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[Notes about changes introduced in aaSIDRA 2.1 included]

# Estimating negotiation radius, distance and speed for vehicles using roundabouts

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## 1 INTRODUCTION

This paper discusses models for estimating negotiation radius, distance and speed values of through and turning vehicles at roundabouts. This is based on the method introduced in aaSIDRA version 2.0 (Akcelik and Associates 2002). [A new method for estimating the side friction factor as a function of speed has been introduced in aaSIDRA version 2.1. Refer to the latest aaSIDRA User Guide. ]

The intersection negotiation parameters are important for both efficiency and safety analysis purposes. In particular, they are needed for determining geometric delays, fuel consumption, pollutant emission and operating cost values for traffic using roundabouts.

Figures showing simplified constructions of vehicle paths for through, left-turning and right-turning vehicles are given. The method for determining negotiation radius, distance and speed of vehicles at roundabouts allows for path smoothing by drivers. Vehicle paths are constructed using the entry and exit kerb line arcs, inscribed and central island circles, and a layout circle. The safe negotiation speed formula uses a side friction factor that is a function of vehicle mass. Graphs showing the side friction factor as a function of vehicle mass, and negotiation speed as a function of turn radius are presented.

The negotiation radius, distance and speed values as a function of the roundabouts size are given for through, left-turn and right-turn movements. Graphs are given to show the sensitivity of average geometric delay for through, left-turn and right-turn movements to (i) roundabout size and (ii) approach and exit cruise speeds.

In aaSIDRA, the method is applied to any origin-destination movement at a roundabout with up to eight legs, for conditions of driving on the left-hand or right-hand side of the road. This paper outlines the method for through, left-turning and right-turning vehicle movements for driving on the left-hand side of the road.

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## 2 NEGOTIATION RADIUS and DISTANCE

Simplified constructions of vehicle paths for through, left-turning and right-turning vehicles are shown in *Figures 2.1 to 2.3*. These movements are defined by the angle between approach and exit legs for these movements, which are 90 degrees for the left-turning movement, 180 degrees for the through movement, and 270 degrees for the right-turning movement. The vehicle path from the entry give-way (yield) line to the exit line (A to B in *Figures 2.1 to 2.3*) is constructed for each movement using the entry and exit kerb line arcs, inscribed and central island circles, and a layout circle.

Through and right-turning vehicles are assumed to travel along a more direct line on the circulating road moving closer to the central island, and left-turning vehicles are assumed to travel closer to the exit kerb. This represents path smoothing by drivers at roundabouts (AUSTROADS 1993, FHWA 2000). The aaSIDRA method uses a path factor for each vehicle movement in order to determine the lateral position of the vehicle on the circulating road in relation to the central island or the exit kerb when the vehicle is half way through its path.

The negotiation distance is the length of the path from A to B in *Figures 2.1 to 2.3*. This is determined from the negotiation radius and negotiation angle:

$$L_n = \pi \, r_n \, \alpha_n / 180 \qquad (2.1)$$

where $L_n$ = negotiation distance (m), $r_n$ = negotiation radius (m), and $\alpha_n$ = negotiation angle (degrees).

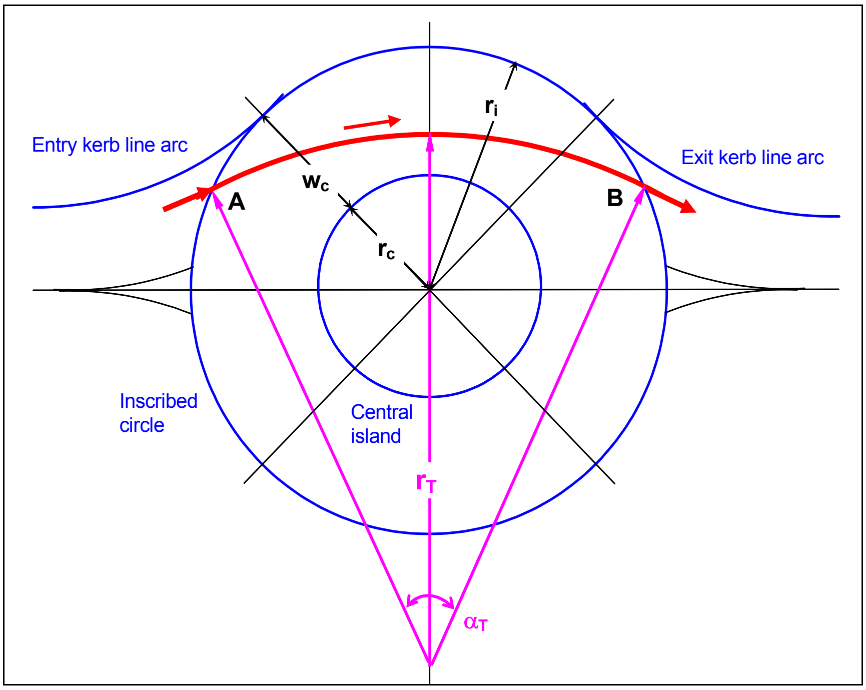


***Figure 2.1 - A simplified construction of the path of a THROUGH VEHICLE negotiating a roundabout***

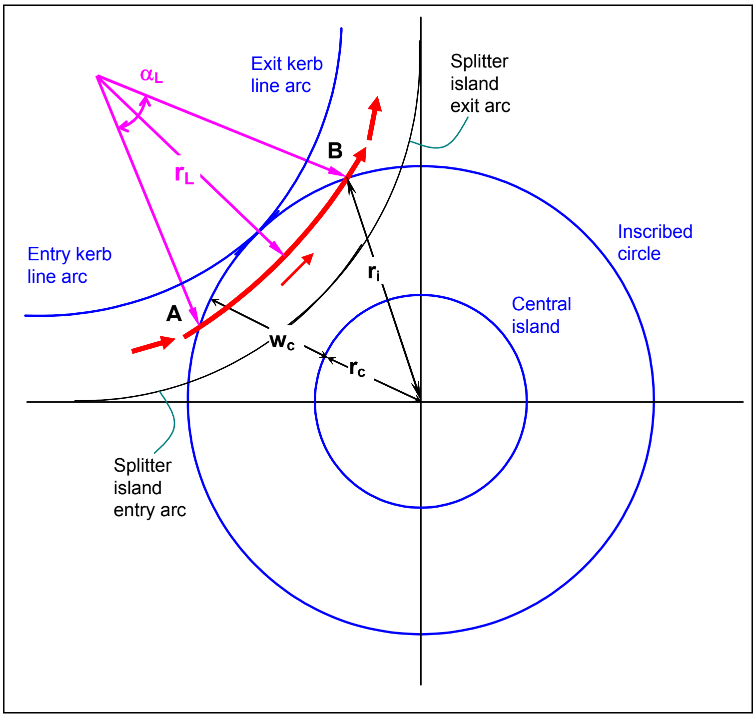


*Figure 2.2 - A simplified construction of the path of a LEFT-TURNING VEHICLE negotiating a roundabout*

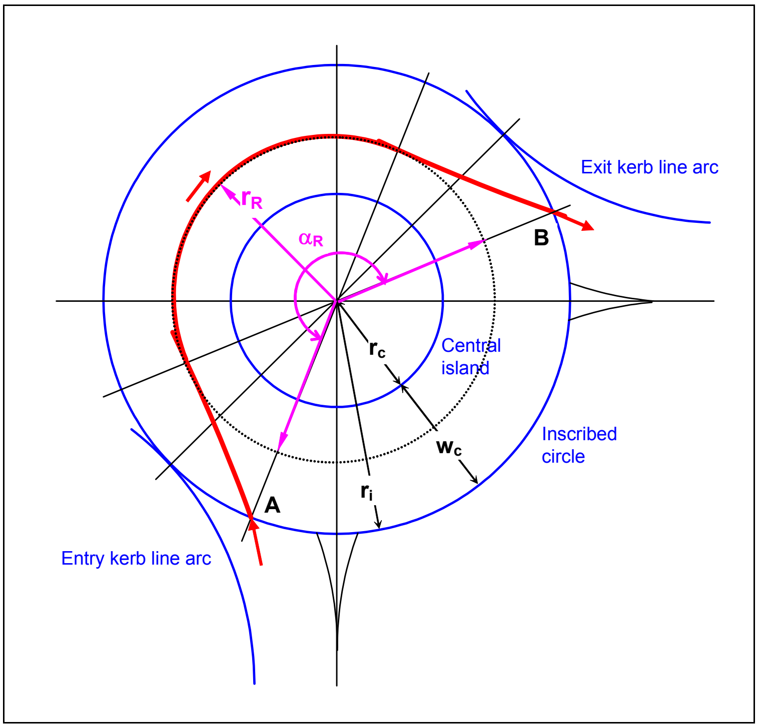


*Figure 2.3 - A simplified construction of the path of a RIGHT-TURNING VEHICLE negotiating a roundabout*

The negotiation radius depends on the size of the roundabout (central island diameter, circulating road width and entry road width) as well as the path factor for lateral distance. The negotiation angles for the through and left-turning movements are determined as a function of the radius. The negotiation angle for the right-turning movement is determined as 225 degrees where the angle between the approach and exit legs is 270 degrees.

*Table 2.1* shows negotiation angle, radius, distance and speed values for through, left-turning and right-turning vehicles estimated for various roundabout sizes. For the values in *Table 2.1*, total entry width = 8 m, and $f_s$ = 0.266 found using default vehicle mass values of $M_{LV}$ = 1400 kg, $M_{HV}$ = 11000 kg and $p_{HV}$ = 0.05 were used.

***Table 2.1***

***Negotiation angle, radius, distance and speed values for through, left-turning and right-turning vehicles estimated for various roundabout sizes***

| Roundabout size | | | Through vehicles | | | | Left-turning vehicles | | | | Right-turning vehicles | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $r_c$ | $w_c$ | $D_i$ | $\alpha_T$ | $r_T$ | $L_T$ | $v_T$ | $\alpha_L$ | $r_L$ | $L_L$ | $v_L$ | $\alpha_R$ | $r_R$ | $L_R$ | $v_R$ |
| 8 | 7 | 30 | 51 | 31 | 28 | 33 | 42 | 16 | 12 | 23 | 225 | 11 | 42 | 19 |
| 10 | 10 | 40 | 53 | 40 | 37 | 37 | 39 | 23 | 16 | 28 | 225 | 14 | 55 | 22 |
| 15 | 10 | 50 | 47 | 57 | 47 | 44 | 32 | 35 | 19 | 34 | 225 | 19 | 75 | 25 |
| 20 | 10 | 60 | 43 | 76 | 57 | 50 | 28 | 47 | 23 | 40 | 225 | 24 | 94 | 28 |
| 25 | 10 | 70 | 40 | 97 | 67 | 50 | 26 | 59 | 27 | 45 | 225 | 29 | 114 | 31 |
| 30 | 10 | 80 | 37 | 100 | 84 | 50 | 25 | 71 | 31 | 49 | 225 | 34 | 134 | 34 |
| 35 | 10 | 90 | 35 | 100 | 93 | 50 | 24 | 83 | 35 | 50 | 225 | 39 | 153 | 36 |
| 40 | 10 | 100 | 33 | 100 | 87 | 50 | 23 | 95 | 39 | 50 | 225 | 44 | 173 | 39 |
| 10 | 8 | 36 | 50 | 39 | 34 | 36 | 37 | 22 | 14 | 27 | 225 | 13 | 52 | 21 |
| 10 | 9 | 38 | 52 | 39 | 35 | 36 | 38 | 22 | 15 | 27 | 225 | 14 | 53 | 21 |
| 10 | 10 | 40 | 53 | 40 | 37 | 37 | 39 | 23 | 16 | 28 | 225 | 14 | 55 | 22 |
| 15 | 8 | 46 | 44 | 57 | 44 | 44 | 30 | 34 | 18 | 34 | 225 | 18 | 71 | 25 |
| 15 | 10 | 50 | 47 | 57 | 47 | 44 | 32 | 35 | 19 | 34 | 225 | 19 | 75 | 25 |
| 15 | 12 | 54 | 50 | 58 | 51 | 44 | 33 | 36 | 21 | 35 | 225 | 20 | 78 | 26 |
| 20 | 8 | 56 | 40 | 78 | 54 | 50 | 27 | 46 | 22 | 39 | 225 | 23 | 91 | 28 |
| 20 | 10 | 60 | 43 | 76 | 57 | 50 | 28 | 47 | 23 | 40 | 225 | 24 | 94 | 28 |
| 20 | 12 | 64 | 46 | 76 | 61 | 50 | 29 | 48 | 25 | 40 | 225 | 25 | 97 | 29 |
| 25 | 8 | 66 | 36 | 100 | 64 | 50 | 25 | 58 | 25 | 44 | 225 | 28 | 111 | 31 |
| 25 | 10 | 70 | 40 | 97 | 67 | 50 | 26 | 59 | 27 | 45 | 225 | 29 | 114 | 31 |
| 25 | 12 | 74 | 42 | 96 | 71 | 50 | 27 | 61 | 29 | 45 | 225 | 30 | 117 | 32 |
| 30 | 10 | 80 | 37 | 100 | 84 | 50 | 25 | 71 | 31 | 49 | 225 | 34 | 134 | 34 |
| 30 | 12 | 84 | 40 | 100 | 90 | 50 | 26 | 73 | 32 | 50 | 225 | 35 | 137 | 34 |
| 30 | 14 | 88 | 42 | 100 | 99 | 50 | 26 | 74 | 34 | 50 | 225 | 36 | 140 | 35 |
| 40 | 10 | 100 | 33 | 100 | 87 | 50 | 23 | 95 | 39 | 50 | 225 | 44 | 173 | 39 |
| 40 | 12 | 104 | 35 | 100 | 87 | 50 | 24 | 97 | 40 | 50 | 225 | 45 | 176 | 39 |
| 40 | 14 | 108 | 38 | 100 | 86 | 50 | 24 | 98 | 42 | 50 | 225 | 46 | 179 | 39 |

$r_c$ = Central island diameter, $w_c$ = Circulating road width,
$\alpha_n$ = negotiation angle (degrees), $r_n$ = negotiation radius (m), $L_n$ = negotiation distance (m), $v_n$ = negotiation speed (km/h)
Entry width = 8 m, $f_s$ = 0.266.

## 3 NEGOTIATION SPEED

The safe negotiation speed is determined from the following formula (see AUSTROADS 1993), Section 4.2.6, and FHWA 2000, Section 6.2.1.4):

$$v_n = 3.6\, sqrt\, (9.81\, (f_s + e)\, r_n) \quad \text{subject to } v_{nmin} \leq v_n \leq v_{nmax} \qquad (3.1)$$

where $v_n$ = negotiation speed (km/h), $f_s$ = side friction factor (coefficient of side frictional force), e = superelevation (m/m) and $r_n$ = negotiation radius (m).

The minimum and maximum values of the negotiation speed are $v_{nmin}$ = 5 km/h and $v_{nmax}$ = *min* ($v_{ec}$, 50 km/h) where $v_{ec}$ = exit cruise speed. The condition $v_n \leq 50$ km/h is based on safety considerations (AUSTROADS 1993). aaSIDRA uses an additional condition for negotiation speeds for all movements other than the through movement that they should not exceed the through vehicle negotiation speed at roundabouts.

FHWA (2000) Roundabout Guide recommends $e_e = +0.2$ for entry and exit curves, and $e_c = -0.2$ for curves around the central island (circulating road). aaSIDRA 2.0 uses e = 0 generally. The resulting negotiation speed difference from the FHWA recommended values is 1-2 km/h (about 1 mi/h). [In aaSIDRA version 2.1, default superelevation value is e = - 0.2 . ]

aaSIDRA uses the following formula to determine the side friction factor for light and heavy vehicles:

$$f_s = 0.30 - 0.00084\, sqrt\, (M_v) \quad \text{subject to } f_s \geq 0 \qquad (3.2)$$

where $M_v$ is the average vehicle mass (kg).

[A new method for estimating the side friction factor as a function of speed has been introduced in aaSIDRA version 2.1. Refer to the latest aaSIDRA User Guide. ]

*Figure 3.1* shows the side friction factor obtained from *Equation (3.2)*. The side friction factors calculated for the default mass values of $M_{vLV}$ = 1400 kg for light vehicles and $M_{vHV}$ = 11000 kg for heavy vehicles used in aaSIDRA (0.269 and 0.212, respectively) are also shown in *Figure 3.1*.

To allow for Light and Heavy Vehicles in the traffic stream, the side friction factor is calculated from:

$$f_s = (1 - p_{HV})\, f_{sLV} + p_{HV}\, f_{sHV} \qquad (3.3)$$

where $p_{HV}$ is the proportion of heavy vehicles in the traffic stream, $f_{sLV}$ is the side friction factor for light vehicles, and $f_{sHV}$ is the side friction factor for heavy vehicles.

For example, with 5 per cent heavy vehicles ($p_{HV}$ = 0.05), $f_s$ = 0.266 is obtained using the side friction factors for aaSIDRA default mass values, $f_{sLV}$ = 0.269 and $f_{sHV}$ = 0.212.

*Figure 3.2* shows the negotiations speeds calculated for Light and Heavy Vehicles using e = 0 and the side friction factors for aaSIDRA default mass values.

Negotiation speed values for through, left-turning and right-turning vehicles estimated for various roundabout sizes are given in *Figure 2.4* in *Section 2*.

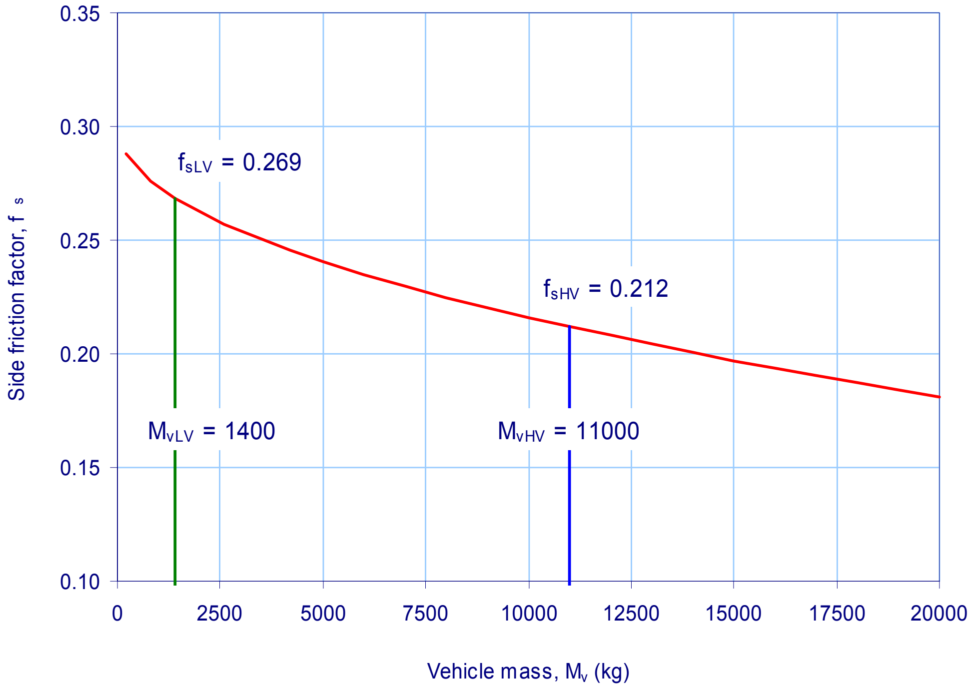


***Figure 3.1 - Side friction factor as a function of the vehicle mass (side friction factors for aaSIDRA default Light and Heavy Vehicle mass values are shown)***

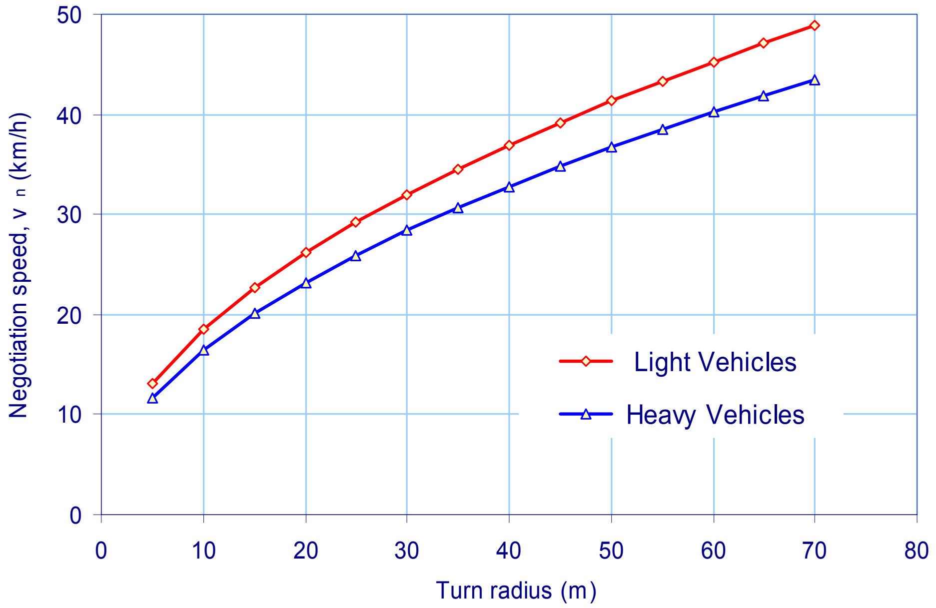


***Figure 3.2 - Negotiation speed as a function of the turn radius (using side friction factors for aaSIDRA default Light and Heavy Vehicle mass values)***

## 4 GEOMETRIC DELAY

*Geometric delay* is the delay experienced by a vehicle negotiating an intersection in the absence of any other vehicles. This delay is due to a deceleration from the approach cruise speed down to a safe (approach) negotiation speed, travel at that speed, acceleration to an exit negotiation speed, and then acceleration to the exit cruise speed.

The delay to a vehicle which decelerates from the approach cruise speed to a full stop (due to a reason such as a red signal, a queue ahead, or lack of an acceptable gap), waits and then accelerates to the exit cruise speed is considered to include (i) the delay due to a deceleration from the approach cruise speed down to an approach negotiation speed and then to zero speed, (ii) idling time, (iii) acceleration to an exit negotiation speed along the negotiation distance, (iv) travelling the rest of the negotiation distance (if any) at the constant exit negotiation speed, and (v) acceleration to the exit cruise speed. This delay is called *control delay*.

The addition of geometric delay to the delay estimated by analytical models (gap-acceptance and queuing theory model in the case of roundabouts) requires a clarification of whether the analytical model delay includes any acceleration and deceleration delays. The method used in aaSIDRA makes the following assumption regarding this issue:

> The delay estimated by analytical models includes the stop-start delay to queued vehicles that results from decelerating from the *approach negotiation speed* to zero speed and accelerating back to the *exit negotiation speed*. Thus, every vehicle in a given stream experiences the same geometric delay as an additional delay associated with decelerating from the *approach cruise speed* to the *approach negotiation speed* and accelerating from the *exit negotiation speed* to the *exit cruise speed*.

As such, the method used in aaSIDRA differs from the Australian roundabout guide (AUSTROADS 1993) that calculates separate geometric delay values for queued and unqueued (stopped and unstopped) vehicles. The AUSTROADS method assumes that the analytical model delay does not include any deceleration and acceleration delays.

aaSIDRA uses a detailed model for determining the geometric delay for each intersection type as a function of the intersection geometry, control type and approach cruise, negotiation and exit cruise speeds. Since the negotiation distance and speed parameters depend on the intersection size (all intersection types), the geometric delay varies with the intersection size. It also depends on approach and exit cruise speed values (usually specified as the posted speed limits).

*Figure 4.1* shows how the geometric delay varies with the roundabout size for a single-lane roundabout (circulating road width of 8 m and an entry width of 4 m). The central island diameter is varied between 9 m and 34 m, therefore the inscribed circle diameter varies between 25 m and 50 m. The results for two cruise speeds are considered, namely 50 km/h and 80 km/h (same for all approaches).

*Figure 4.2* shows how the geometric delay varies with the approach and exit cruise speeds (same speed for all legs) for a given roundabout size. A single-lane roundabout is assumed (circulating road width of 8 m, entry width of 4 m). Two roundabout sizes are considered by specifying central island diameters of 14 m and 34 m (inscribed circle diameters of 30 m and 50 m).

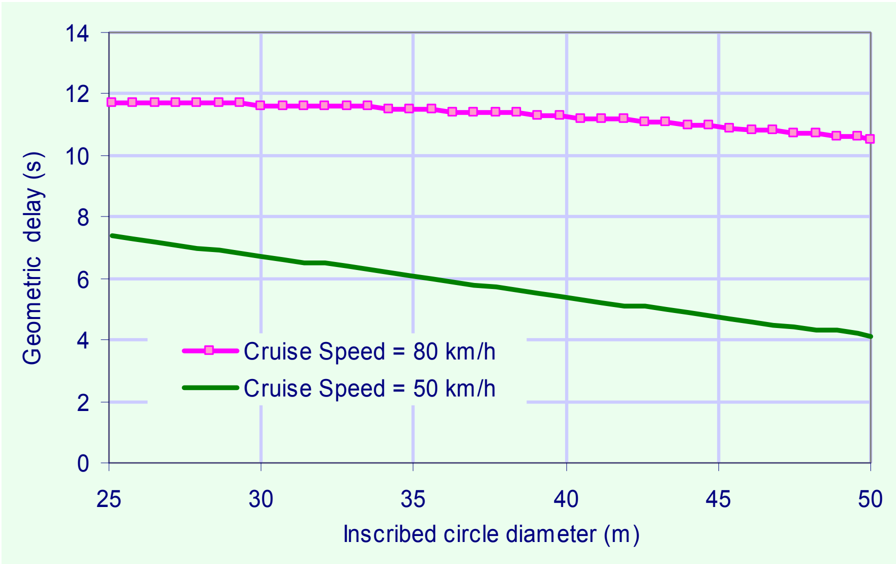


***Figure 4.1 - Average geometric delay for through, left-turning and right-turning vehicles as a function of the roundabout size (single-lane roundabout with circulating road width= 8 m and entry width = 4 m)***

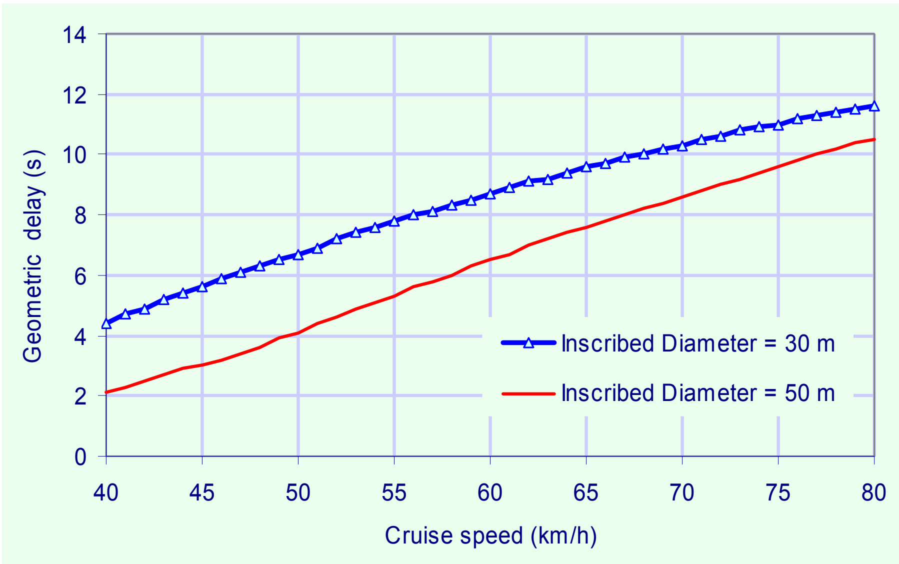


***Figure 4.2 - Average geometric delay for through, left-turning and right-turning vehicles as a function of the cruise speed (single-lane roundabout with circulating road width= 8 m and entry width = 4 m)***

*Figures 4.1 and 4.2* show average geometric delays for through, left-turning and right-turning vehicles using values calculated by aaSIDRA. Acceleration and deceleration models used in aaSIDRA for this purpose are discussed in Akçelik and Besley (2001a).

## 5 CONCLUSION

The estimates of roundabout negotiation radius, distance and speed parameters given in this paper are based on a model that approximates the complex geometric features of roundabouts as well as the complex behaviour of drivers using them. However, the model provides a good analytical base for determining such performance measures as delay, operating cost, fuel consumption and pollutant emissions.

It is recommended that various microsimulation models (Akçelik and Besley 2001b) are examined in relation to sensitivity of intersection negotiation speeds and the resulting performance measures to the geometric characteristics of intersections, in general, and roundabouts, in particular.

## DISCLAIMER



## REFERENCES

AKCELIK & ASSOCIATES (2002). *aaSIDRA User Guide*. Akcelik and Associates Pty Ltd, Melbourne, Australia.

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