface (with a value **W*cos α**) and the other along the road surface (with a value **W*sin α**). The component along the road surface is the one that tries to restrict the motion.

The uphill, or gradient resistance is given by: $\boldsymbol{F_G = W^*\sin\alpha \text{ or } W^*e}$

where the gradient **e = sinα~tgα**

Examples:

1. The uphill resistance of a car with weight W=1500 N on a slope with gradient e=4% can be estimated as

$$F_r = 0.04\ (1500) = \underline{\mathbf{6.0}}\ \mathbf{N}$$

2. **Question:**

   A car of weight W=3000 N possesses an engine whose maximum power output is P=160 kW. The maximum speed of this car on a level road is v=35 m/s. Assuming that the resistive force (due to a combination of friction and air resistance) remains constant, what is the car's maximum speed on an incline of e=5% (i. e., if α is the angle of the incline with respect to tg α ~ sin α = 0.05)

   Answer:

   When the car is traveling on a level road at its maximum speed, v, then all of the power output, P, of its engine is used to overcome the power dissipated by the resistive F force. Hence: P = f*v, where the left-hand side is the power output of the engine, and the right-hand side is the power dissipated by the resistive force (i.e., minus the rate at which this force does work on the car). It follows that

$$f = P/v = (160*10^3)/35 = \underline{4.57*10^3}\ N = \underline{\mathbf{4.57}}\ kN$$

   When the car, whose weight is W, is traveling up an incline, whose angle with respect to the horizontal is α, it is subject to the additional force f' = W*sin α , which acts to impede its motion. Of course, this force is just the component of the car's weight acting down the incline. Thus, the new power balance equation is written as

$$P = f^*v' + W^*\sin\alpha^*v'$$

   where v' is the maximum speed of the car up the incline. Here, the left-hand side represents the power output of the car, whereas the right-hand side represents the sum of the power dissipated by the resistive force and the power expended to overcome the component of the car's weight acting down the incline. It follows that

$$v' = P / (f + W^*\sin\alpha) = (160*10^3) / (4.57*10^3) + (3000/20) = \underline{\mathbf{33.90}}\ m/s$$

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C. Drag resistance calculation

Drag resistance equation is given by:

$$F_D = 0.5*C_D*\rho*v^2*A$$

where

C_D is the drag coefficient (dimensionless)
ρ is the density of the air (kg/m^3)
v is the speed of the vehicle (m/s)
A is the cross-sectional area of the vehicle (m^2)

Examples

Question:

A car traveling with the speed of v=90 km/h (25 m/s) is having a drag coefficient as C_D=0.26. If the area of cross section is A=5 m^2, calculate the drag force.

Solution:

Speed v=90 km/h, drag coefficient C_D=0.26, Area A=5 m^2, density of air ρ=1.2 kg/m^3
The drag force is given by $F_D=0.5*C_D*\rho*v^2*A$; thus

$$F_D=0.5*0.26*1.2*625*5 = \underline{\mathbf{487.5}}\text{ N}$$

Question

What is the drag coefficient of a car running at a speed of v=32 m/s (115.2 km/h) against a drag force of F_D=230 N with a total front area of A=1.41 m^2, while the density of air is ρ=1.2 kg/m^3

Solution

$$C_D=2*F_D\,/\,\rho*v^2*A = 2*230\,/\,1.2*1024*1.41 = \underline{\mathbf{0.26}}$$

(in comparison, a ***Toyota Prius*** car has a drag coefficient of **0.29**).

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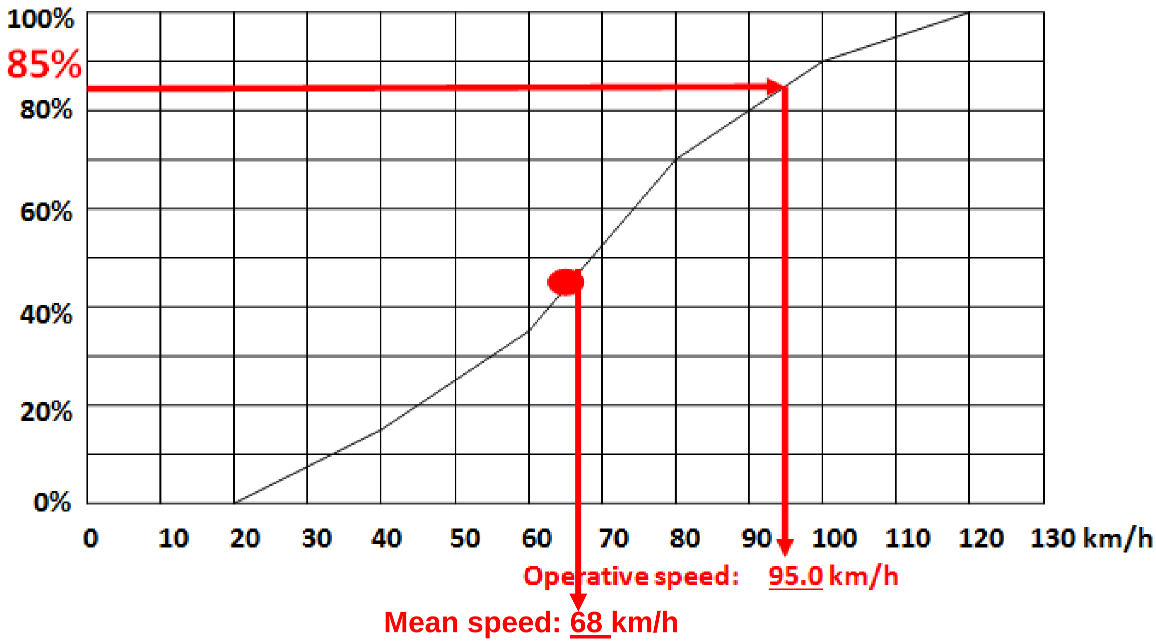
D. Speed distribution

The data related to the speed of vehicles on a road section in a morning rush hour is given in the following table:

Speed (km/h)	Percentage of vehicles running below that speed
120	100
100	90
80	70
60	35
40	15
20	0

Questions:

1. Draw the speed distribution function of the observed traffic flow
2. Estimate the mean or average speed value
3. Estimate the operative speed value



Mean/average speed: 0.1x110+0.2x90+0.35x70+0.2x50+0.15x30=11+18+24.5+10+4.5 = **<u>68</u> km/h**

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E. Stopping Sight Distance

Question

While descending a -7% grade at a speed of 90 km/h, Peter notices a large object in the roadway ahead of him. Without thinking about any alternatives, Peter stabs his brakes and begins to slow down. Assuming that Peter is so paralyzed with fear that he won't engage in an avoidance maneuver, calculate the minimum distance at which he must have seen the object in order to avoid colliding with it. You can assume that the roadway surface is concrete and that the surface is wet. You can also assume that Peter has a brake reaction time of 0.9 seconds because he is always alert on this stretch of the road.

Solution

First, we need to calculate the distance that Peter traveled during his brake reaction time. This is done using the equation $\mathbf{D_1}$ = v*T from physics. Since Peter's brake reaction time was 0.9 seconds and his speed was 25 m/s (90 km/h), the distance he traveled during his brake reaction time was

$$\mathbf{D_1}=25*0.9 = \underline{\mathbf{22.5}}\ m$$

Second, we need to calculate the distance Peter will travel while braking. This is done using the equation shown below:

$$D_2 = v^2/2g(f + G)$$

where:

- v = Peter's speed, 25 m/sec (90 km/h)
- g = acceleration due to gravity, 9.81 m/sec^2
- f = coefficient of friction, 0.29
- G = the grade of the road, -0.07 (-7%)

$$\mathbf{D_2} = 625 / (2*9.81(0.29-0.07) = 625 / 4.3164 = \underline{\mathbf{144.8}}\ m$$

Summing the distance traveled while braking and the distance traveled during the brake reaction time yields a total stopping sight distance of **167.3 m**. Peter needed to be about that far away from the object at the instant he first saw it in order to avoid a collision.

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F. Passing/Overtaking Sight Distance

Question

A vehicle moving at a speed of 80 km/h is slowing traffic on a two-lane road. What passing sight distance is necessary, in order for a passing maneuver to be carried out safely?

Calculate the passing sight distance by hand, and then compare it to the value estimated by the rule of thumb (distance travelled by the passing vehicle in 22 seconds). In your calculations, assume that the following variables have the values given:

- Passing vehicle driver's perception/reaction time = 2.5 sec
- Passing vehicle's acceleration rate = 2.35 km/h/sec
- Initial speed of passing vehicle = 80 km/h
- Passing speed of passing vehicle = 96 km/h
- Speed of slow vehicle = 80 km/h
- Speed of opposing vehicle = 96 km/h
- Length of passing vehicle = 7 m
- Length of slow vehicle = 7 m
- Clearance distance between passing and slow vehicles at lane change = 6 m
- Clearance distance between passing and slow vehicles at lane re-entry = 6 m
- Clearance distance between passing and opposing vehicles at lane re-entry = 76 m

You should also assume that the passing vehicle accelerates to passing speed before moving into the left lane.

Solution

The first step in calculating the passing sight distance is the calculation of the distance $\boldsymbol{D_1}$. This distance includes the distance traveled during the perception/reaction time and the distance traveled while accelerating to the passing speed. The distance traveled during the perception reaction time is computed using $D=v*T$ from physics, where v = 22.2 m/s (80 km/h) and T = 2.5 seconds. Solving for $\boldsymbol{D_1'}$ yields a value of **<u>55.5</u>** m.

The distance $\mathbf{D_1''}$ traveled during the acceleration portion of $\mathbf{D_1}$ is computed using the equation

$$v_f^2 = v_i^2 + 2AD_1''$$

where v_f = 26.7 m/s (96 km/h), v_i = 22.2 m/s (80 km/h), and A = 0.653 m/sec^2 (2.35 km/h/sec). Solving for $\mathbf{D_1''}$ yields

$$D_1'' = (v_f^2 - v_i^2) / 2A = (712.9 - 492.8) / 2*0.653 = 220 / 1.306 = \underline{\mathbf{168.5}}\ m$$

The total D_1 distance is: $D_1 = D_1' + D_1'' = 55.5 + 168.5 = \underline{\mathbf{224}}\ m$

The second portion of the passing sight distance is the distance D_2, which is defined as the distance that the passing vehicle travels while in the left lane. This distance can be calculated in the following way.

While in the left lane, the passing vehicle must traverse the clearance distance between itself and the slow vehicle, the length of the slow vehicle, the length of itself and the length of the clearance distance between itself and the slow vehicle at lane re-entry. The time it takes the passing vehicle to traverse these distances relative to the slow vehicle can be computed from the equation *D=v*T*, where D = 26 m (6m + 7 m + 7 m + 6 m) and v = 4.45 m/s (16 km/h = relative speed of passing vehicle with reference point on the slow vehicle).

Solving for the time T_2 yields a value of 5.84 seconds. The real distance traveled by the passing vehicle during the time T_2 is calculated using D=v*T, where v = 26.7 m/s. (96 km/h) and T_2 = 5.84 seconds. Solving for D yields the distance D_2 = **155.7** m.

The distance D_3 is the clearance distance between the passing vehicle and the opposing vehicle at the moment the passing vehicle returns to the right lane. This distance was given as **76** m.The distance D_4 is the final component of the passing sight distance and is defined as the distance the opposing vehicle travels during 66% of the time that the passing vehicle is in the left lane. This distance is computed using D=v*T, where v = 26.7 m/s (96 km/h) and T = 3.85 seconds (5.84*0.67). Solving for D yields a value of **103** m for D_4.

The total passing sight distance is, therefore, $D_1 + D_2 + D_3 + D_4 = \mathbf{558.7}\ m$. The passing sight distance estimated on the base of minimum passing time (22 s) yield by the equation D=v*T is

$$D = 26.7 * 22 = \mathbf{587.4}\ m$$

apparently very close to the value calculated above.

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G. Horizontal Curve Radius

Question

A young civil engineer is charged with the design of a horizontal curve for a two-lane main feeder road. His final design calls for a curve with a radius of 500 m. Would you sign your name to his plans?

Assume that the design speed v_D for the main road is 110 km/h, as well as snow and ice will be present on the roadway from time to time (continental climate prevails). For a design speed of 110 km/h, the comfortable side-friction factor is 0.10. In addition, since the roadway will be covered with snow and ice from time to time, the maximum superelevation rate is 8%.

Solution

The first step in a review of the plans would be to make sure that the curve radius ***R,*** as designed is greater than the minimum curve radius required by road design standards (R_{min}). The minimum horizontal curve radius is calculated using the equation below:

$$R_{min} = v_D^2/127(q_{max}/100+f_{max})$$

where:

R_{min} = minimum radius of horizontal curve (m)
v_D= design speed, 110 km/h
q_{max} = maximum superelevation rate, 8%
f_{max} = maximum side-friction factor, 0.10

Substituting and solving yields a minimum radius of

$$\mathbf{R_{min}} = 12\,100 / \ 127*(0.08+0.10) = \underline{\mathbf{530}}\ m$$

The 500 m radius that is called for in the plans would probably work, but it might be uncomfortable for the vehicle occupants. A larger radius would be more appropriate.

Question

When an existing road is rehabilitated and upgraded, the vertical and horizontal elements should be thoroughly checked for compliance with appropriate design standards. Please check, whether speed limit signs should be placed or not at the starting and ending cross sections of a horizontal curve which radius is R=550 m and superelevation q=4%, lying in a deep cut where the side-friction coefficient of the pavement is f_{2max}=0.10; assuming that design speed v_D=110 km/h approved for the upgraded design is higher, than the originally applied v_D=100 km/h.

Solution

The value of allowed maximum speed in a horizontal curve is estimated by the equation below:

$$v_{max} = \sqrt{127 * R * (f_2 + q)} \quad (km/h)$$

where

R is the radius of the horizontal curve (m)
f_2 is the coefficient of side-friction
q is the superelevation (m/100m)

Substituting and solving yields a maximum speed of

$$v_{max} = \sqrt{127 * 550 * (0.1 + 0.04)} = \underline{\mathbf{98.9}}\ km/h$$

for the current alignment.

Applying the increased design speed either the radius of the curve should be increased (assuming the superelevation remains unchanged):

$$R_{min} = v_D^2 / 127 * (f_2 + q) = 12100 / 127 * (0.1 + 0.4) = \underline{\mathbf{680}}\ \text{m; or}$$

the superelevation should be substantially increased (assuming, the radius of the curve remains unchanged):

$$q = (v_D^2 / 127 * R) - f_2 = (12100 / 127 * 550) - 0.1 = 0.17 - 0.1 = \underline{\mathbf{0.07\%}}\ \text{(m/100m); or}$$

traffic signs prescribing a **100 km/h speed limit** for vehicles running on the curve, should be placed appropriately.

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H. Transition Segments

After designing a horizontal curve with a radius of 580 m for a road with a design speed of 110 km/h, your final task is to design the transition segments. Your local design code requires that any superelevation within the curve be run-off over a distance equal to or greater than the distance a vehicle would travel in two seconds at your design speed. In addition, the spiral curves must have the minimum length given by the equation below:

$$L = (v^3) / (R*C)$$

where:

- L = minimum length of the spiral transition curve (m)
- v_D = design speed (km/h)
- R = circular curve radius (m)
- C = centripetal acceleration development rate (usually between 0.3 and 0.9 m/sec^3)

If you use a centripetal acceleration development rate of 0.7 m/sec^3, what is the minimum length of your transition segments?

Solution

We'll calculate the required length of your transition segments based on the superelevation restrictions first. At 110 km/h (30.6 m/s) you would travel a distance of 61.2 m in two seconds. Your transition segments should, therefore, slowly change the cross-section of the road over the course of **<u>61.2</u>** m. The minimum length of the spiral curve is investigated by substituting the correct values into the equation below:

$$L_{min} = (v^3) / (R*C)$$

where:

- L = minimum length of the spiral curve (m)
- v = Design speed, 30.6 m/s
- R = Circular curve radius, 580 m
- C = Centripetal acceleration development rate, 0.7 m/sec^3

Solving for the curve length:

$$L = (28653) / 406 = 90256 / 406 = \underline{\mathbf{70.6}}\ m$$

yields a minimum spiral curve length of **70.6** m.

Since you are required to have a 70.6 meter-long spiral curve, you should gradually change the road cross-section from its normal state to the superelevated state over 70.6 m > 61.2 m.