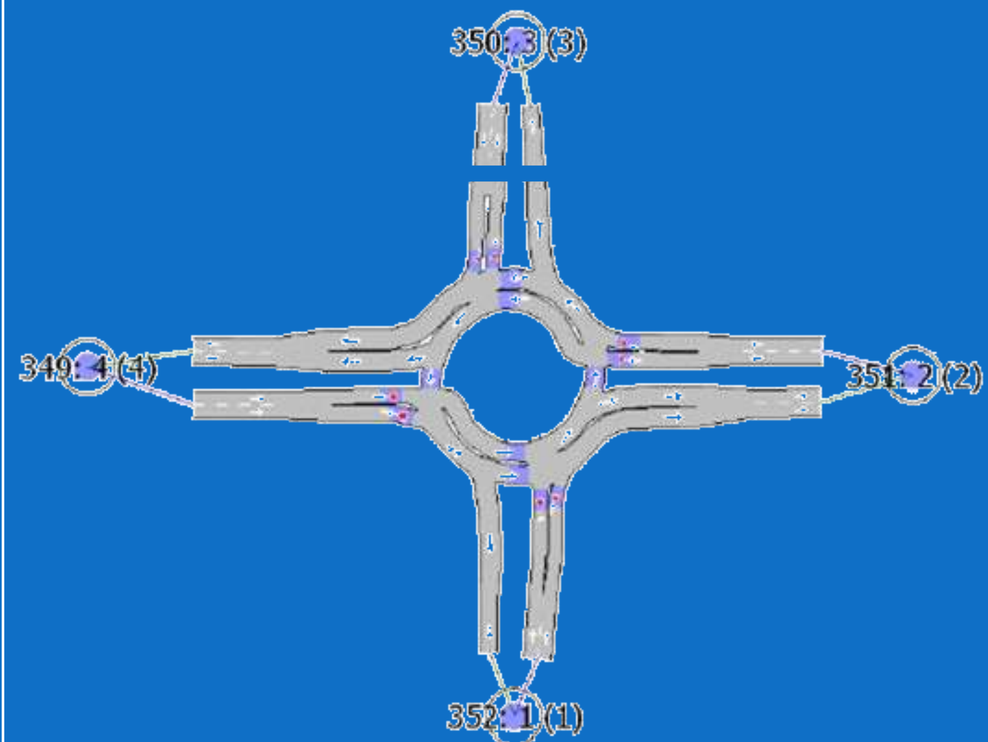
Conferência **AVALIAÇÃO OPERACIONAL E AMBIENTAL DE ROTUNDAS ,**
9 de dezembro 2014

Designing Turbo-roundabouts



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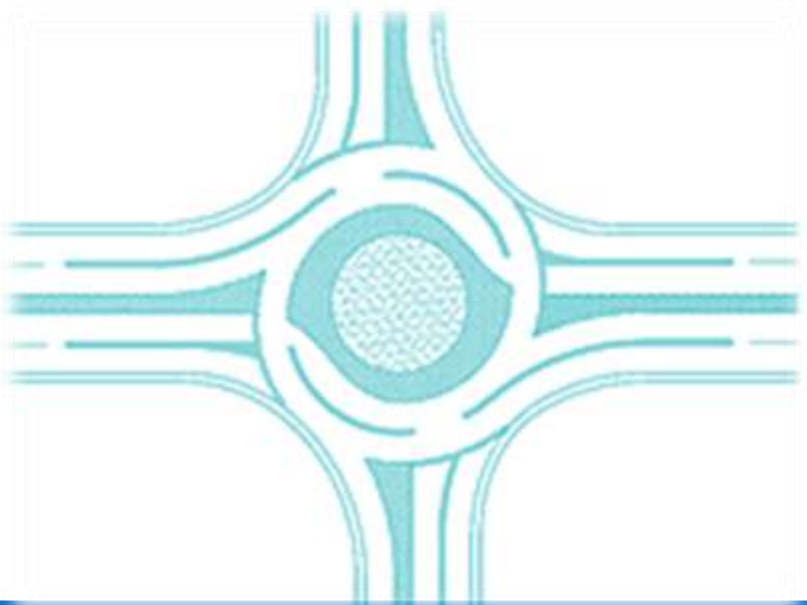
outlines

- ✓ What's the turbo-roundabout?
- ✓ Turboroundabouts vs roundabouts in brief



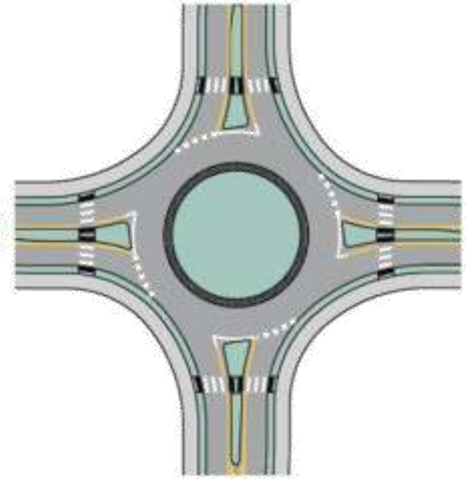
What's the turbo-roundabout?

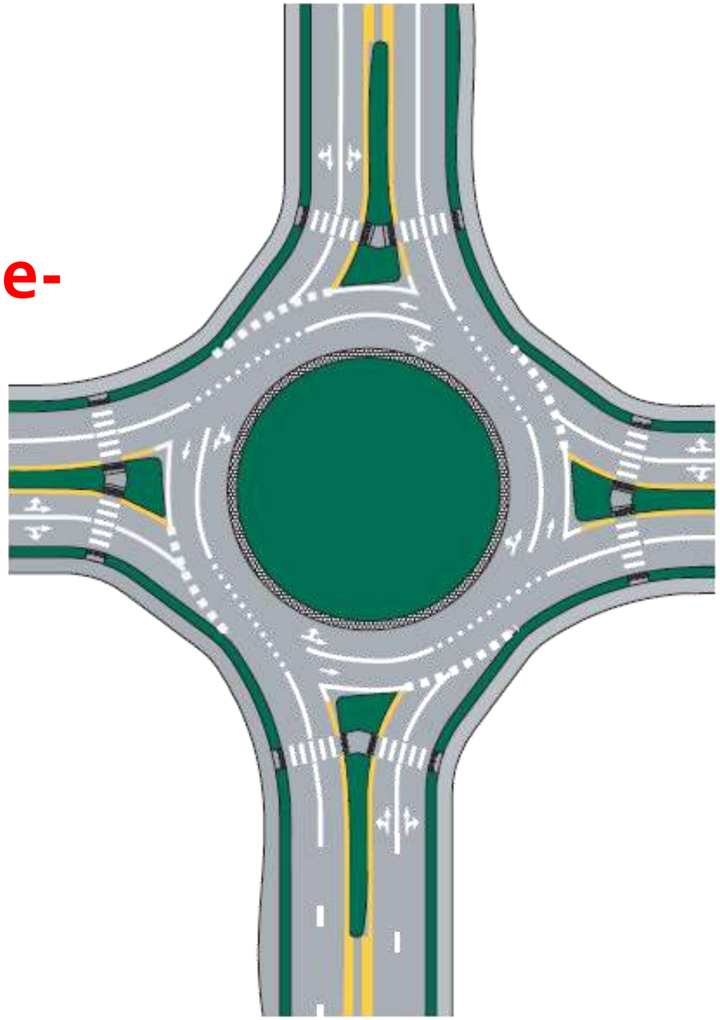
- ✓ **Turbo-roundabout** is an innovative roundabout where lanes are bounded by traffic signs and raised curbs placed at entering and circulating lanes;
- ✓ **spiral lines** and **raised lane separators** on the ring require drivers to **choose the lane** before entering the intersection;

- ✓ **spiral lines** on the ring guide drivers **to the correct exit.**

What's the turbo-roundabout?

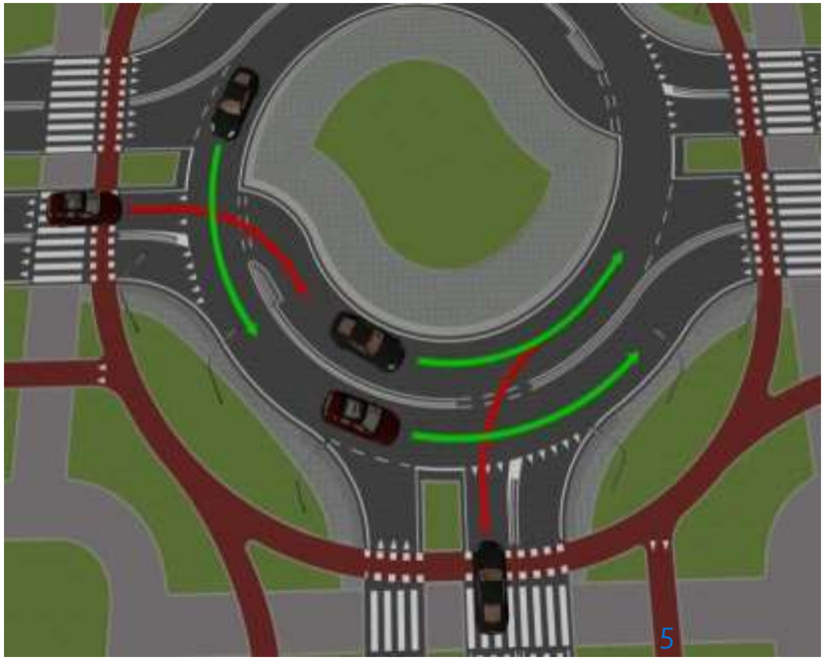
✓ **Fortuijn** (2009) **revolutionized** the **roundabout design** in The Netherlands, creating a roundabout with a **same** or a **higher** capacity than the **double-lane** roundabout, but with the **same safety** features as the **single-lane** roundabout.





What's the turbo-roundabout?

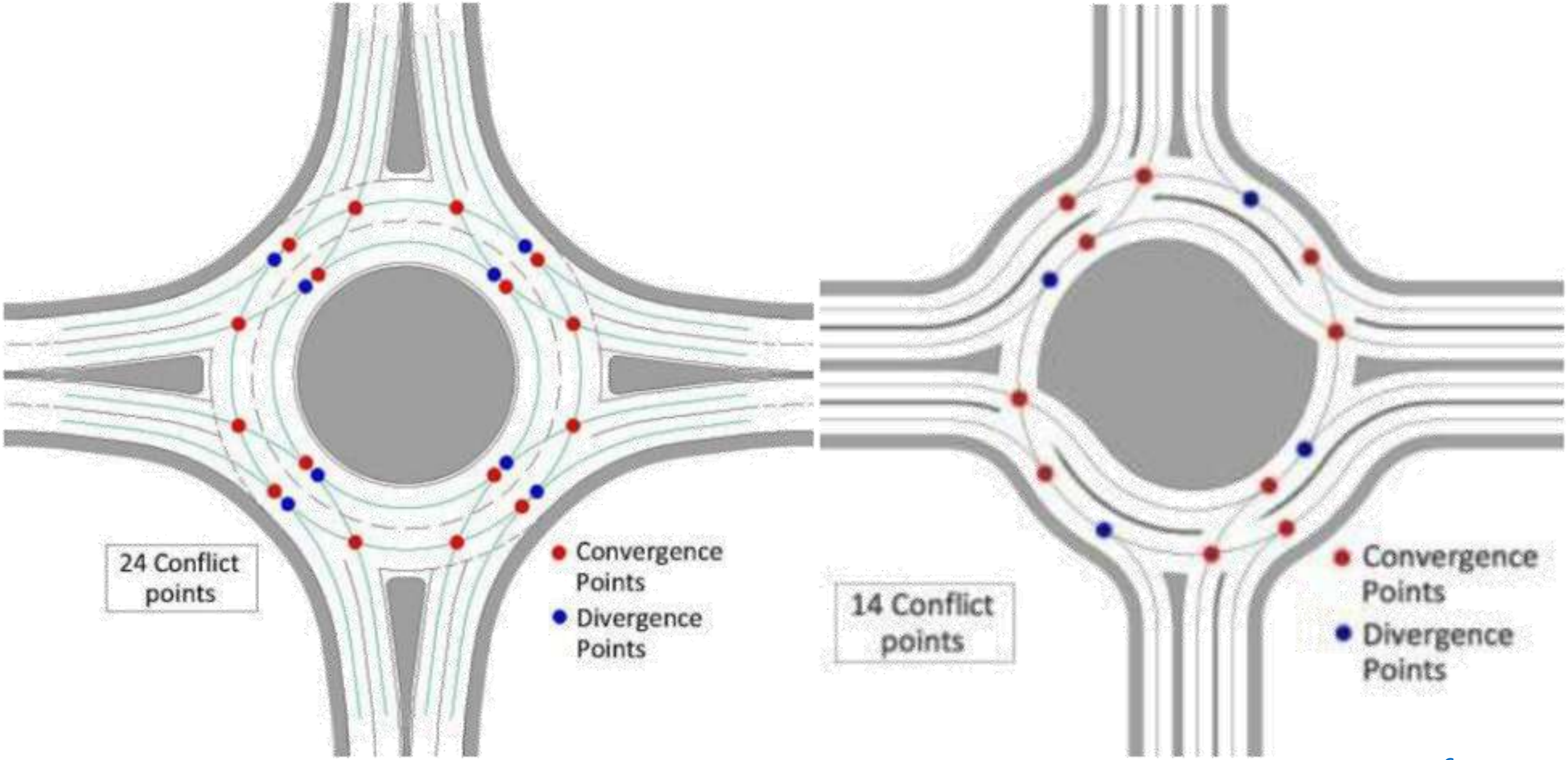
- ✓ The turbo-roundabout meets the following conditions:
  - ❖ no lane changing on the roundabout;
  - ❖ no need to yield to more than two lanes;
  - ❖ low driving speed through the roundabout.



What's the turbo-roundabout?

The turbo roundabout answers three problems of the double-lane roundabout:

✓reduction in the number of conflicts, eliminating weaving and cut-in conflicts;



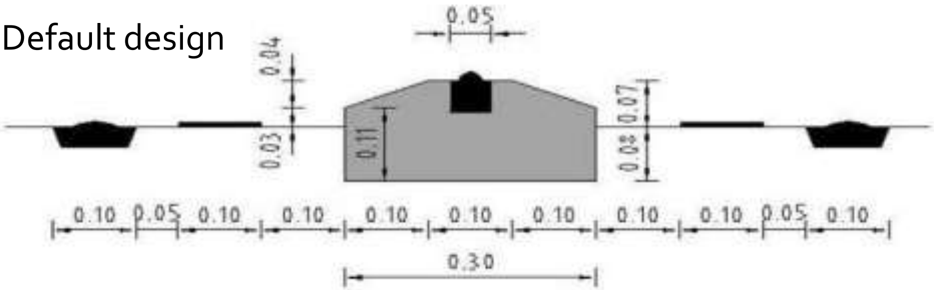
Conflict points in standard double-roundabout vs. turbo-roundabout

What's the turbo-roundabout?

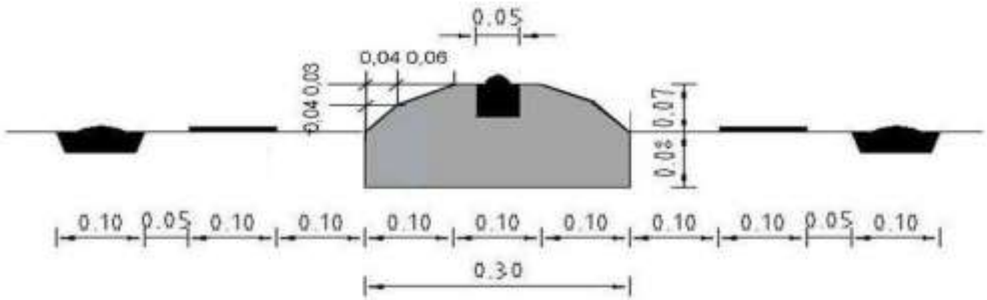
The turbo roundabout answers three problems of the double-lane roundabout:

- ✓Because weaving is unnecessary, **it is possible to apply raised lane dividers**, **making it impossible to cut in to reduce path curvature** without accepting a high level of discomfort;
- ✓thus, physical separation is achieved by specially shaped elements, which hinder the change of traffic lanes in the roundabout.

Default design



Modified to permit use for snow plough



Cross-sectional view of raised mountable lane divider (Fortujin, 2009)

What's the turbo-roundabout?

✓**Physical separation** of traffic lanes is stopped only at the inner roundabout traffic lane.

What's the turbo-roundabout?

The turbo roundabout answers three problems of the double-lane roundabout:

✓the **spiral lane marking**, together with **raised lane dividers**, allows the traffic flow to be distributed over the different lanes;

✓thus, the **turbo roundabout** has a **higher capacity**, compared to the double-lane roundabout.

REASONS

I. there are usually **2 entering lanes** continuing into **2 circulating lanes**,

II. the use of the **inner circulating lane** is more **attractive**, since there is no need for weaving,

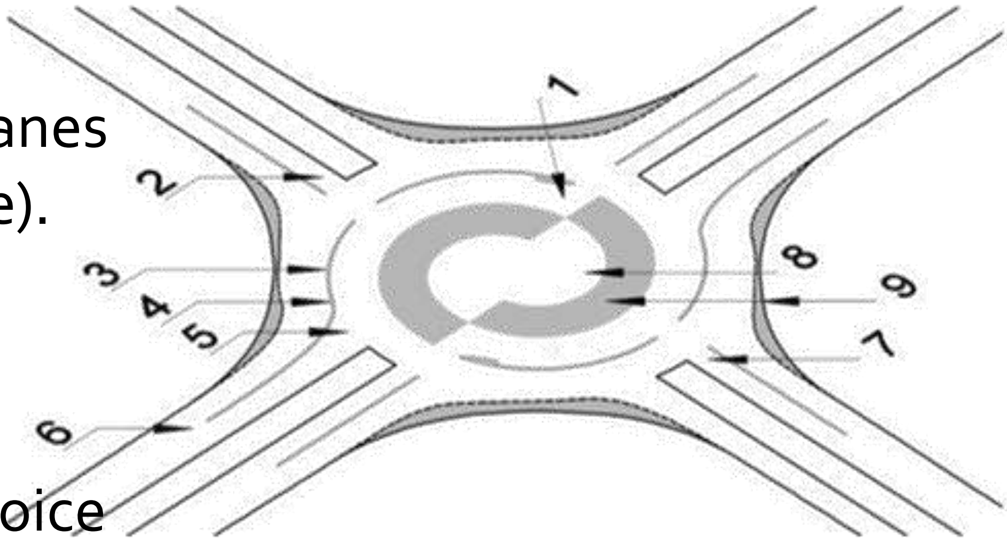
III. the entering flow is no longer **hesitant**, which increases the entry capacity.

Cross-sectional view of raised mountable lane divider (Fortujin, 2009)

What's the turbo-roundabout?

Features of a Turbo roundabout

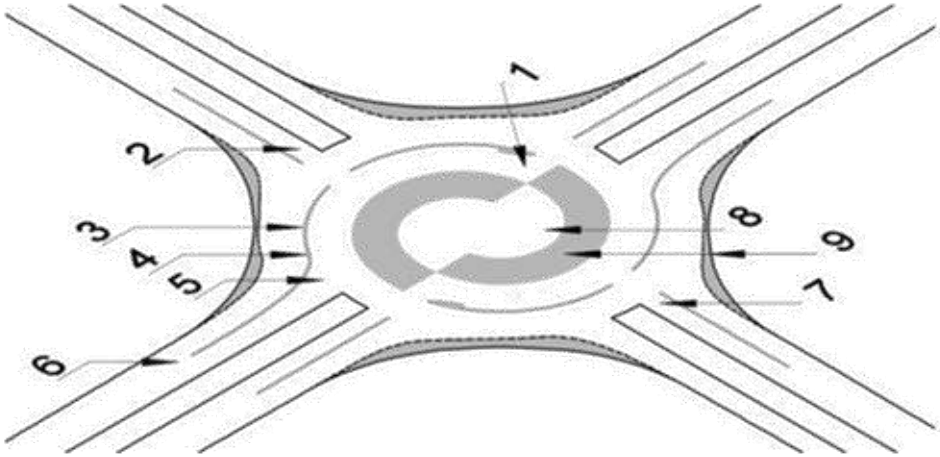
1. Nested spiral lane at one or more entries.
2. Yield to no more than two lanes (deviation might be possible).
3. Smooth spiral markings.
4. Raised and mountable lane dividers.
5. At least one lane offers a choice for direction.
6. At least two exit legs have two exit lanes.
7. Entry approach are at right angles to roundabouts.



What's the turbo-roundabout?

Features of a Turbo roundabout

8. Roundabout signage cuts off the horizon for optimal recognition.
9. Aprons in central island are established to keep narrow lane width for passenger vehicles but provide additional driving surface for heavy vehicles.



✓ A number of different types of roundabouts can be constructed on the basis of the principle above indicated.

What’s the turbo-roundabout?

DIFFERENT VARIANTS OF THE TURBO ROUNDABOUT - Fortuijn (2009)

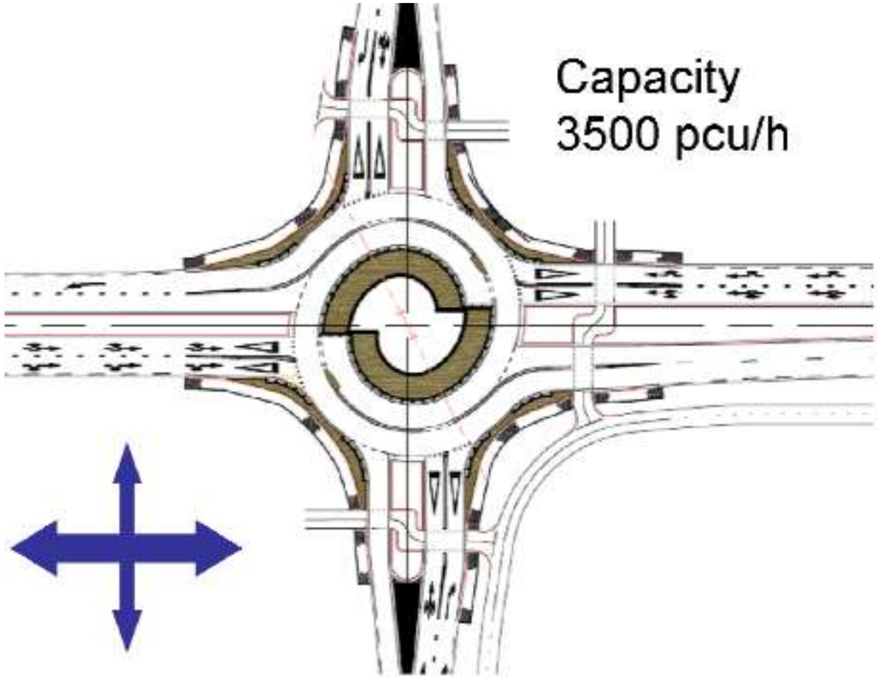
- ✓ all the different variants meet the requirement that **the number of lanes at entries** corresponds with the **number on the ring**.

- ✓ **Three or four legs**:
  - Basic turbo roundabout
  - Spiral roundabout
  - Knee roundabout
  - Rotor roundabout (less suitable for three-leg junctions)
- ✓ **Three legs only**:
  - Stretched-knee roundabout
  - Star roundabout

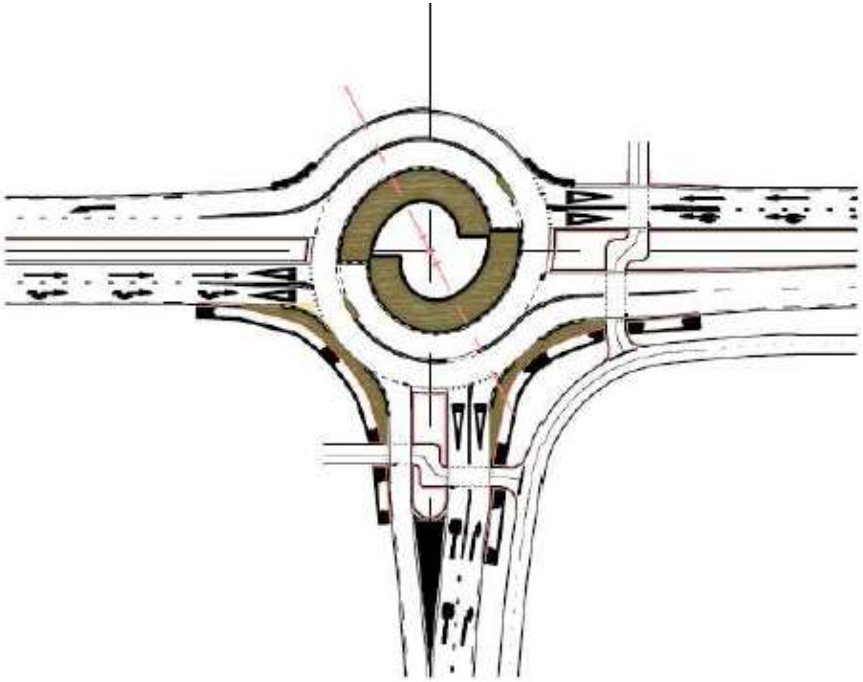
Fortujin, 2009

What's the turbo-roundabout?

✓ The variant initially called simply 'Turbo roundabout' is now named the 'Basic Turbo roundabout' to distinguish it from all the others (CROW, 2008)



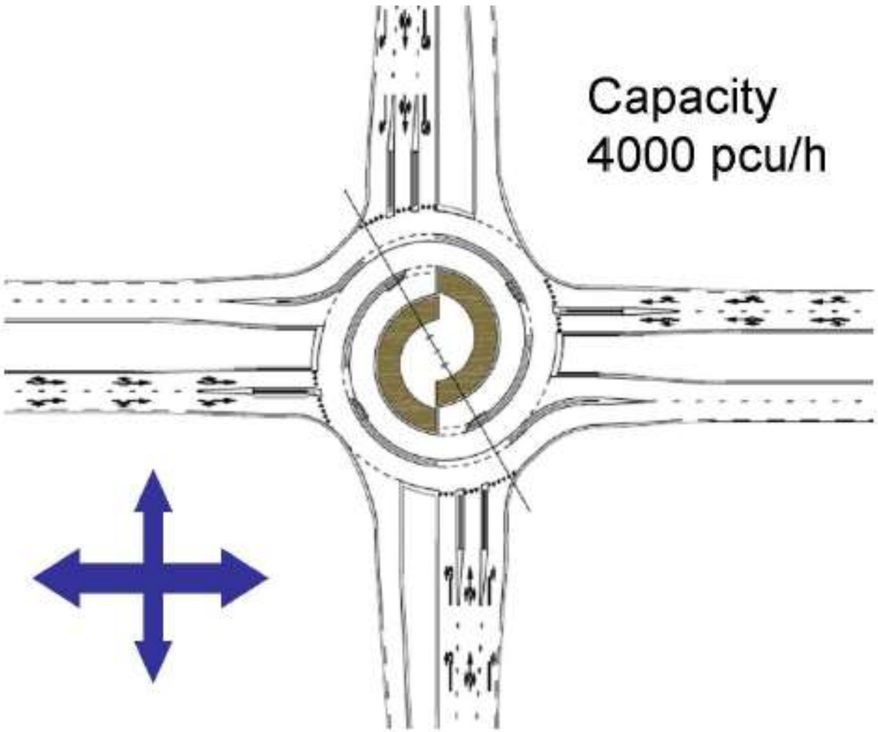
Basic turbo roundabout



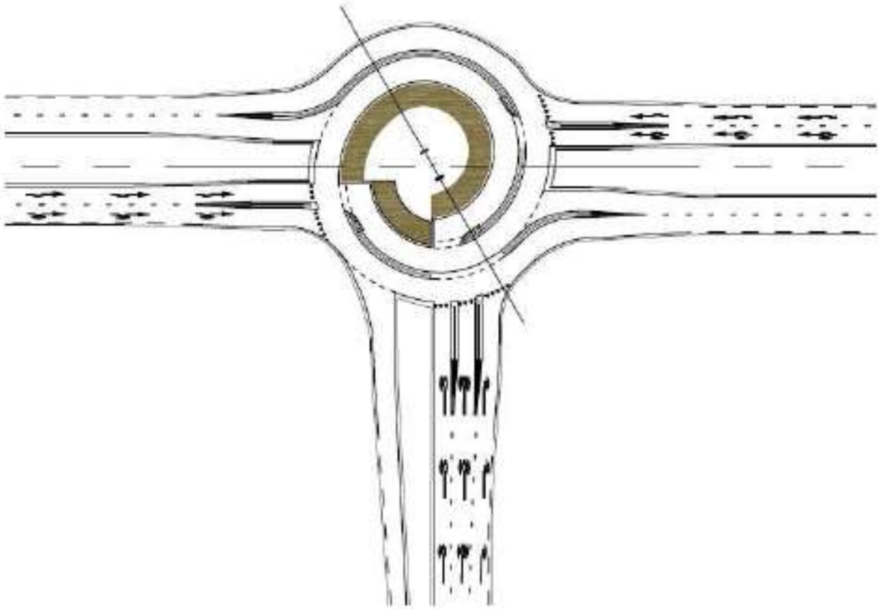
Three-leg Basic turbo roundabout

Fortujin, 2009

What’s the turbo-roundabout?



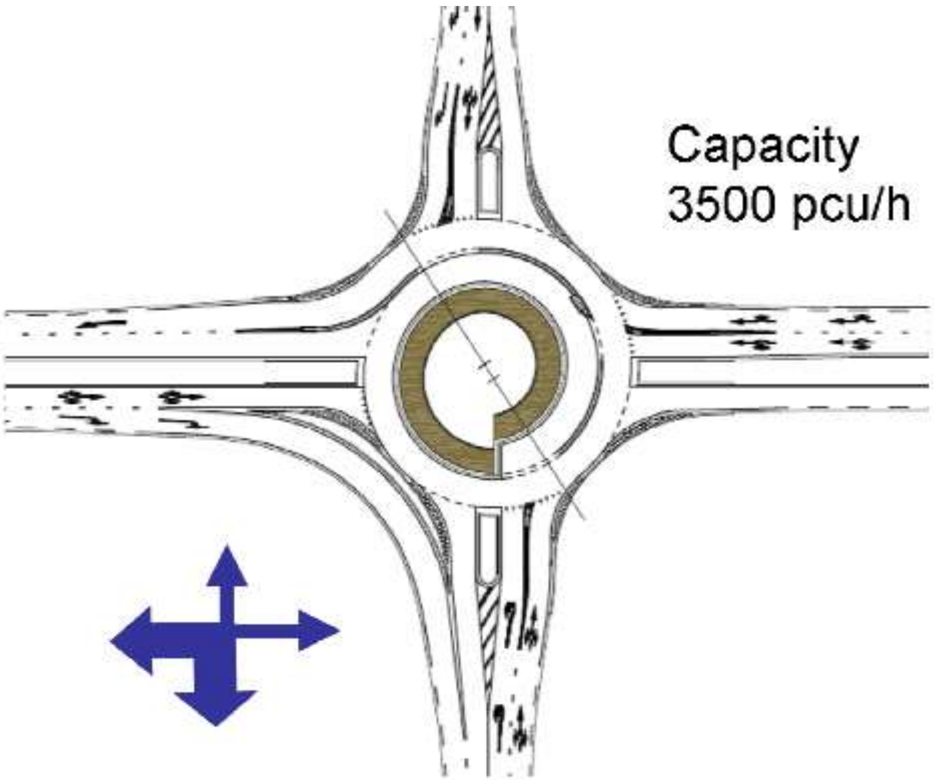
Spiral roundabout



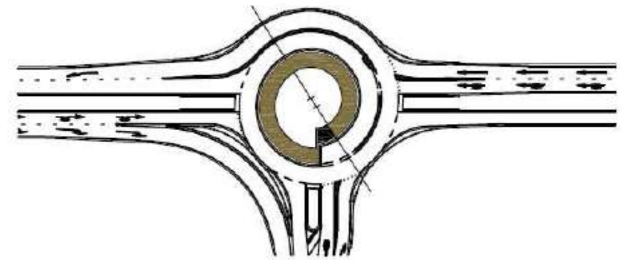
Three-leg Spiral roundabout

Fortujin, 2009

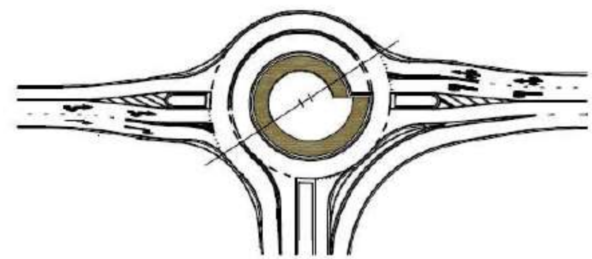
What's the turbo-roundabout?



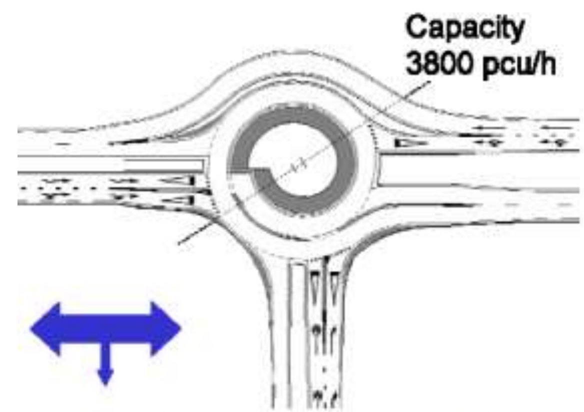
Knee roundabout



Three-leg Knee roundabout



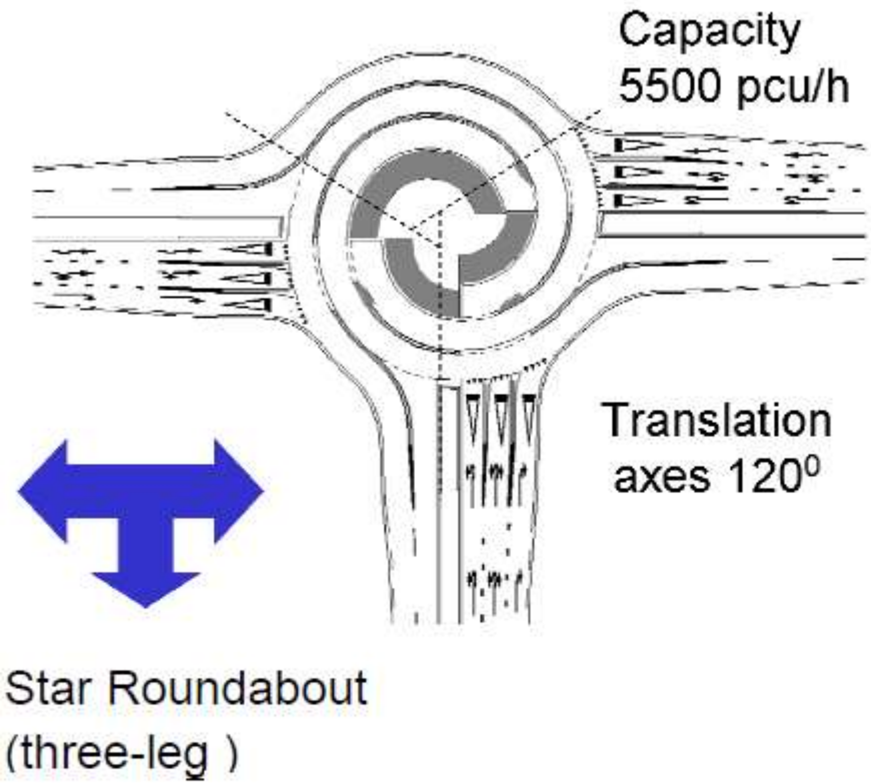
Three-leg Knee roundabout



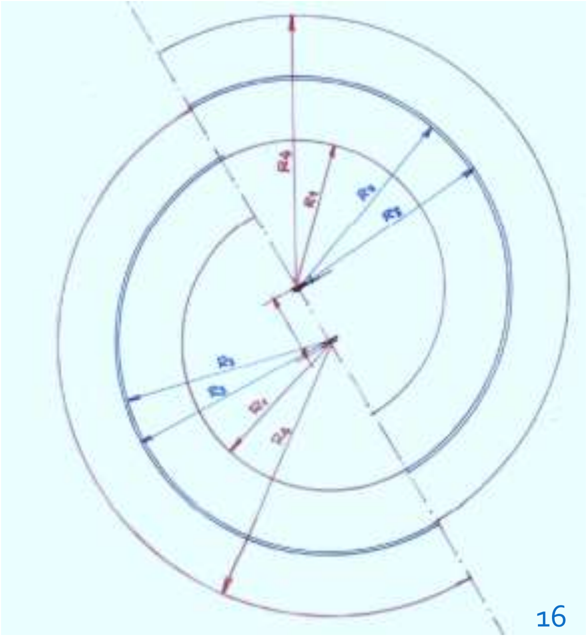
Three-leg Stretched Knee roundabout

Fortujin, 2009

What's the turbo-roundabout?



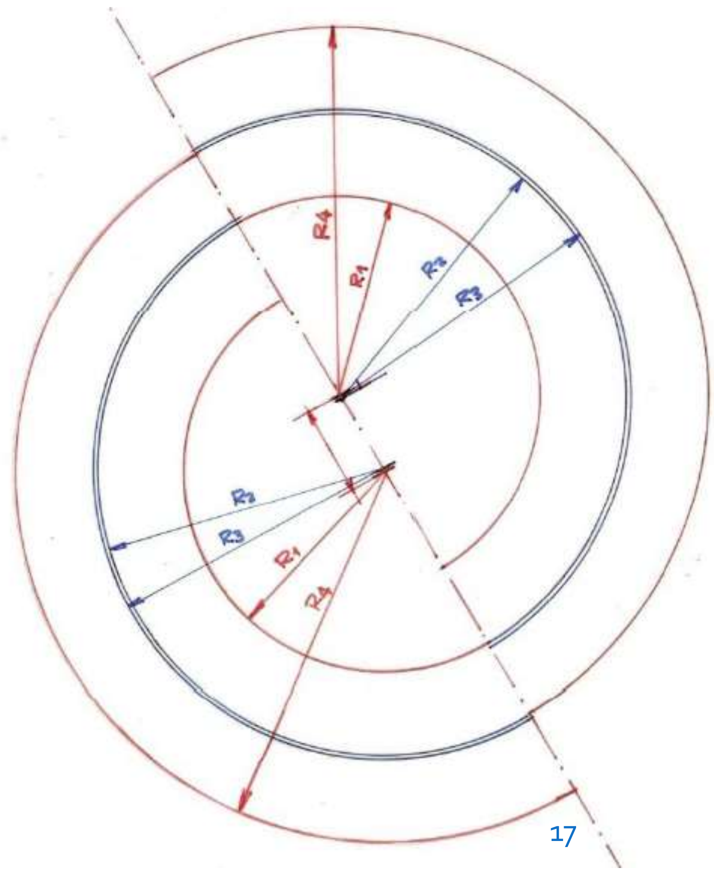
- ✓ It goes without saying that **combinations of forms** **sharing the same basic geometry** or '**turbo block**' are also possible



What's the turbo-roundabout?

- ✓ The **geometrical form** of the turbo roundabout **is formed by the** so-called "**turbo block**" **of all the necessary radii**, which must be **rotated** in a certain way, thereby **obtaining traffic lanes**.

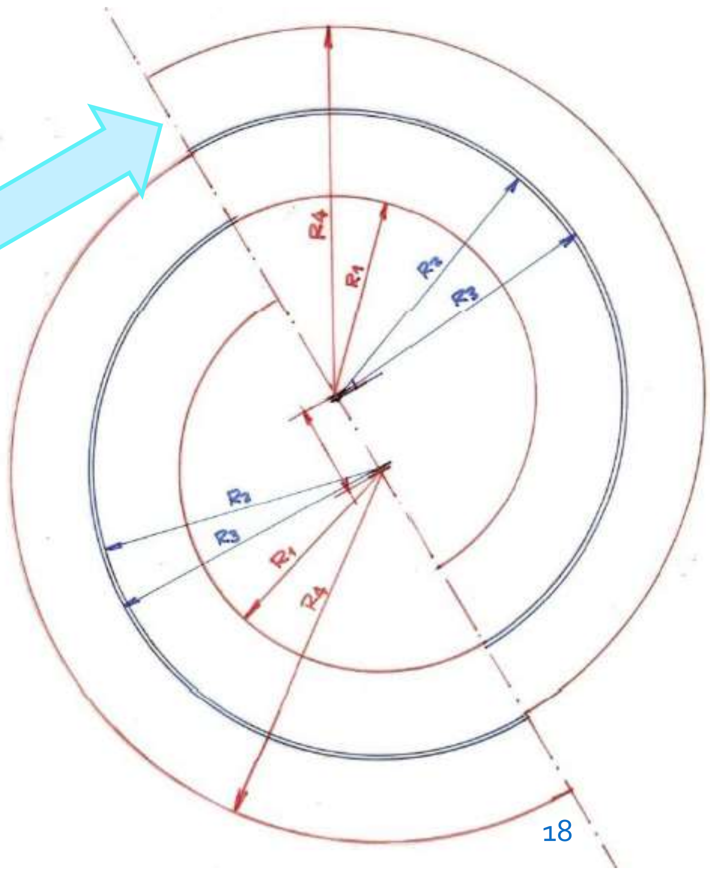
- ✓ The **dimensions of this turbo-block** must **ensure** that the **speed** does not exceed **40 km/h**, and the swept path of the design vehicle can be accommodated;



What's the turbo-roundabout?

- ✓ All the swept paths are wider, when the radius is tighter;
- ✓ so there is a need to introduce an extra width to the inner lane that will **decrease throughout the development** of the spiral.

- ✓ To obtain this extra width, one must have **4 central points**: 2 right-side points and 2 left-side points;



Translatory axle with the best position:
"five minutes to five o'clock" in the case of 4- legs
or
"ten minutes past eight o'clock" in the case of 3-legs

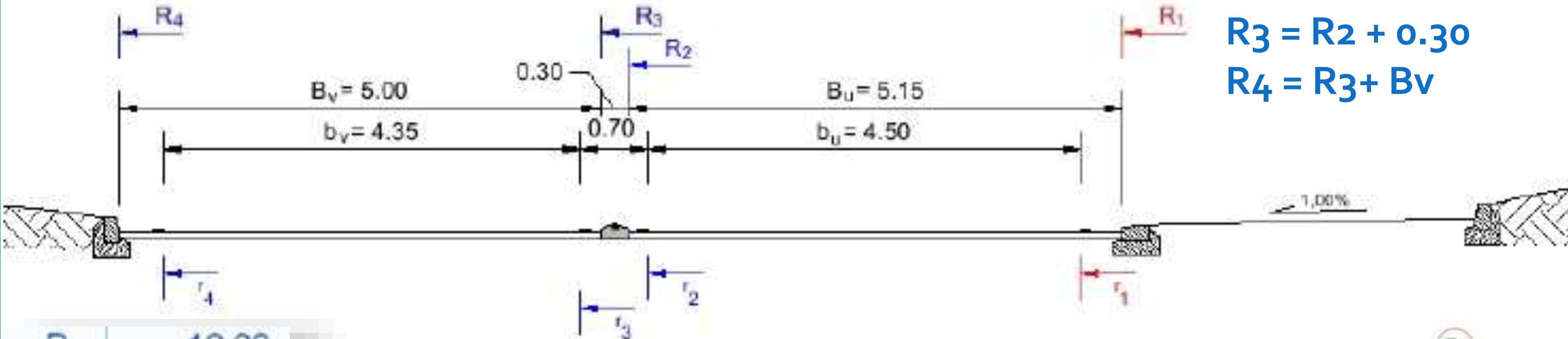
What’s the turbo-roundabout?

R1: 10,50 m; 12 m; 15 m; 20 m

R2 = R1 + Bu

R3 = R2 + 0.30

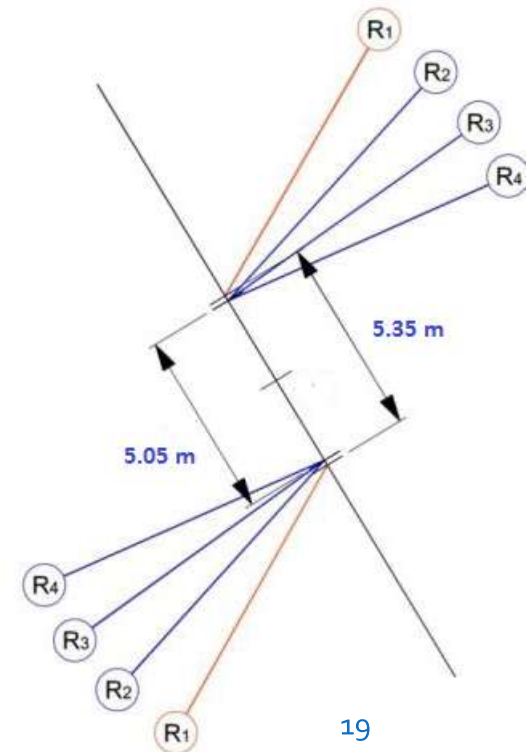
R4 = R3+ Bv



R_1	12.00
R_2	17.15
R_3	17.45
R_4	22.45
r_1	12.45
r_2	16.95
r_3	17.65
r_4	22.00
B_v	5.00
Bu	5.15
b_v	4.35
bu	4.50
D_v	5.35
Du	5.05

✓ The geometric design starts with the definition of the basic dimensions:

- the inner radius of the inner lane - R1;
- the width of the traffic (inner and outer) lanes;
- the width of the lane divider;



the shift of the centre points

“Today we count about 300 turbo-roundabouts worldwide”

http://www.turboroundabout.com/turbo-roundabout.html

Pijnacker, South Holland

Sassenheim - The Netherlands

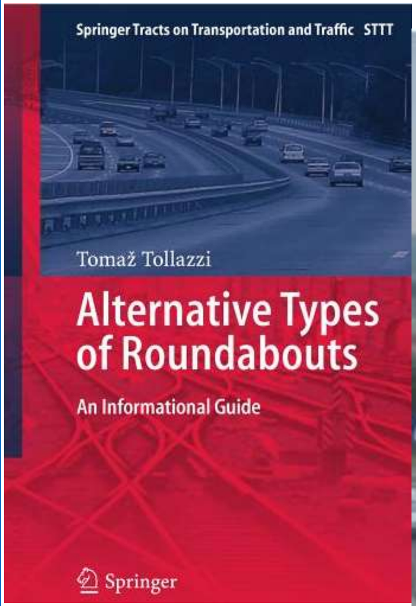
Monster - The Netherlands

Dutch turbo roundabout, from SWOV publication

Rotterdam - The Netherlands

Oud Beijerland- The Netherlands

Szolnok - Hungary

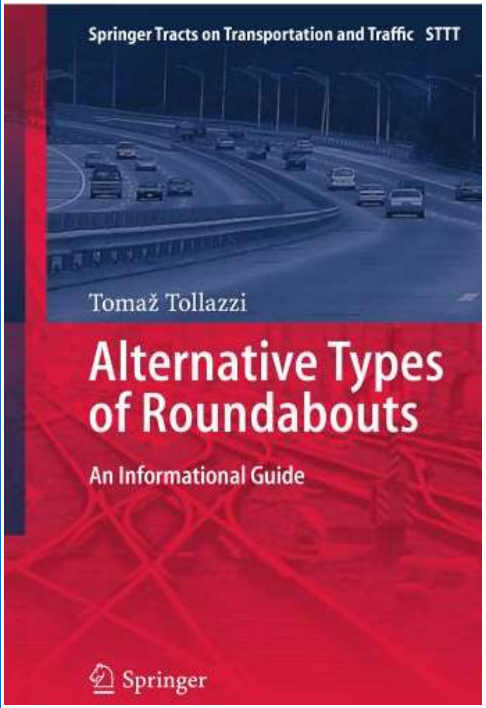


The first Slovenian Turbo Roundabout - under construction; city Koper 2008

Tollazzi, 2014 «The Netherlands (about 80); Slovenia (11); Germany (1); Hungary (1) ; Belgium (1); Indiana USA (2)........»

		2008-2009	2010 - 2012
"Standard" double - lane	the duration of construction	4-5 months	4-5 months
	indicative price	800.000 - 1.500.000,00	600.000 - 1.100.000,00
Turbo roundabout	the duration of construction	5 months	5 – 6 months
	indicative price	800.000 - 1.650.000,00	500.000 - 1.[illegible]00.000,00

"*this comparation is stupid because every case is unique*" Tollazzi, 2014



The second Slovenian Turbo Roundabout – under construction; city Maribor 2008

The first turbo roundabout in the city Maribor; 2010

Turboroundabouts vs roundabouts in brief

- ✓ **Patterns of conflict** with one and two conflicting traffic streams are coexisting at turbo-roundabouts;
- ✓ evaluation of operational performances **more complex** compared to traditional roundabouts.

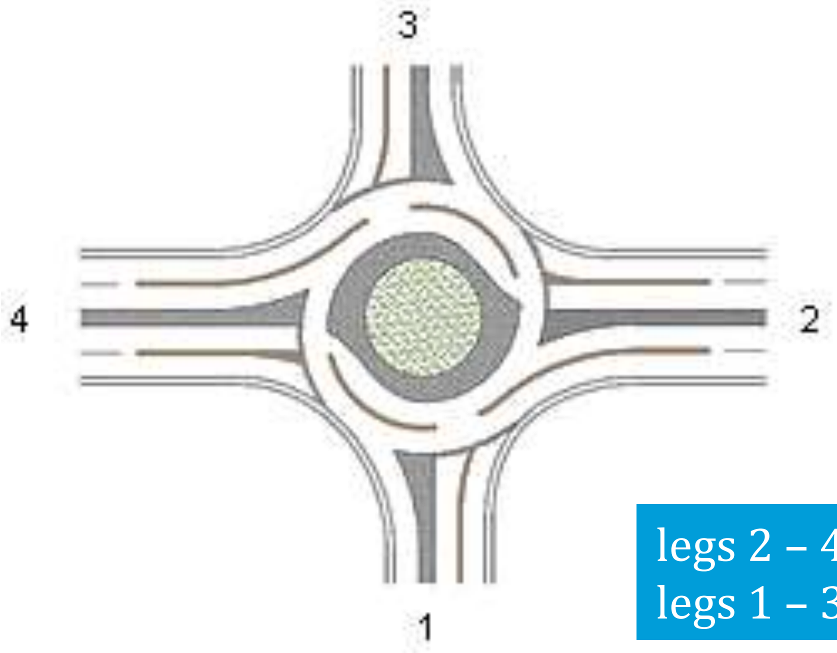
What's the matter?

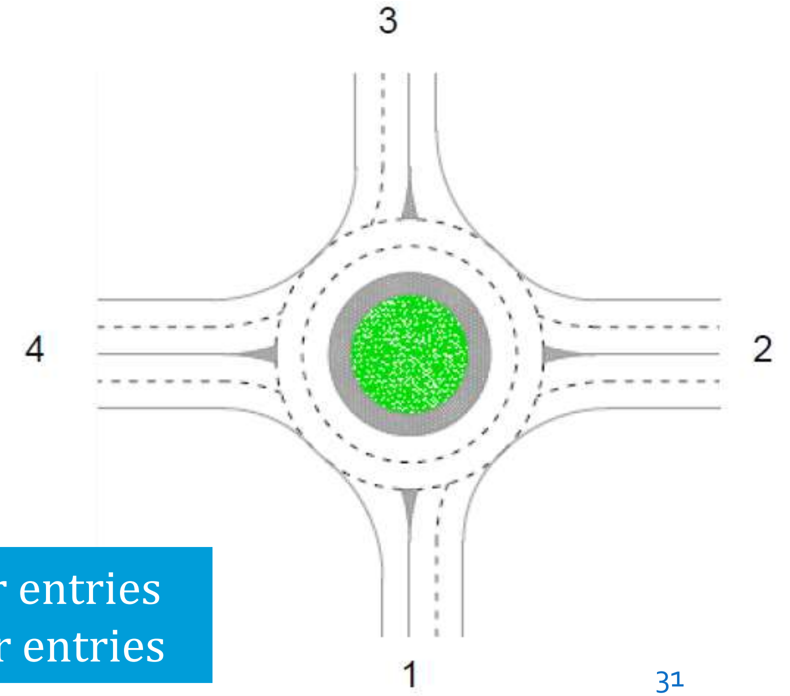
- ✓ Among roundabouts with high capacity and improved traffic performances, the design choice may fall on **a basic turbo-roundabout** or a **standard double-lane roundabout**.

How to Compare Basic Turbo-roundabouts and Double-lane Roundabouts to Evaluate Operational Benefits?

Turboroundabouts vs roundabouts in brief

✓ the schemes of basic turbo-roundabout and standard double-lane roundabout here simulated with a hierarchy between roads reaching the intersection.





legs 2 – 4: major entries
legs 1 – 3: minor entries

Turboroundabouts vs roundabouts in brief

Capacity models based on **gap-acceptance theory**

- ✓ to specify the probability distribution of headways between vehicles in major streams (ie in circulating traffic flows at roundabouts, where entering vehicles look for and accept gaps in circulating streams).

- ✓ At intersections with multiple turning movements, capacity models homogeneous each other should be selected by manoeuvre.

$$f(\tau) = 1 - \varphi \qquad \tau = \Delta$$

$$f(\tau) = \varphi \cdot \lambda \cdot \exp(\lambda \cdot (\tau - \Delta)) \qquad \tau > \Delta$$

$$\lambda = \frac{\varphi \cdot Q_C}{1 - \Delta Q_C}$$

Cowan's Distribution – Shifted Negative Exponential Distribution – M3

$$C = Q_c \cdot \varphi \cdot \frac{\exp(-\lambda \cdot (T_c - \Delta))}{1 - \exp(-\lambda \cdot T_f)}$$

Step function, Tanner 1962

$$C = \frac{Q_c \cdot \varphi \cdot \exp(-\lambda \cdot (T_0 - \Delta))}{\lambda \cdot T_f}$$

Linear function, Jacobs, 1979

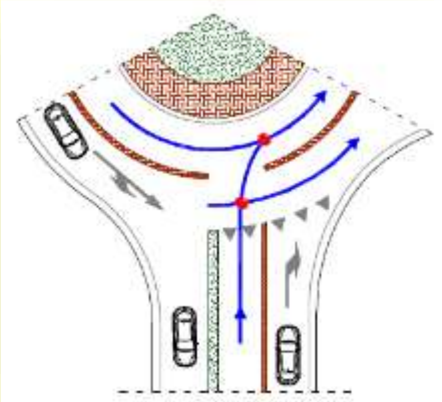
λ: scale parameter where the conflicting flow rate (Qc) is in pcu/h;
Δ: the minimum headway between vehicles moving along the opposing lane [s]
Tc :Critical gap [s]; Tf : Follow-up time, [s];

Assumptions on Entry Capacity Evaluations

- ✓ Hagring (1998) derived a more general capacity formula for multi-lane intersections:

$$C_e = 3600 \cdot \sum_j \frac{\varphi_j \cdot Q_{c,j}}{3600 - \Delta_j \cdot Q_{c,j}} \cdot \prod_k \left(\frac{3600 - \Delta_k \cdot Q_{c,k}}{3600} \right) \cdot \frac{\exp\left[-\sum_l \frac{\varphi_l \cdot Q_{c,l}}{3600 - \Delta_l \cdot Q_{c,l}} \cdot (T_{c,l} - \Delta_l) \right]}{1 - \exp\left(-\sum_m \frac{\varphi_m \cdot Q_{c,m}}{3600 - \Delta_m \cdot Q_{c,m}} \cdot T_{f,m}\right)}$$

Ce:	entry lane capacity [pcu/h];
φ_:	Cowan's M3 parameter representing the proportion of free traffic within the major stream;
Qc,_:	conflicting traffic flow [pcu/h];
Tc,_ :	critical gap for circulating lane [s];
Tf,_ :	follow-up time, [s];
Δ_:	minimum headway of circulating traffic [s];
j, k, l, m:	indices for conflicting lanes (differing in mathematical form, but repeatedly representing the same lanes).



- ✓ The **Hagring model** allows to **assume a** Cowan's M3 headway distribution in each conflicting stream, considering lane-by-lane values for Tc, Tf, Δ and antagonist traffic flows moving on one or two circulating lanes.

Assumptions on Entry Capacity Evaluations at Turbo-roundabouts and Double-lane roundabouts

Adaptations of Hagring model made to consider different *conflicting schemes at entries*.

At turbo-roundabouts

- Right- and left-lane capacity of **entries 2-4** and right-lane capacity of **entries 1-3** as a function of the only one circulating traffic flow (Qc,e) in the outer circle lane; **see eq. a**
- Left-lane capacity of **entries 1-3** as a function of circulating traffic flows in the outer (Qc,e) and in the inner circle lane (Qc,i); **see eq. b**

Eq. a

$$C_e = Q_{c,e} \cdot \left(1 - \frac{\Delta \cdot Q_{c,e}}{3600}\right) \cdot \frac{\exp\left(\frac{-Q_{c,e}}{3600} \cdot (T_c - \Delta)\right)}{1 - \exp\left(\frac{-Q_{c,e}}{3600} \cdot T_f\right)}$$

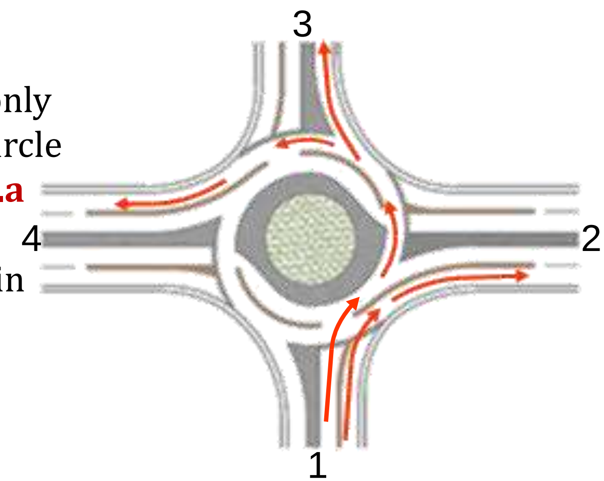
Eq. b

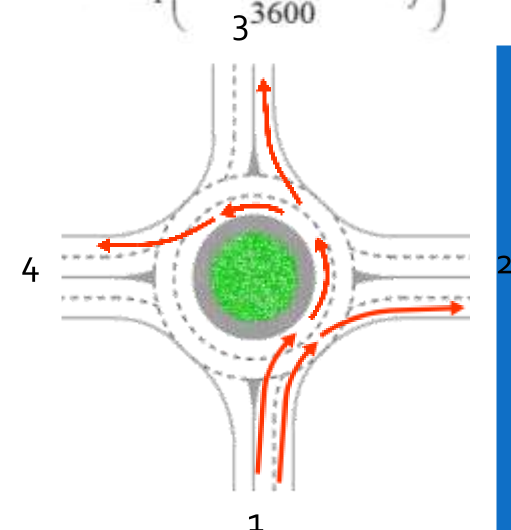
$$C_e = (Q_{c,e} + Q_{c,i}) \cdot \left(1 - \frac{\Delta \cdot Q_{c,e}}{3600}\right) \cdot \left(1 - \frac{\Delta \cdot Q_{c,i}}{3600}\right) \cdot \frac{\exp\left(\frac{-Q_{c,e}}{3600} \cdot (T_{c,e} - \Delta) \frac{-Q_{c,i}}{3600} \cdot (T_{c,i} - \Delta)\right)}{1 - \exp\left(\frac{-(Q_{c,e} + Q_{c,i})}{3600} \cdot T_f\right)}$$

At double-lane -roundabouts

- Right-lane capacity as a function of the only *one circulating traffic flow* in the outer circle lane in front of the subject entry; **see eq.a**
- Left-lane capacity as a function of *two circulating traffic flows* in the outer and in the inner circle lanes. **see eq b**

$$\varphi = 1 - \Delta q_c \qquad \text{eq. Tanner, 1962}$$





q_c : the conflicting flow rate [pcu/s]
Δ: the average intrabunch headway [s]

Assumptions on T_c, T_f and Δ

- ✓ Gap acceptance parameters (T_c and T_f) for basic turbo-roundabouts were adopted on the basis of those obtained by means of experimental observations in the Netherlands [*]:

Tc and Tf the values assumed for **turbo- roundabout**

Tc and Tf the values assumed for **double-lane roundabout**

Entry	Lane	T_c		T_f [s]	Δ [s]
		T_{ci} [s]	T_{ce} [s]		
Major entries	Left	-	3.60	2.26	2.10
	Right	-	3.87	2.13	2.10
Minor entries	Left	3.19	3.03	2.26	2.10
	Right	-	3.74	2.13	2.10

- ✓ for each gap acceptance parameter, a weighted mean was assumed starting from values surveyed by Fortuijn [*] in different sites, each of them with a sample size.

[*] Fortuijn, L.G.H. (2009). Turbo roundabouts. Estimation of capacity. *Transportation Research Record*, 2130, 83-92.

Traffic situations

- ✓ Three traffic situations (through three o-d matrices of traffic flows in percentage terms) were simulated;

Case a

O/D	1	2	3	4
1	0	0.33	0.33	0.33
2	0.33	0	0.33	0.33
3	0.33	0.33	0	0.33
4	0.33	0.33	0.33	0

Case c

O/D	1	2	3	4
1	0	0.65	0.05	0.30
2	0.05	0	0.05	0.90
3	0.05	0.30	0	0.65
4	0.05	0.90	0.05	0

Case b

O/D	1	2	3	4
1	0	0.30	0.05	0.65
2	0.05	0	0.05	0.90
3	0.05	0.65	0	0.30
4	0.05	0.90	0.05	0

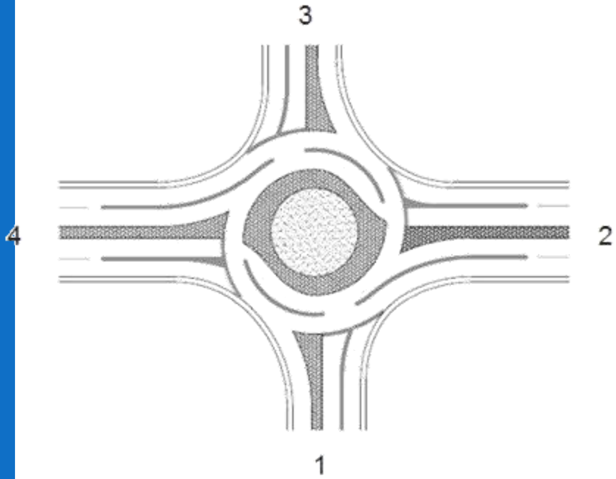
- **Case a**: traffic flow percentages were assumed balanced
- **Case b**: • percentages of **through vehicles** from and to entries 2-4 were prevalent compared to other turning vehicles;
  • percentages of **left and right turning vehicles** from entries 1-3 were prevalent compared to through vehicles from and to entries 1-3
- **Case c**: similar to case b but percentages of left and right turning movements from minor to major entries are inverted.

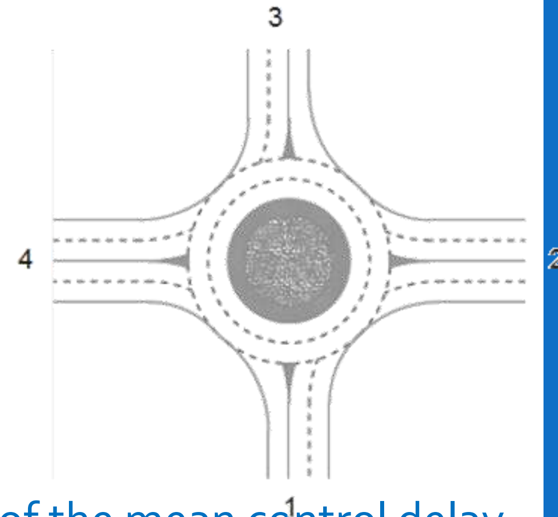
- ✓ At entries $Q_{e1} = Q_{e3}$ and $Q_{e2} = Q_{e4}$ were assumed;
- ✓ All cases where $(Q_{e2}+Q_{e4})<(Q_{e3}+Q_{e1})$ were excluded from suitability domains.

Entry	Lane	Right turn manoeuvre [%]
Entries 1 and 3	Right lane	90
	Left lane	10
Entry	**Lane**	**Through manoeuvre [%]**
Entries 2 and 4	Right lane	50
	Left lane	50

Lane selection percentages performed by turning vehicles from entries

Comparison criterion





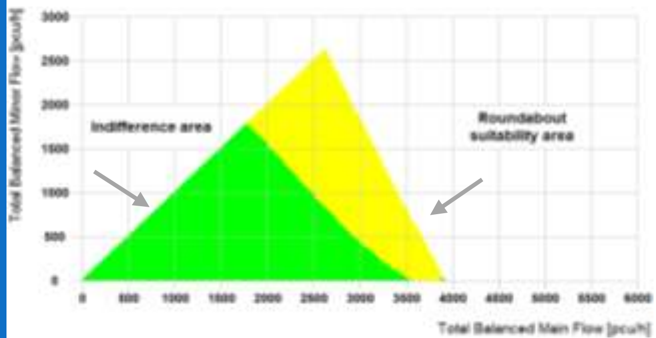
- ✓ the **control delay** was computed as the weighted mean value of the mean control delay d_i at each entry lane i;

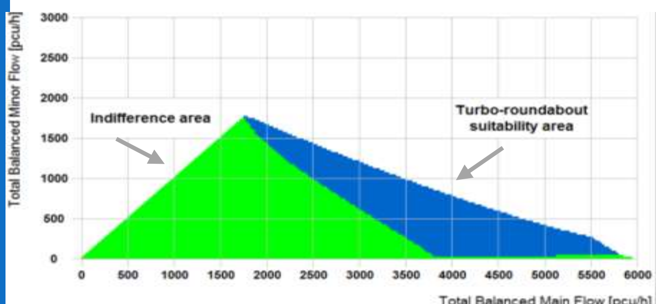
$$\bar{d} = \frac{\sum_{i=1}^{4} d_i \cdot Q_{e,i}}{\sum_{i=1}^{4} Q_{e,i}}$$

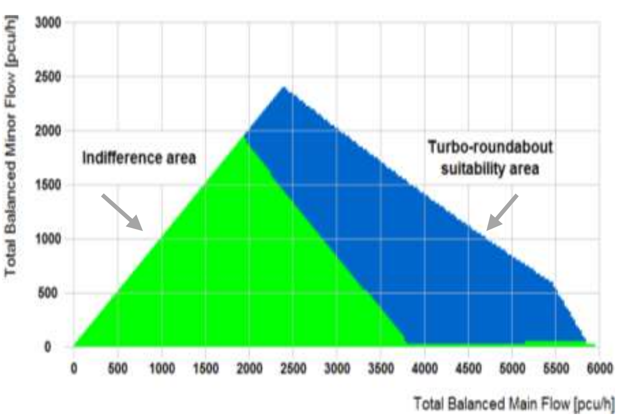
- ✓ At **double-lane roundabout**, the mean control delay d_i is the control delay at the whole entry *i*.

$$d_i = \frac{3600}{C_{e,i}} + 900T\left[\frac{Q_{e,i}}{C_{e,i}} - 1 + \sqrt{\left(\frac{Q_{e,i}}{C_{e,i}} - 1\right)^2 + \frac{\left(\frac{3600}{C_{e,i}}\right)\left(\frac{Q_{e,i}}{C_{e,i}}\right)}{450T}}\right] + 5$$

Comparing Basic Turbo-roundabouts and Double-lane Roundabouts to Evaluate Operational Benefits







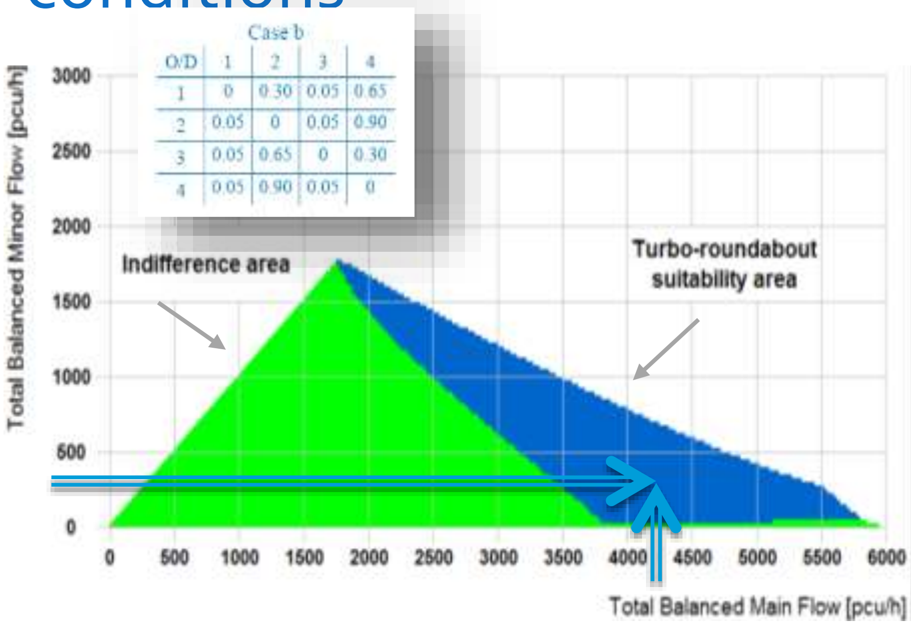
x-axis represents the variable (Qe2+Qe4);
y-axis represents the variable (Qe1+Qe3);
*these variables are the basis for **suitability domains in undersaturated flow conditions** having the distinction between suitability areas*:

The **yellow area** is the roundabout suitability area (delays at roundabouts are less than 50% of those experienced at turbo-roundabouts);

the **blue area** corresponds to case in which delays at turbo-roundabouts are less than 50% of those that users suffer at roundabouts.

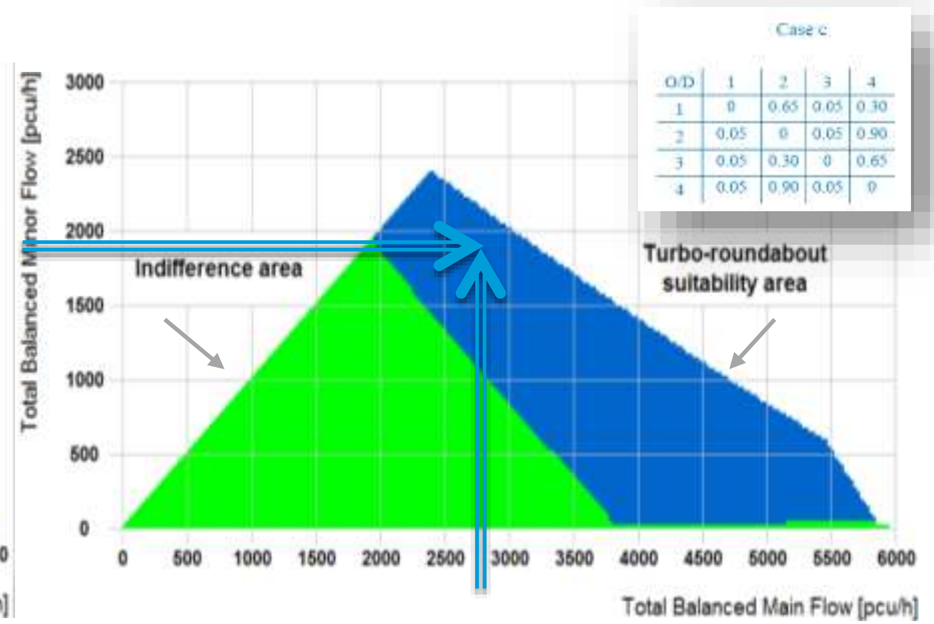
In all cases the **green area** represents situations where no clear benefits of the one over the other roundabout can be deducted.

Examples of suitability domains in undersaturated conditions



Case b

O/D	1	2	3	4
1	0	0.30	0.05	0.65
2	0.05	0	0.05	0.90
3	0.05	0.65	0	0.30
4	0.05	0.90	0.05	0



Case c

O/D	1	2	3	4
1	0	0.65	0.05	0.30
2	0.05	0	0.05	0.90
3	0.05	0.30	0	0.65
4	0.05	0.90	0.05	0

✓ ***turbo-roundabouts perform better than double-lane roundabouts*** when **high traffic flows enter from major roads** and *low traffic flows enter from minor roads*.

✓ ***Case c*** allows significantly **larger minor traffic flows** than ***case b*** because in case c *right turning movements from minor roads* are prevalent on the others.

conclusions

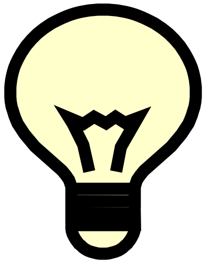
- ✓ **Applications of Hagring model** to evaluate entry capacity at turbo-roundabouts where movements with only 1 and 2 conflicting traffic streams coexist.

- ✓ Results of the analyses show that **efficiency of basic turbo-roundabouts** depends on **traffic situations** and can be **significant** when **major roads capture most of the traffic demand**.

- ✓ All the procedures and the conclusions based on them are theoretical and the result of **adaptations of capacity formulas not specific for** turbo-roundabouts.

- ✓ It is hoped that **surveys on operating turbo-roundabouts** will be possible to **develop** models **more realistic** for estimating performances.

The microsimulation to estimate the impact of trucks on the quality of traffic flow



- Introduction
- Step 1: construction of the network model for the turbo-roundabout
- Step 2: calibration of the software
- Step 3: experimental design and data acquisition
- Step 4: statistical regression of the data obtained by microsimulation and analysis of the results
- Step 5: calculating passenger car equivalency factors for trucks at turbo-roundabouts and results

Developing passenger car equivalency factors for truck at turbo-roundabouts

✓ **Technical literature** still presents **few studies** related to the calculation of passenger car equivalency factors for trucks at roundabouts (single-lane, double-lane, multi-lane).

introduction → Step 1 → Step 2 → Step 3 → Step 4

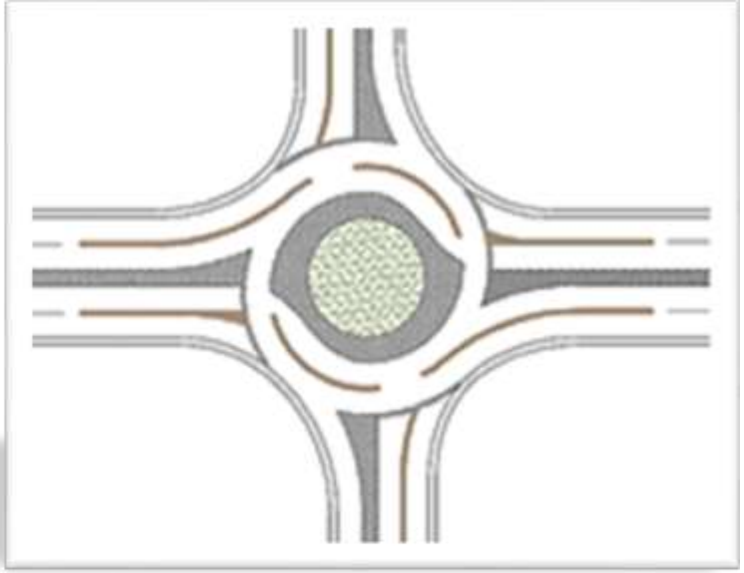
✓ The **microsimulation** can be a useful tool when the **variation of the traffic quality** in roundabout **should be evaluated**, in the presence of a **traffic demand** characterized by different percentages of trucks.

- ✓ By micro-simulation it is possible to **isolate traffic conditions** difficult to observe on field and **replicate** them to have a number of data as much as possible numerous.

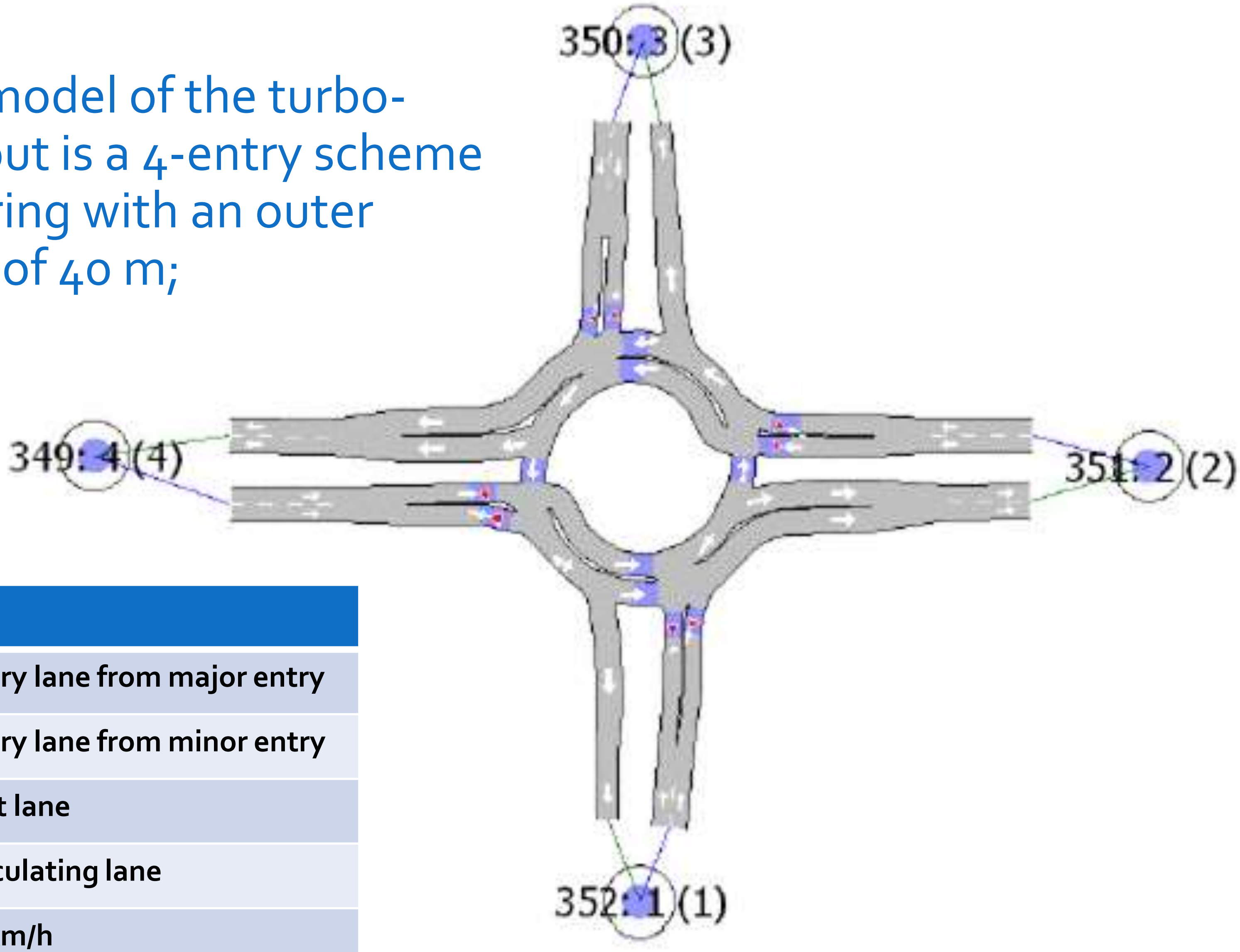
- ✓ In simulation it is possible to **obtain capacity values** varying the percentage of trucks at entries and in the circulating lanes.

✓The first step for executing Aimsun was to create a **new model**;

✓In this case the "**network model**" was represented by a single intersection (the basic turbo roundabout);



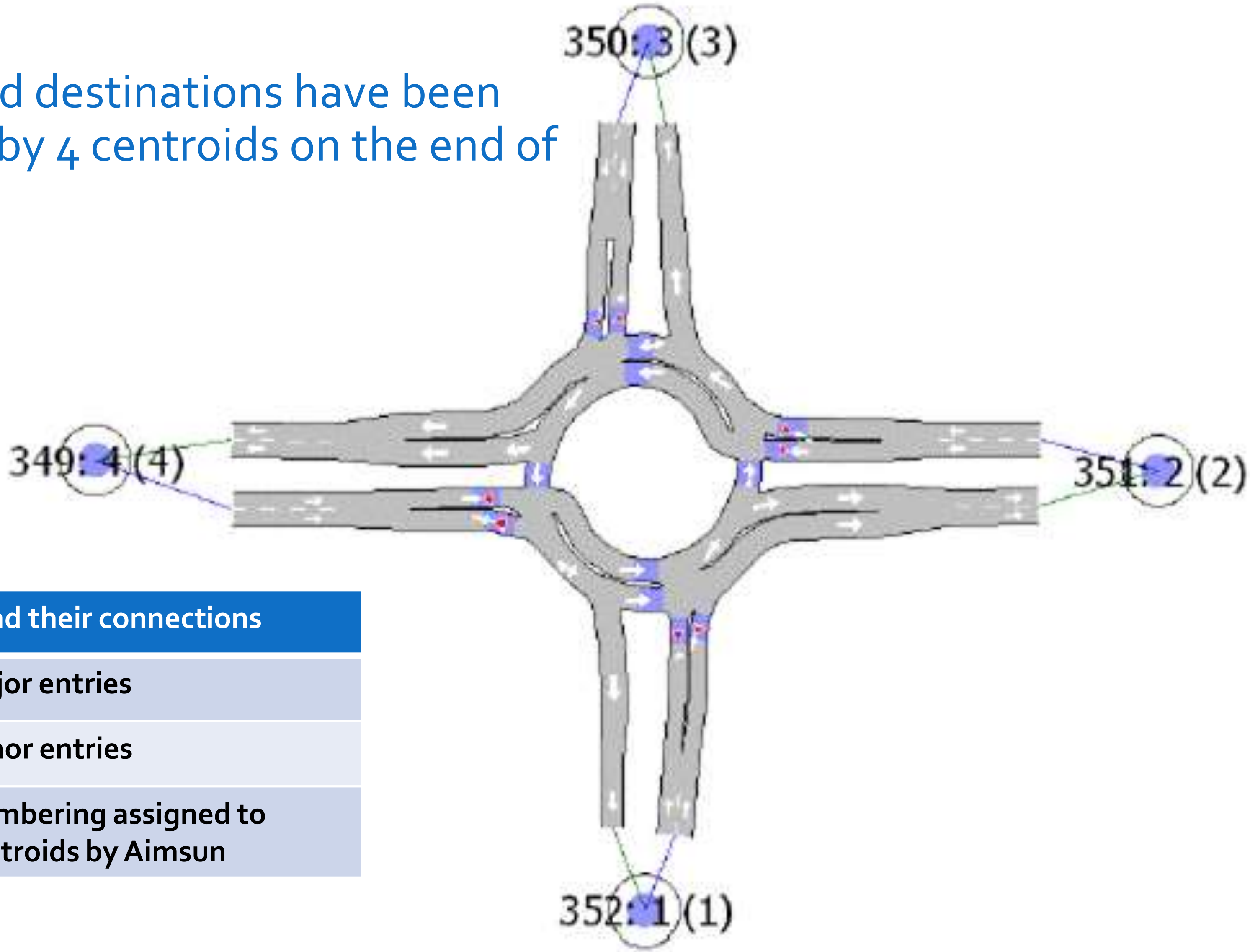
✓ Aimsun model of the turbo-roundabout is a 4-entry scheme having a ring with an outer diameter of 40 m;



Lane width	
3.50 m	Entry lane from major entry
3 m	Entry lane from minor entry
4.50 m	Exit lane
4.20	Circulating lane
Speed limit 50 km/h	

introduction | Step 1 | Step 2 | Step 3 | Step 4 | Step 5

✓ origins and destinations have been identified by 4 centroids on the end of each leg;



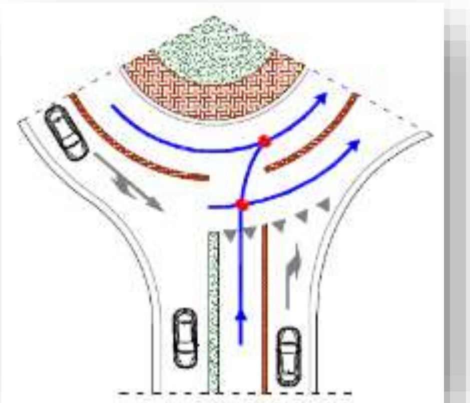
the centroids and their connections	
2-4	**Major entries**
1-3	**Minor entries**
349, 350, 351, 352	**Numbering assigned to centroids by Aimsun**

- ✓ according to Barcelo (2011), **calibration of a traffic microsimulation model** is an **iterative process** consisting in **changing and adjusting** numerous **model parameters** and **comparing model outputs with a set of empirical data until a** predefined level of agreement between the two data sets is **achieved**;
- ✓ every microsimulation software has a set of **user-adjustable parameters** which enable the analyst to calibrate the model to match locally observed conditions;
- ✓ The **achievement** of **calibration targets**, i.e. when the model outputs are similar to empirical data**, can be influenced by the simplification** of which microsimulation models are not free;

✓ In the context of the activities developed **in micro-simulation, the search for the calibration was carried out by ensuring that Aimsun** for the different entry lanes at the turbo-roundabout **gave results close to those derived from the Hagring model (1998) using the times** obtained by Fortuijn (2009).

$$C_e = 3600 \cdot \sum_j \frac{\varphi_j \cdot Q_{c,j}}{3600 - \Delta_j \cdot Q_{c,j}} \cdot \prod_k \left(\frac{3600 - \Delta_k \cdot Q_{c,k}}{3600} \right) \cdot \frac{\exp\left[-\sum_l \frac{\varphi_l \cdot Q_{c,l}}{3600 - \Delta_l \cdot Q_{c,l}} \cdot (T_{c,l} - \Delta_l) \right]}{1 - \exp\left(-\sum_m \frac{\varphi_m \cdot Q_{c,m}}{3600 - \Delta_m \cdot Q_{c,m}} \cdot T_{f,m}\right)}$$

Ce:	entry lane capacity [pcu/h];
φ_:	Cowan's M3 parameter representing the proportion of free traffic within the major stream;
Qc,_:	conflicting traffic flow [pcu/h];
Tc,_ :	critical gap for circulating lane [s];
Tf,_ :	follow-up time, [s];
Δ_:	minimum headway of circulating traffic [s];
j, k, l, m:	indices for conflicting lanes (differing in mathematical form, but repeatedly representing the same lanes).

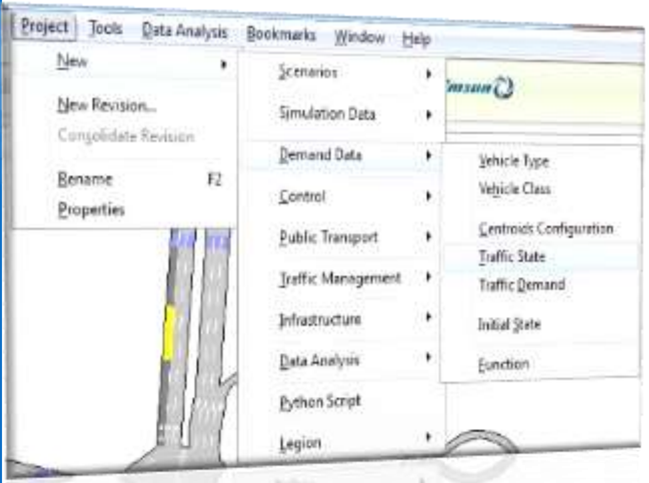


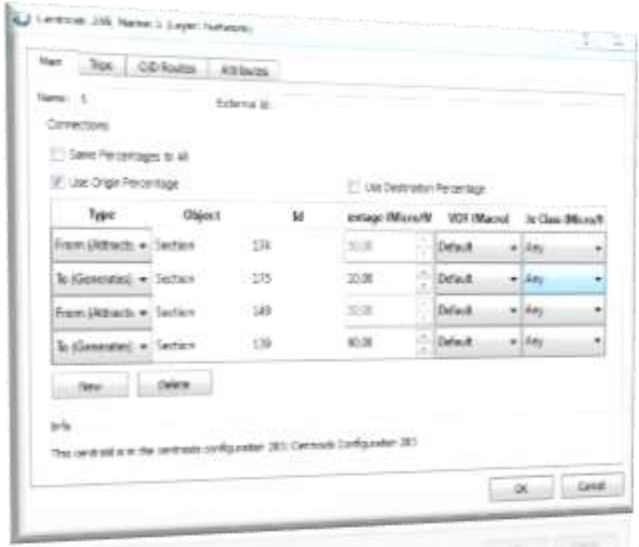
Hagring O (1998). A further generalization of the Tanner's formula *Transportation Research part B: methodological* 32(6): 423-429
Fortuijn, L.G.H. (2009). Turbo roundabouts. Estimation of capacity. *Transportation Research Record*, 2130, 83-92.

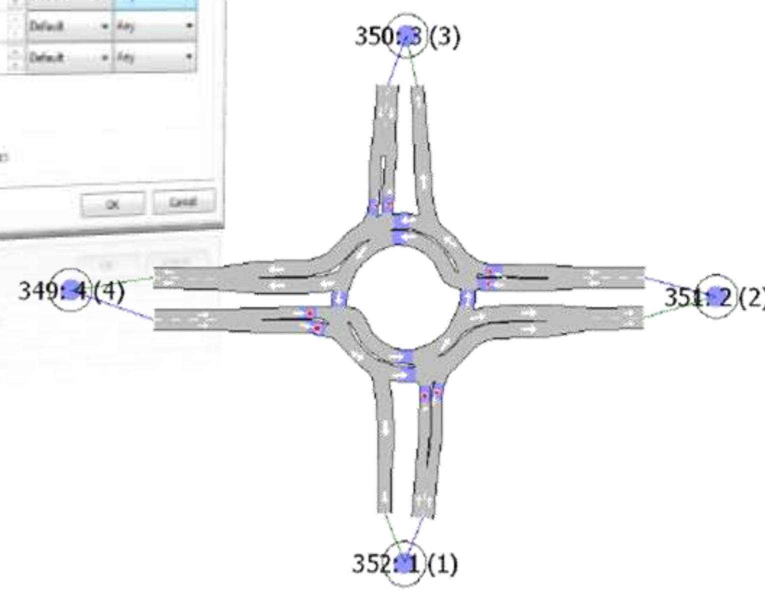
✓ this choice, based on the **absence of turbo-roundabouts operating in Italy** and **the need to have a large amount of data**, does not compromise the reliability of the calibration process **if one considers that the abstraction of the theoretical model** here chosen **is tempered by the realism of the values of behavioral parameters** obtained experimentally **by Fortuijn** (2009) at existing turbo-roundabouts in the Netherlands (see eg (*)).

(*) A M C Bastos Silva & L Vasconcelos, **Microsimulation Applied to Roundabout Performance Analysis: the Effect of Pedestrian Crossings.** European Transport Conference, Association for European Transport and contributors 2009

- ✓ **values of circulating flows** and **entry capacity** by entry lane, as obtained from the Hagring model, **were compared with simulated data**;





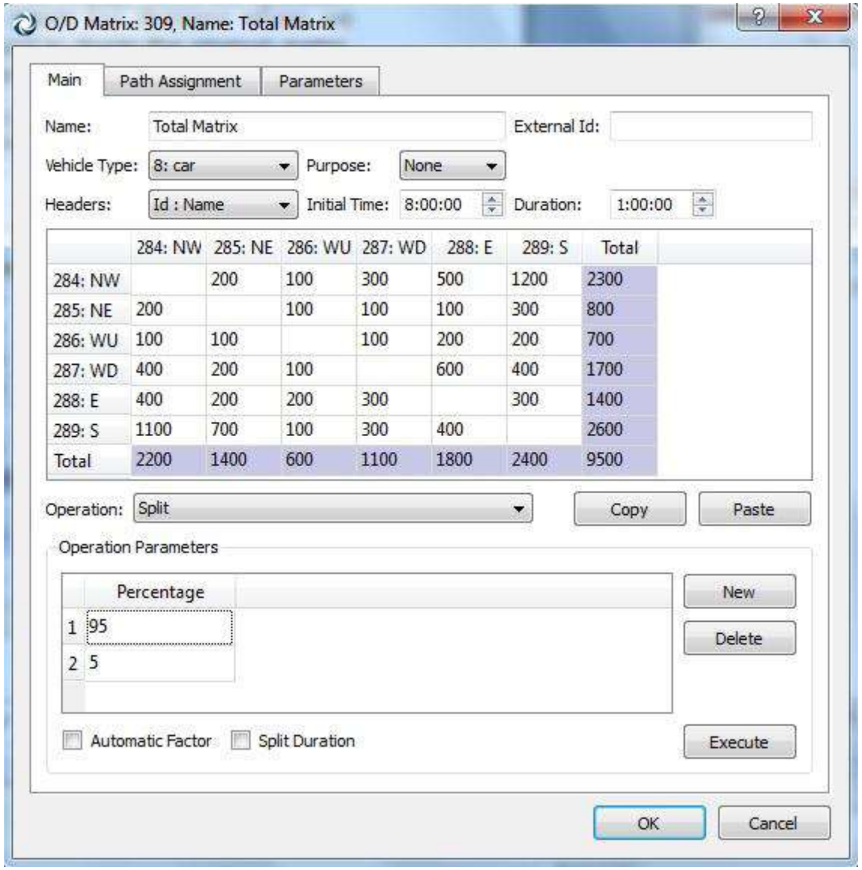


- ✓ **the circulating flows** and **entry capacity** values were obtained **assigning** in Aimsun specific O/D matrices;

- ✓ **saturation at each entry lane** was necessary to derive the capacity values;

- Since traffic demand was given as an O/D Matrix, the first step was defining the centroids to which the matrix corresponds;

- The **procedure** was **iterated** so many times in order to make the necessary **evaluations about the calibration conditions** for different values of the circulating and entering flow;



	284: NW	285: NE	286: WU	287: WD	288: E	289: S	Total
284: NW		200	100	300	500	1200	2300
285: NE	200		100	100	100	300	800
286: WU	100	100		100	200	200	700
287: WD	400	200	100		600	400	1700
288: E	400	200	200	300		300	1400
289: S	1100	700	100	300	400		2600
Total	2200	1400	600	1100	1800	2400	9500

✓ due to **unrealistic simulation results** when **Aimsun default parameters** were used, **some parameters were changed**, basing on experience gained so far;

Parameter	definition	Default	Used
minimum headway [s]	the time between the leader and the follower vehicle	2.10	1.70
reaction time [s]	the time a driver takes for reacting to speed changes in the preceding vehicle	1.35	1.00

the selected parameters and their default/used values

- **numerous iteration were carried out**, manually **adjusting various combinations of these parameters** to improve the performance of the system;

- **iterations were stopped** when **a good match between empirical and simulated data was achieved**, with maximum differences of approximately 10%;

Parameter	definition	Default	Used
minimum headway [s]	the time between the leader and the follower vehicle	2.10	1.70
reaction time [s]	the time a driver takes for reacting to speed changes in the preceding vehicle	1.35	1..00

the selected parameters and their default/used values

✓ Adaptations of Hagring model made to consider **different conflicting schemes at entries and used in model calibration**;

Right- and left-lane capacity of entries **2-4** and **right-lane capacity** of entries **1-3** as a function of the only one circulating traffic flow (Qc,e) in the outer circle lane; *see eq. a*

Left-lane capacity of entries **1-3** as a function of circulating traffic flows in the outer (Qc,e) and in the inner circle lane (Qc,i); *see eq. b*;

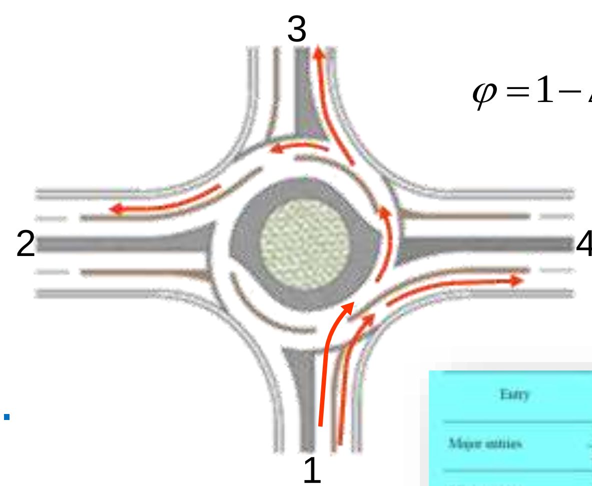
Eq. a

$$C_e = Q_{c,e} \cdot \left(1 - \frac{\Delta \cdot Q_{c,e}}{3600}\right) \cdot \frac{\exp\left(\frac{-Q_{c,e}}{3600} \cdot (T_c - \Delta)\right)}{1 - \exp\left(\frac{-Q_{c,e}}{3600} \cdot T_f\right)}$$

Eq. b

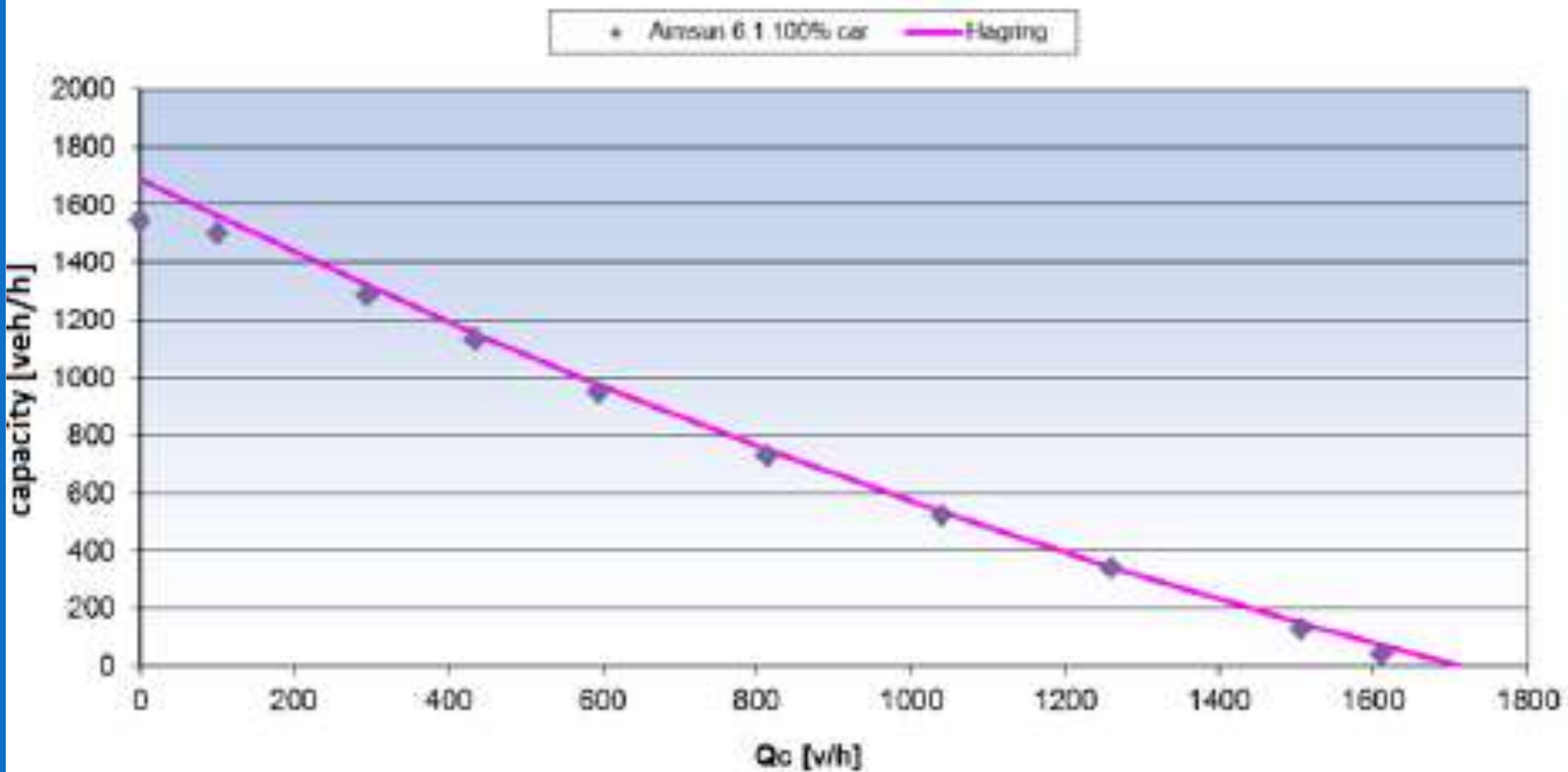
$$C_e = (Q_{c,e} + Q_{c,i}) \cdot \left(1 - \frac{\Delta \cdot Q_{c,e}}{3600}\right) \cdot \left(1 - \frac{\Delta \cdot Q_{c,i}}{3600}\right) \cdot \frac{\exp\left(\frac{-Q_{c,e}}{3600} \cdot (T_{c,e} - \Delta) \frac{-Q_{c,i}}{3600} \cdot (T_{c,i} - \Delta)\right)}{1 - \exp\left(\frac{-(Q_{c,e} + Q_{c,i})}{3600} \cdot T_f\right)}$$

$$\varphi = 1 - \Delta q_c \quad \text{Tanner, 1962}$$

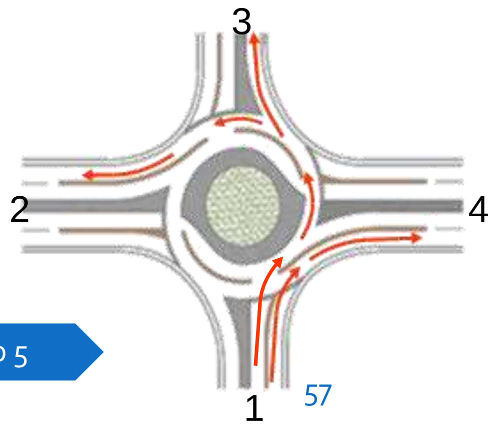


✓ **Gap acceptance parameters** (Tc and Tf) for basic turbo-roundabouts **were already presented in t**he previous section.

Entry	Lane	T_c: $T_{c,i}$ [s]	T_c: $T_{c,e}$ [s]	T_f [s]	Δ [s]
Major entries	Left	-	3.60	2.26	2.10
	Right	-	3.87	2.13	2.10
Minor entries	Left	3.19	3.03	2.26	2.10
	Right	-	3.74	2.13	2.10



Right lane capacity on major entry
Simulation *vs* theorical data



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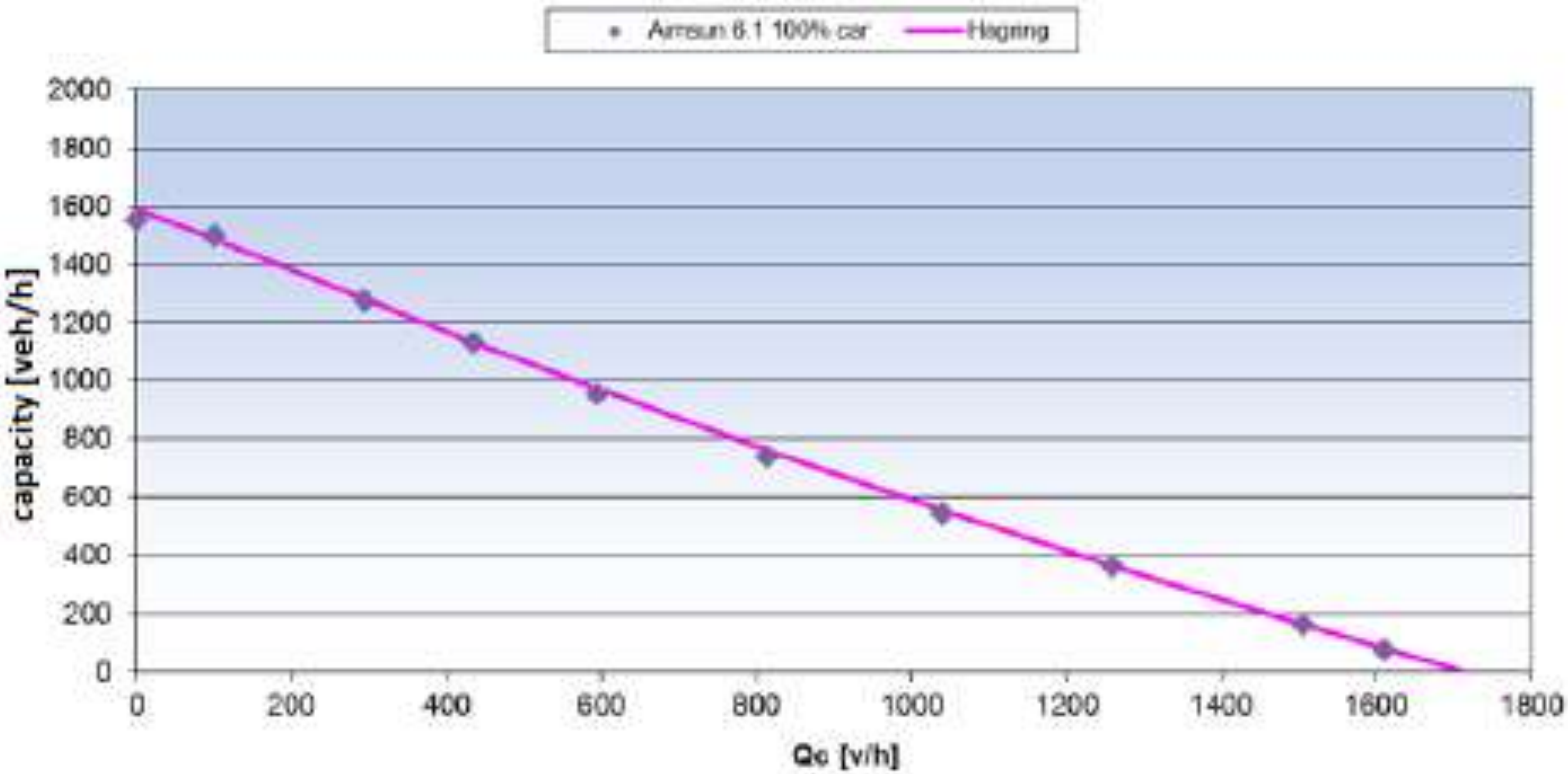
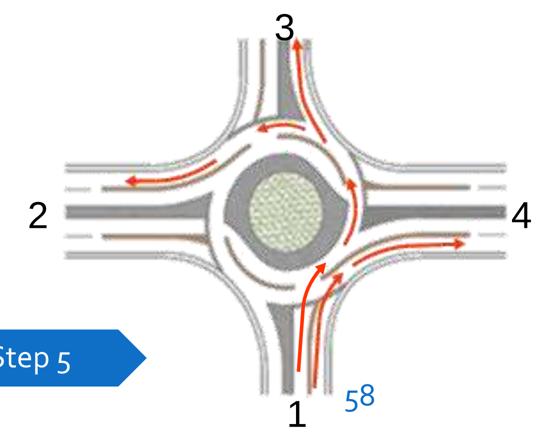
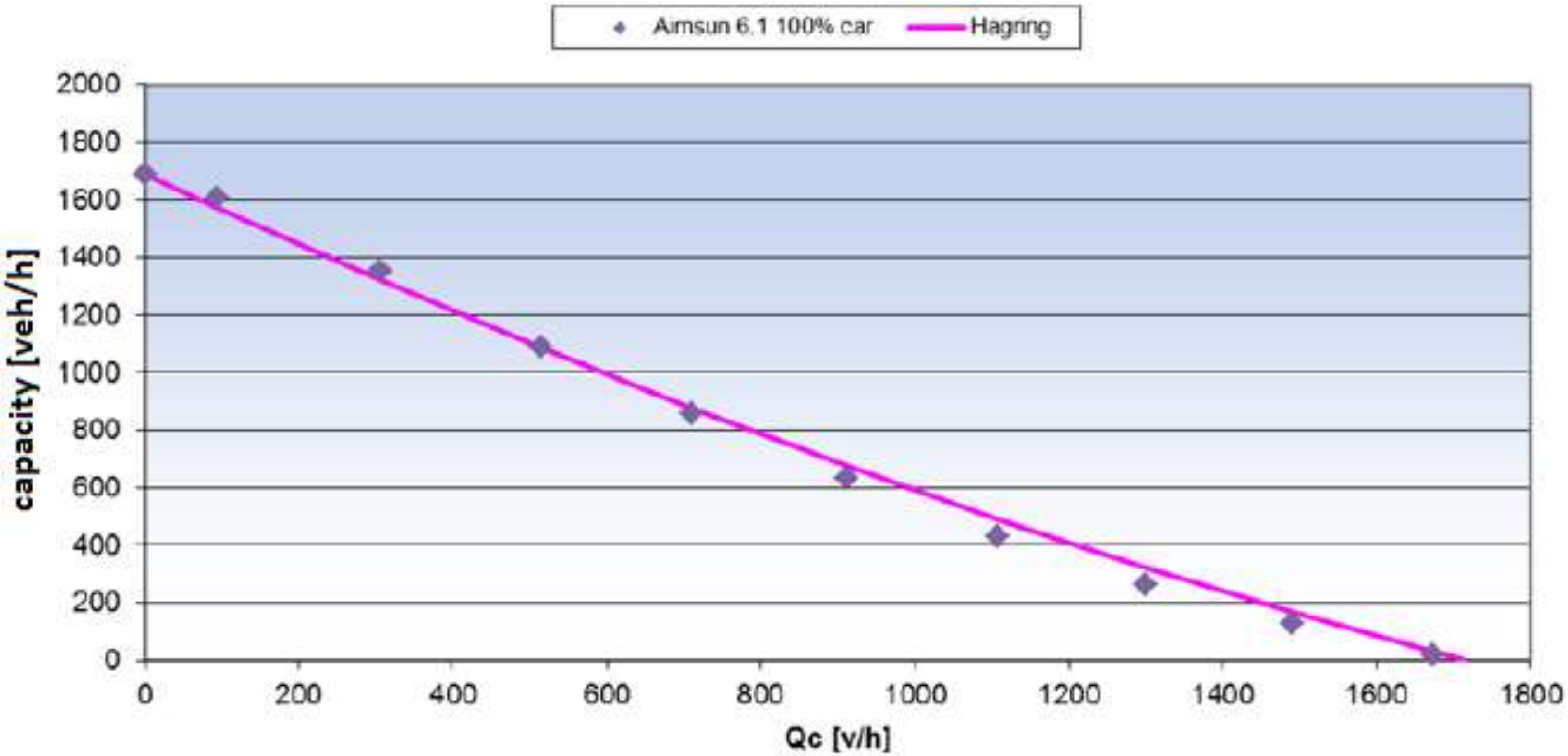
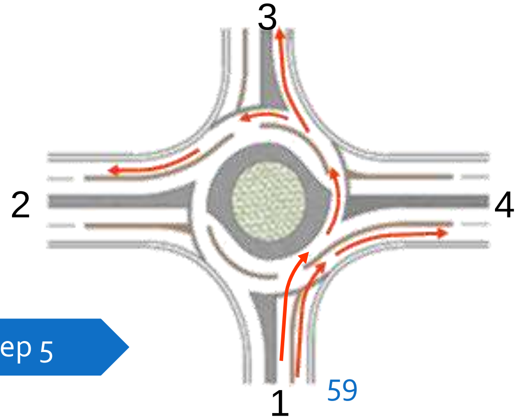


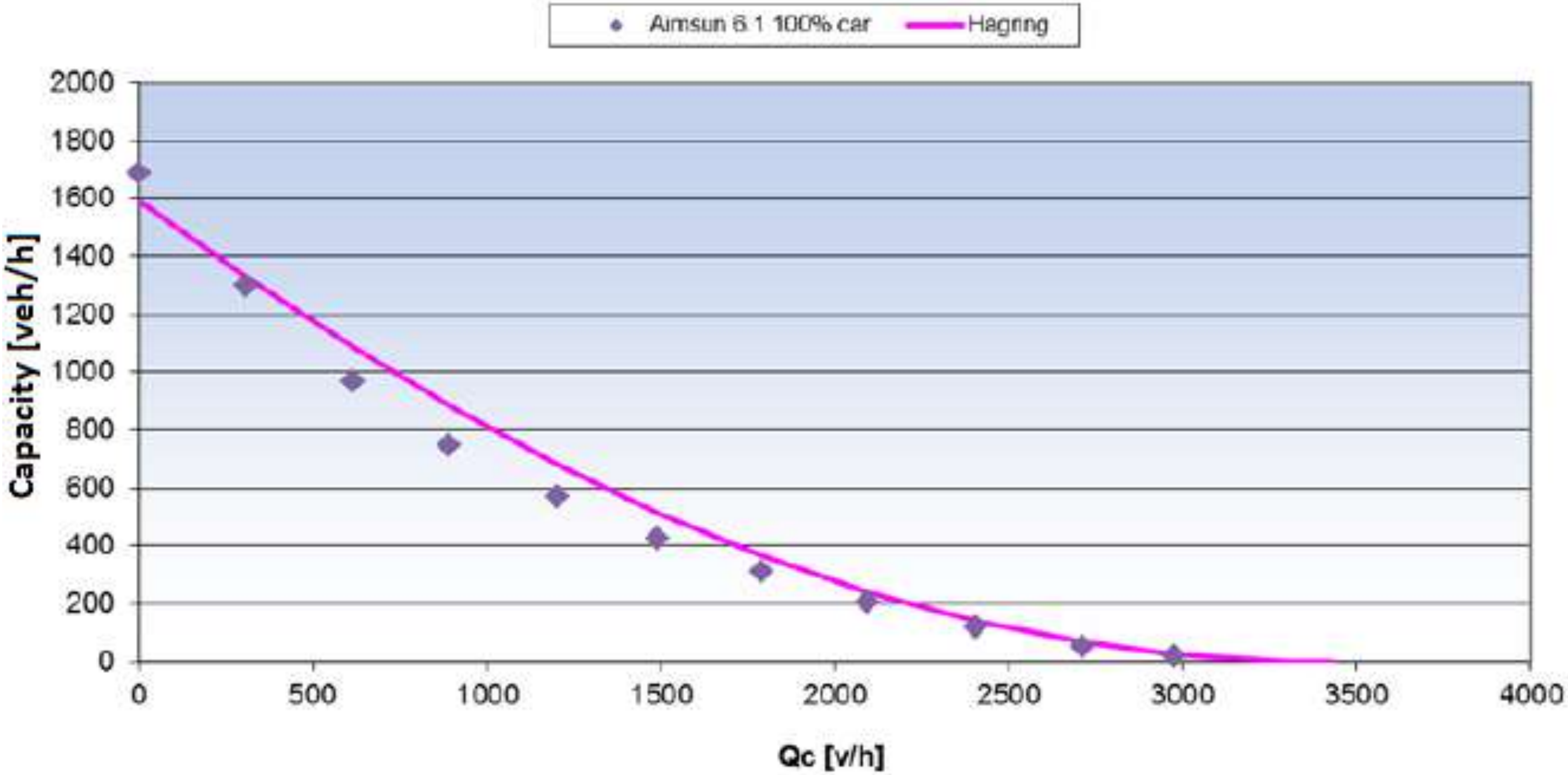
Left lane capacity on major entry
Simulation *vs* theorical data





Right lane capacity on minor entry
Simulation *vs* theorical data

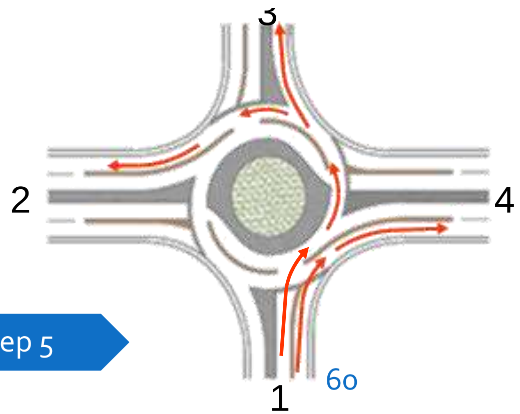




Left lane capacity on minor entry

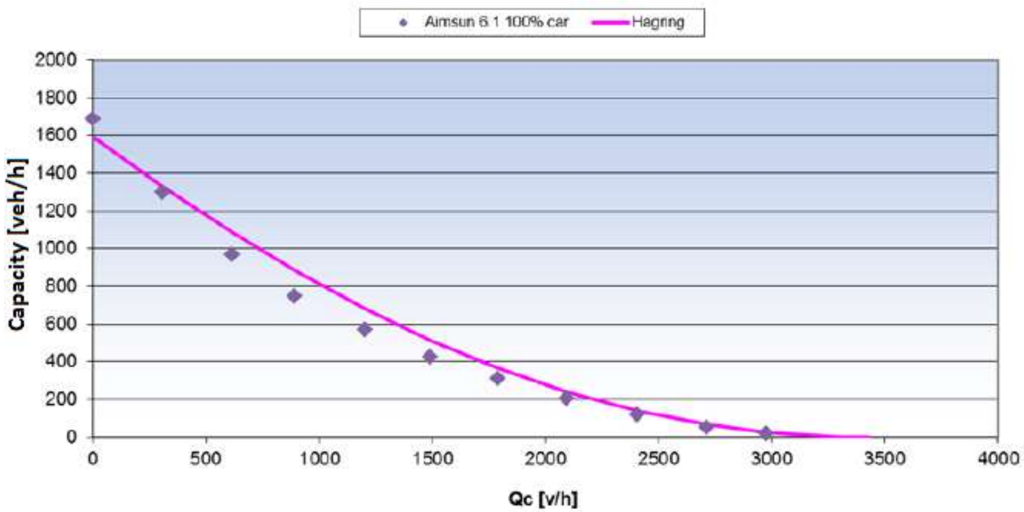
Simulation *vs* theorical data

NB: Qc = Qce+Qci and Qci/Qce=1



- ✓ For "**Left lane capacity on minor entry** ", Aimsun gave **capacity** values less than those derived from the model used for the comparison;

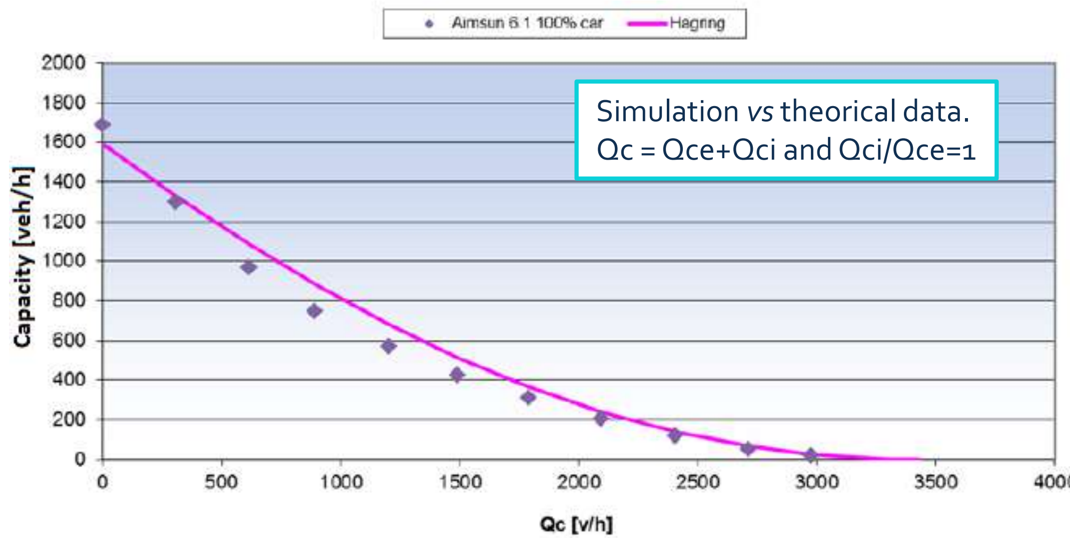
- ✓ **Maybe**, **Tce =3.03 s and Tci =3.19 s** were underestimated by Fortuijn for left turning movements;

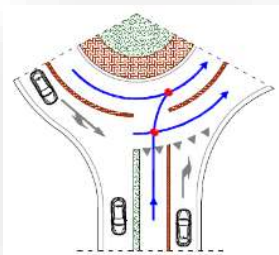


Entry	Lane	T_c		T_f[s]	Δ [s]
		T_{ci} [s]	T_{ce} [s]		
Major entries	Left	-	3.60	2.26	2.10
	Right	-	3.87	2.13	2.10
Minor entries	Left	3.19	3.03	2.26	2.10
	Right	-	3.74	2.13	2.10

- ✓ Moreover **Tce is less that Tci, but it should be the contrary**;

- ✓ Mcdowell et al (1983) highlited that the **critical gap** is **higher** when **the conflict occurs with a closer antagonist traffic flow** and **lower** when **the conflict occurs with a farther antagonist traffic flow.**



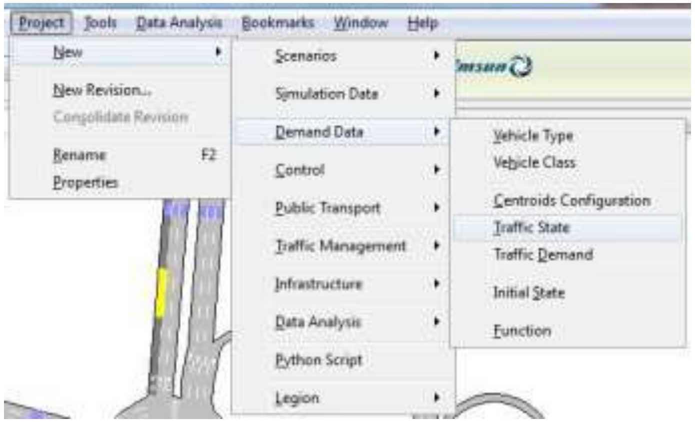


Entry	Lane	T_c		T_f[s]	Δ [s]
		T_{ci} [s]	T_{ce} [s]		
Major entries	Left	-	3.60	2.26	2.10
	Right	-	3.87	2.13	2.10
Minor entries	Left	3.19	3.03	2.26	2.10
	Right	-	3.74	2.13	2.10

* Mcdowell et al (1983). Gap acceptance and traffic conflict simulation as a measure of risk. TRRL SR 776.

	Mean	Deviation	Min	Max
Length	4 m	0,50 m	3,40 m	4,60 m
Width	2 m	0 m	2 m	2 m
Max Desired Speed	110 km/h	10 km/h	80 km/h	150 km/h
Max Acceleration	3 m/s2	3 m/s2	3 m/s2	3 m/s2
Normal Deceleration	4 m/s2	0,25 m/s2	3,50 m/s2	4,50 m/s2
Max Deceleration	6 m/s2	0,50 m/s2	5 m/s2	7 m/s2
Speed Acceptance	1,10	0,10	0,90	1,30
Min Distance Veh	1 m	0,30 m	0,50 m	1,10 m
Maximum Give Way Time	11 Secs	2,50 Secs	5 Secs	15 Secs
Guidance Acceptance	75 %	10 %	65 %	90 %
Sensitivity Factor	1	0	1	1

Default values in Aimsun for traffic state "car"

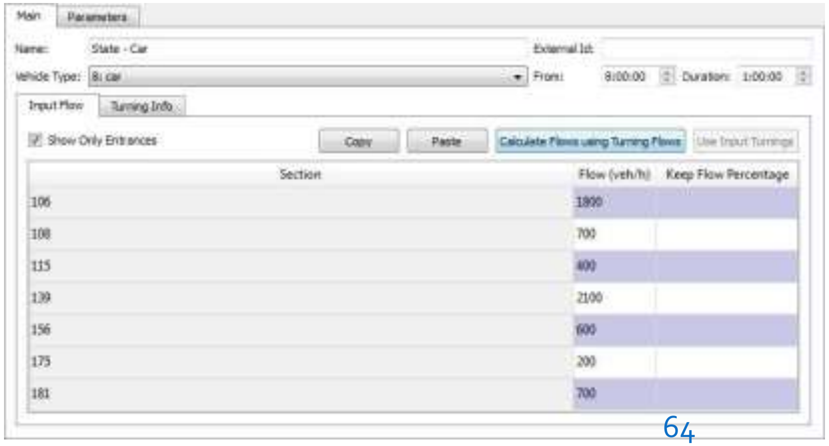


✓ they express the properties and cinematic performance attributed to the category vehicular "car"

	Mean	Deviation	Min	Max
Length	7,50 m	2 m	6 m	10 m
Width	2,30 m	0,50 m	1,90 m	3 m
Max Desired Speed	85 km/h	10 km/h	70 km/h	100 km/h
Max Acceleration	1 m/s2	1 m/s2	1 m/s2	1 m/s2
Normal Deceleration	3,50 m/s2	1 m/s2	2,50 m/s2	4,80 m/s2
Max Deceleration	5 m/s2	0,50 m/s2	4 m/s2	6 m/s2
Speed Acceptance	1	0	1	1
Min Distance Veh	1,50 m	0,50 m	1 m	2,50 m
Maximum Give Way Time	50 Secs	20 Secs	30 Secs	80 Secs
Guidance Acceptance	80 %	10 %	70 %	90 %
Sensitivity Factor	1	0	1	1

Default values in Aimsun for traffic state "truck"

✓ they express the properties and cinematic performance attributed to the category vehicular "truck"**

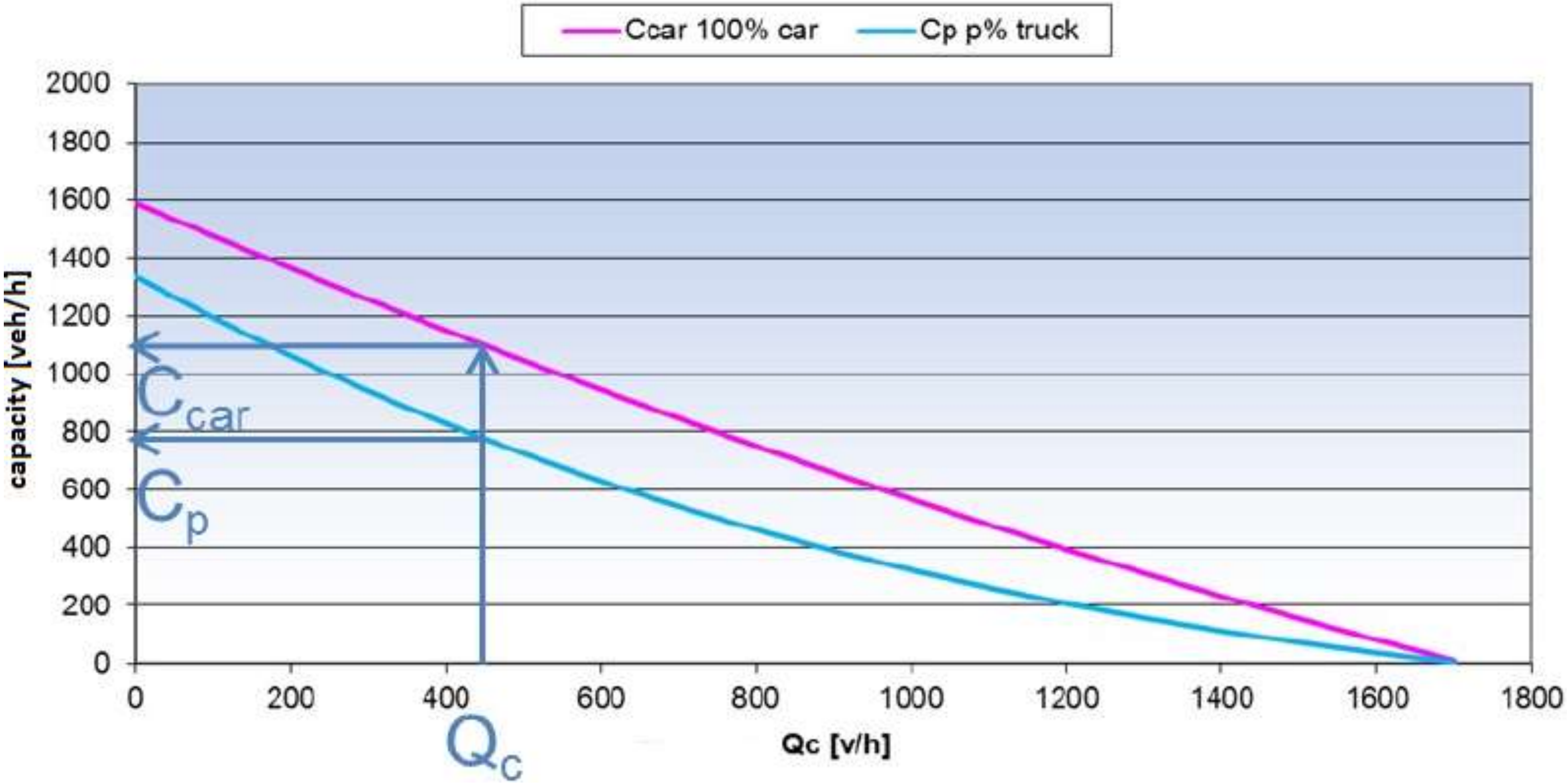


- Data acquisition was planned according to an experimental plan;
- For **entering lanes**, 4 schemes of flow percentages were selected:
  - 100% "car";
  - 10% "truck"+ 90% "car" →more usual operations
  - 20% "truck"+ 80% "car" →more usual operations
  - 100% "truck"→unusual operations
- for **circulating flows**, traffic flows of cars only were considered in order **to compare demand flows** from entries **characterized by different truck percentages**.

- ✓ Capacity functions for the **different entering lanes** in presence of **different percentages of trucks** were developed;
- ✓ O/D matrices were assigned to reproduce saturation conditions at entries.
    - ❖ So the **number of vehicles** entering the intersection **represents** the **capacity value for the specific entry lane**, veh/h;

Estimation of passenger car equivalency factors, for a given percentage of trucks, was made comparing the **capacity values** of **entering traffic flows of cars only** (C_{car}) with the **capacity values** (C_p) corresponding to a traffic demand characterized by a **percentage p** of heavy vehicles.

Estimation of passenger car equivalency factors for a given % of heavy vehicles (Et)

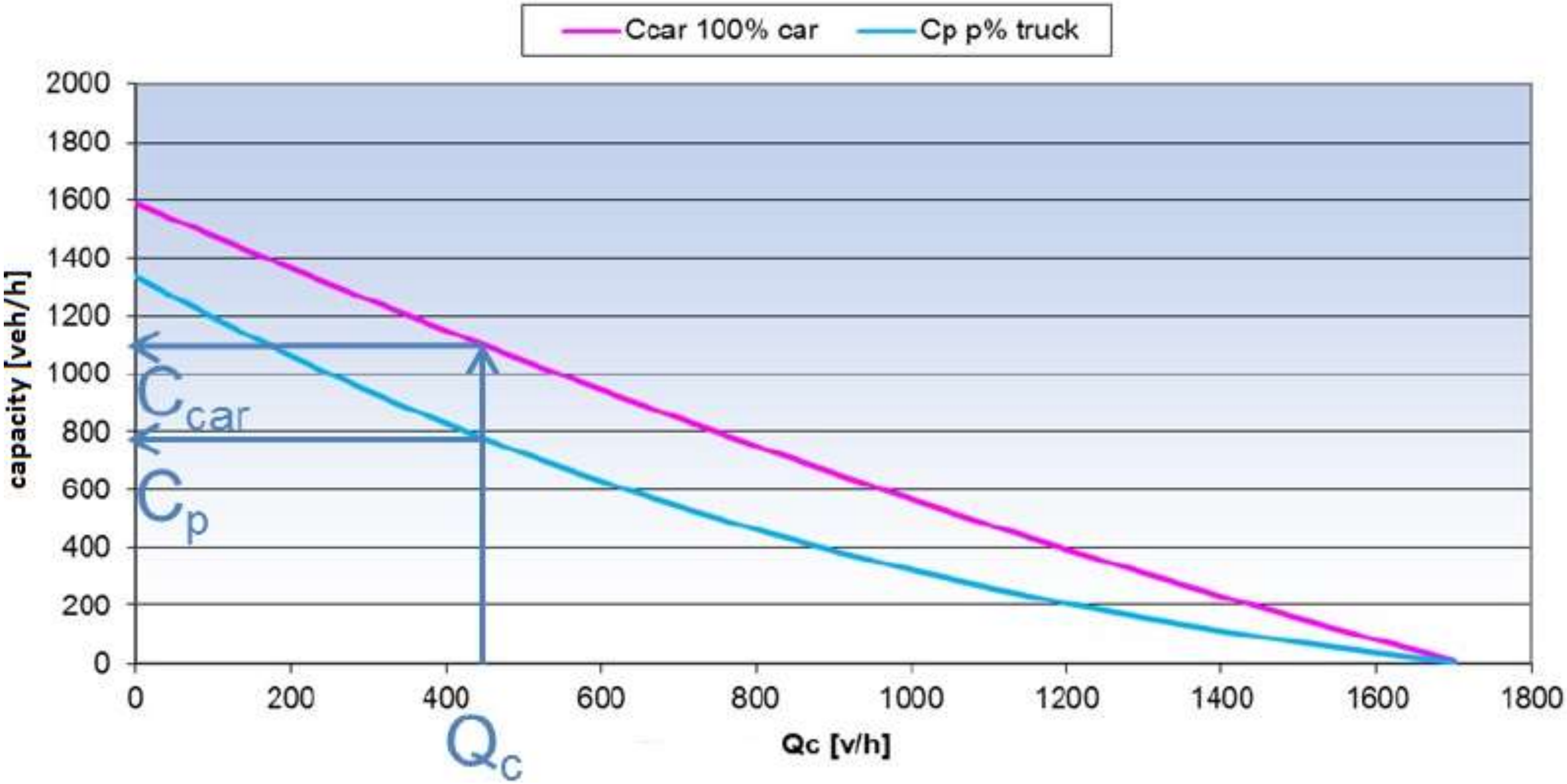


✓ This estimation was developed considering: $C_{car} = (1\text{-}p)\,C_p + p\,C_p E_t$

C_p : a mixed flow including the **share** of passenger cars **(1-p) Cp** and heavy vehicles **(p Cp)**, **multiplied by Et** for homogeneity.

introduction → Step 1 → Step 2 → **Step 3** → Step 4 → Step 5

Estimation of passenger car equivalency factors for a given % of heavy vehicles (Et)



- ✓ Capacity functions for C_{car} and C_p for different schemes of flow percentages were developed;
- ✓ So: $E_t = [C_{car} - (1-p)\, C_p\,]/\, p\, C_p$

passenger car equivalency factors for a given % of heavy vehicles were estimated.

introduction | Step 1 | Step 2 | Step 3 | Step 4 | Step 5

experimental plan for the estimation of passenger car equivalency factors

Lanes with one antagonist traffic flow

Right lane on major entry	Left lane on major entry	Right lane on minor entry
4 flow percentages	4 flow percentages	4 flow percentages
100% "car"; 10% "truck"+90% "car"; 20% "truck"+80% "car"; 100% truck	100% "car"; 10% "truck"+90% "car"; 20% "truck"+80% "car"; 100% truck	100% "car"; 10% "truck"+90% "car"; 20% "truck"+80% "car"; 100% truck
10 capacity values for a given combinations of flow percentages	10 capacity values for a given combinations of flow percentages	10 capacity values for a given combinations of flow percentages

Lanes with two antagonist traffic flow

Left lane on minor entry → 7 combinations of circulating flows

$Q_{ci}=0$ $Q_{ce}=var.$	$Q_{ci}/Q_{ce}=0,33$	$Q_{ci}/Q_{ce}=0,5$	$Q_{ci}/Q_{ce}=1$	$Q_{ci}/Q_{ce}=2$	$Q_{ci}/Q_{ce}=3$	$Q_{ci}=var.$ $Q_{ce}=0$

4 combinations of flow percentages

100% car; 10% truck+90% car; 20% truck+80% car; 100% truck

10 capacity values for a given flow composition for 7 combinations of circulating flows

120+280 = 400 simulated values of capacity → 4000 simulations

- ✓ Left-entry lane **capacity values at minor roads** were higher than other values **for combinations of circulating flows with $Qce<Qci$** (i.e. Qci in the inner lane of the ring **higher than** values of Qce in the outer lane of the ring);

$$C^*(Qci/\ Qce=x)>C^*(Qci/\ Qce=1/x) \qquad \text{for } x>1$$

- ✓ **So Aimun outputs agree with** Mcdowell et al (1983) observations **(Tce> Tci)**, but **disagree with** Tc **values** observed **by Fortujin**.

* Mcdowell et al (1983). Gap acceptance and traffic conflict simulation as a measure of risk. TRRL SR 776.

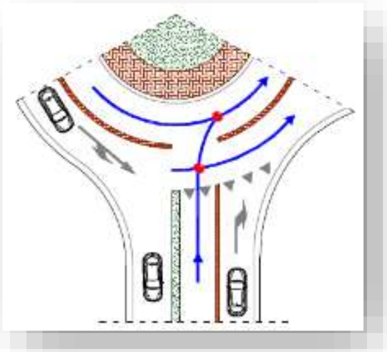
- ✓ **Statistical regressions** of the microsimulation outputs (C; Qc) and analysis of the results were then carried out;
- ✓ Non linear statistical regressions of the data obtained were developed using Mathematica 9.0; **Hagring model was specified again**:

$$C_e = Q_{c,e} \cdot \left(1 - \frac{\Delta \cdot Q_{c,e}}{3600}\right) \cdot \frac{\exp\left(\frac{-Q_{c,e}}{3600} \cdot (T_c - \Delta)\right)}{1 - \exp\left(\frac{-Q_{c,e}}{3600} \cdot T_f\right)}$$

→ For a conflict scheme with one antagonist traffic flow .

$$C_e = (Q_{c,e} + Q_{c,i}) \cdot \left(1 - \frac{\Delta \cdot Q_{c,e}}{3600}\right) \cdot \left(1 - \frac{\Delta \cdot Q_{c,i}}{3600}\right) \cdot \frac{\exp\left(\frac{-Q_{c,e}}{3600} \cdot (T_{c,e} - \Delta) \frac{-Q_{c,i}}{3600} \cdot (T_{c,i} - \Delta)\right)}{1 - \exp\left(\frac{-(Q_{c,e} + Q_{c,i})}{3600} \cdot T_f\right)}$$

→ For a conflict scheme with two antagonist traffic flow .



vehicular percentages	R^2	parameter	parameter estimation	standard error	t-statistic	p-value	confidence interval *
100% truck	0,999523	T_c	5,32656	0,0964877	55,2045	$1,28624\times10^{-11}$	5,10406 5,54906
		T_f	2,69525	0,0270715	99,5604	$1,15681\times10^{-13}$	2,63282 2,75768
20% truck 80%car	0,999755	T_c	4,08475	0,0630056	64,8316	$3,56411\times10^{-12}$	3,93946 4,23004
		T_f	2,35396	0,017734	132,738	$1,16025\times10^{-14}$	2,31307 2,39486
10% truck 90%car	0,999706	T_c	3,90996	0,0674909	57,9332	$8,75134\times10^{-12}$	3,75433 4,0656
		T_f	2,30904	0,0191305	120,7	$2,48147\times10^{-14}$	2,26493 2,35316
100% car	0,999428	T_c	3,73143	0,092694	40,2553	$1,59563\times10^{-10}$	3,51767 3,94518
		T_f	2,26604	0,0264516	85,6673	$3,84587\times10^{-13}$	2,20504 2,32704

Results of regressions for the **right lane** on major entry

✓ **for the parameter estimates, p-value well below the threshold** of 1‰ were obtained; **so all estimates were considered statistically significant.**

* α **significance level**

vehicular percentages	R^2	parameter	parameter estimation	standard error	t-statistic	p-value	confidence interval *
100% truck	0,999633	T_c	5,21216	0,0831251	62,7026	$4{,}65326\times10^{-12}$	5,02047 5,40385
		T_f	2,74204	0,024255	113,051	$4{,}18844\times10^{-14}$	2,68611 2,79797
20% truck 80%car	0,999962	T_c	3,99916	0,0245052	163,197	$2{,}22362\times10^{-15}$	3,94265 4,05567
		T_f	2,36964	0,00704609	336,306	$6{,}8427\times10^{-18}$	2,3534 2,38589
10% truck 90%car	0,999822	T_c	3,77777	0,0516165	73,1892	$1{,}35303\times10^{-12}$	3,65874 3,89679
		T_f	2,33173	0,0151171	154,244	$3{,}49154\times10^{-15}$	2,29687 2,36659
100% car	0,999787	T_c	3,62675	0,0558058	64,9888	$3{,}49585\times10^{-12}$	3,49806 3,75544
		T_f	2,28131	0,0163185	139,799	$7{,}66559\times10^{-15}$	2,24368 2,31894

Results of regressions for the **left lane** on major entry

✓ for left- and right-lane on **major entries** and right-lane on **minor entries** and **100% car**, **Tc is <u>close</u> to values observed by Fortuijn**.

* α **significance level**

vehicular percentages	R^2	parameter	parameter estimation	standard error	t-statistic	p-value	confidence interval *
100% truck	0,996428	T_c	6,83515	0,313297	21,8168	$2,05503\times10^{-8}$	6,11269 7,55761
		T_f	2,7624	0,0720031	38,365	$2,34022\times10^{-10}$	2,59636 2,92844
20% truck 80%car	0,999934	T_c	4,91513	0,0344126	142,829	$6,45751\times10^{-15}$	4,83578 4,99449
		T_f	2,20238	0,00808662	272,349	$3,69864\times10^{-17}$	2,18374 2,22103
10% truck 90%car	0,999743	T_c	4,54072	0,0651728	69,6721	$2,00528\times10^{-12}$	4,39044 4,69101
		T_f	2,14082	0,01572	136,185	$9,45183\times10^{-15}$	2,10457 2,17707
100% car	0,999305	T_c	4,02581	0,100879	39,9072	$1,7099\times10^{-10}$	3,79318 4,25844
		T_f	2,08169	0,0255953	81,3312	$5,82469\times10^{-13}$	2,02267 2,14071

Results of regressions for the **right lane** on <u>minor entry</u>

* α significance level

vehicular percentages	R^2	parameter	parameter estimation	standard error	t-statistic	p-value	confidence interval*
100% truck	0,98733	T_{ci}	5,26815	0,195772	26,9096	$1,32323\times10^{-36}$	4,87705 5,65925
		T_{ce}	5,63962	0,204802	27,537	$3,3981\times10^{-37}$	5,23048 6,04876
		T_f	3,22537	0,0777851	41,4652	$5,7937\times10^{-48}$	3,06998 3,38076
20% truck 80%car	0,996322	T_{ci}	4,19798	0,0978292	42,9113	$2,06056\times10^{-49}$	4,0026 4,39336
		T_{ce}	4,49392	0,101208	44,4029	$2,40324\times10^{-50}$	4,2918 4,69605
		T_f	2,39767	0,0310105	77,3181	$1,05895\times10^{-65}$	2,33574 2,4596
10% truck 90%car	0,998326	T_{ci}	3,97144	0,0647749	61,3115	$3,05426\times10^{-59}$	3,84208 4,10081
		T_{ce}	4,23483	0,0666998	63,4908	$3,27244\times10^{-60}$	4,10162 4,36803
		T_f	2,30234	0,0201487	114,268	$1,20079\times10^{-76}$	2,2621 2,34258
100% car	0,999064	T_{ci}	3,6684	0,0465887	78,7402	$5,45744\times10^{-67}$	3,57538 3,76142
		T_{ce}	3,94255	0,0481695	81,8474	$4,35206\times10^{-68}$	3,84637 4,03872
		T_f	2,19418	0,0143212	153,212	$5,84016\times10^{-86}$	2,16559 2,22278

Results of regressions for the **left lane** on minor entry

* α **significance level**

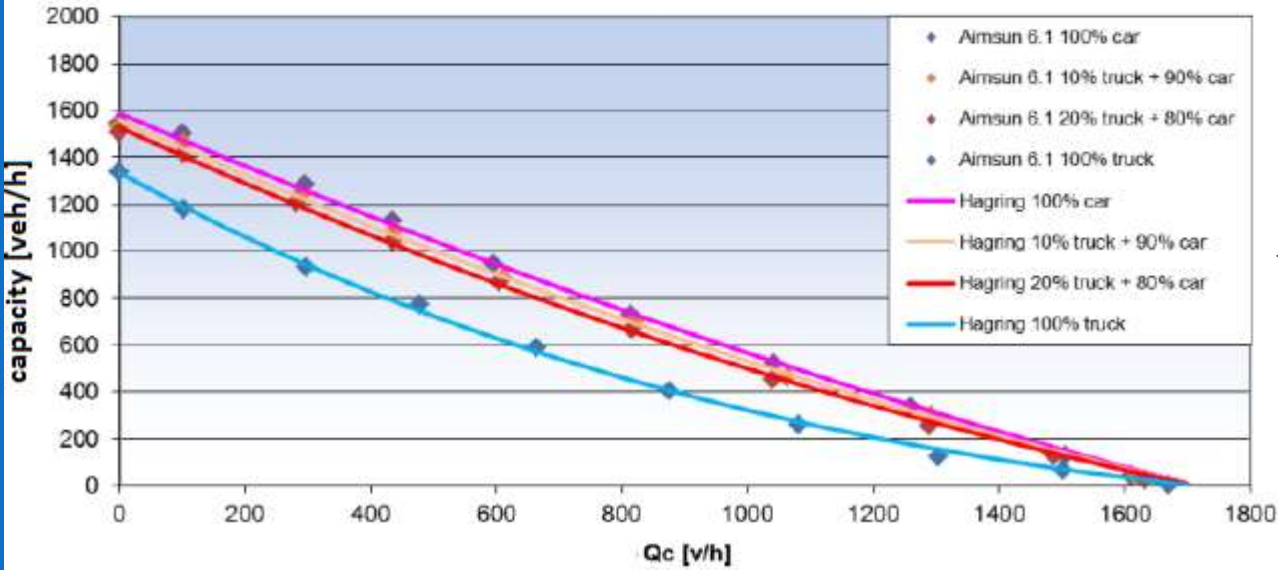
- ✓ **Increasing truck percentages**, **behavioral parameters** estimated by statistical regression **increased** at all the entry lanes.
- ✓ Similarly , **increasing truck percentages**, **simulated capacity values decreased**, being the same the conflicting flows of cars only.

Why?

- ✓ Trucks have poor performances;
- ✓ Trucks reduce the **insertion** between gaps in major lanes;

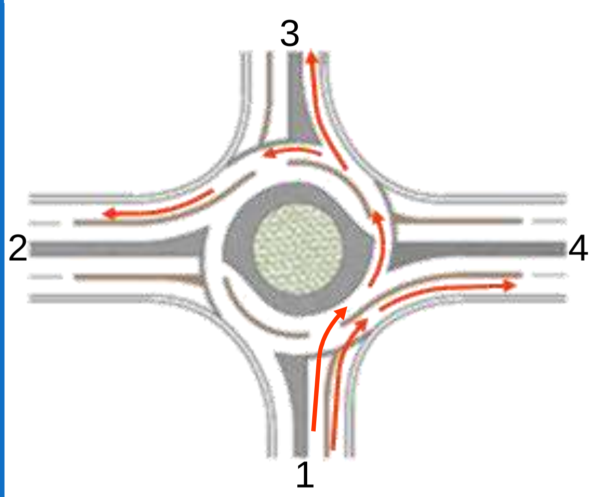
According to Hagring model, capacity functions were developed by each entry lane at turbo-roundabout and for every truck percentages here considered.

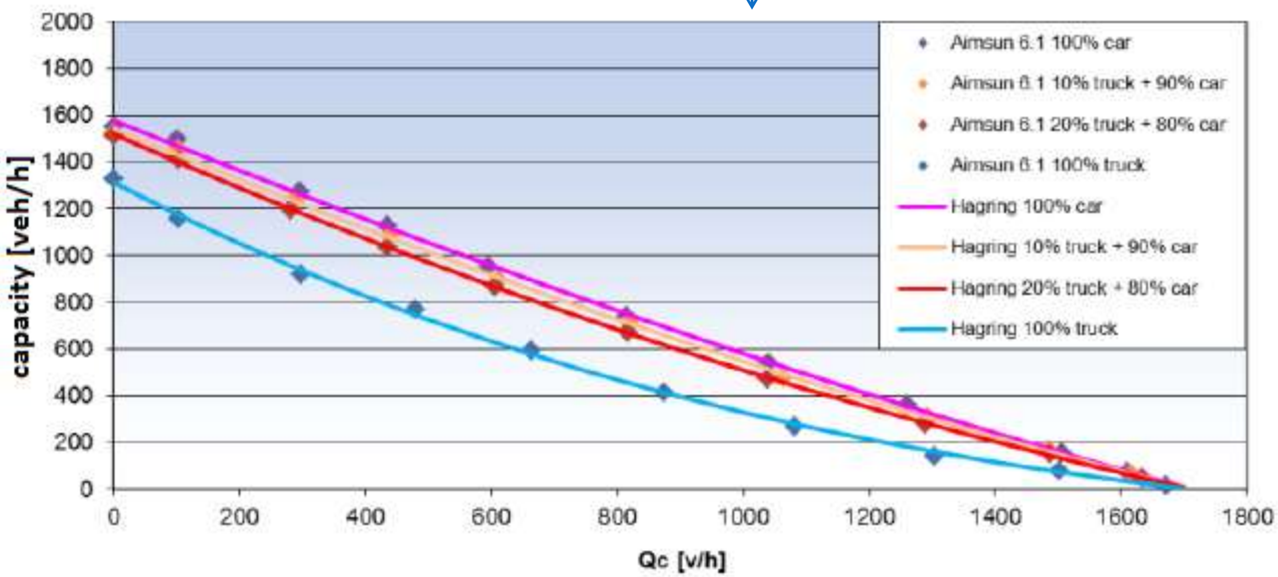
They are shown in the following slides.



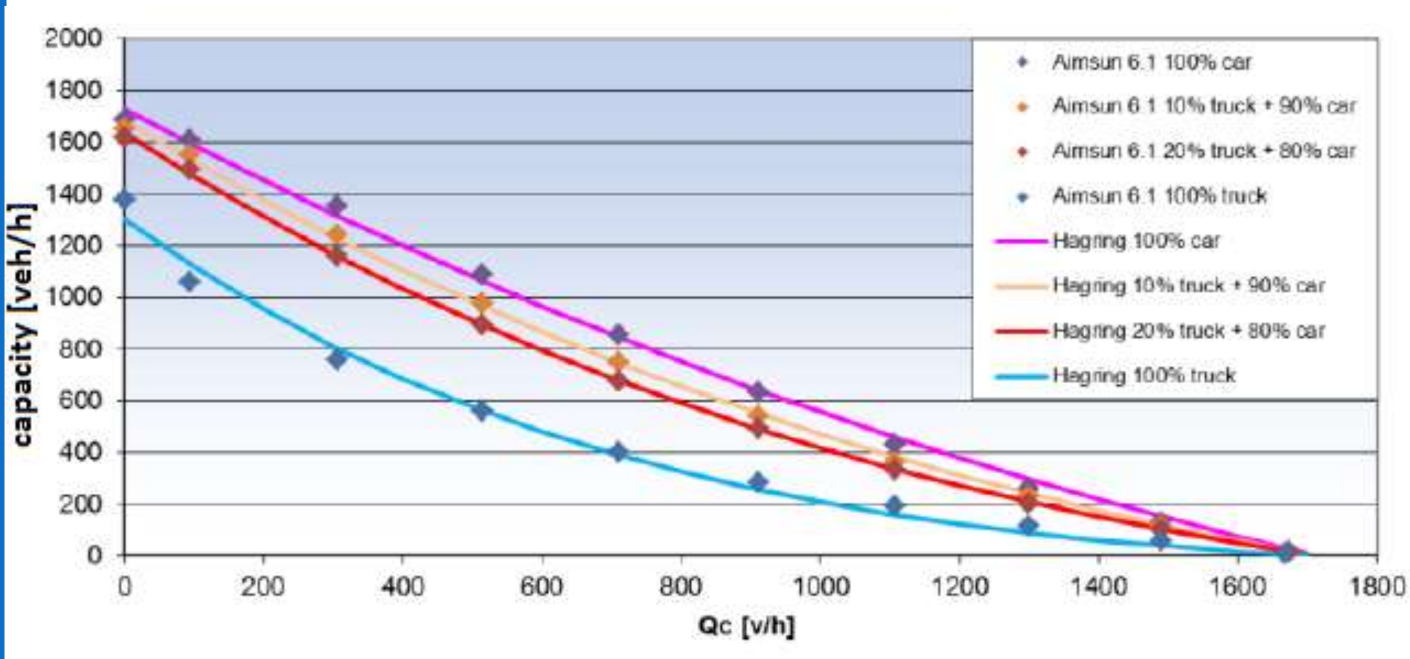
Simulated data and regressions for the **right lane on major entry**

Simulated data and regressions for the **left lane on major entry**





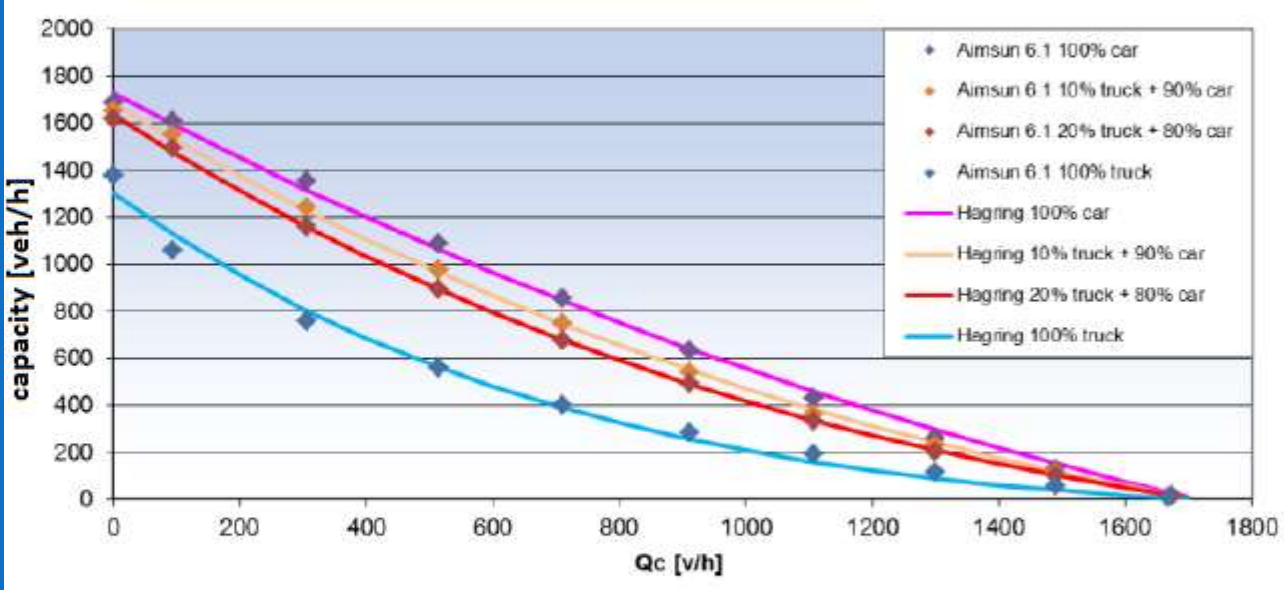
The functions are the same because the behavioral parameters were similar for each truck percentage

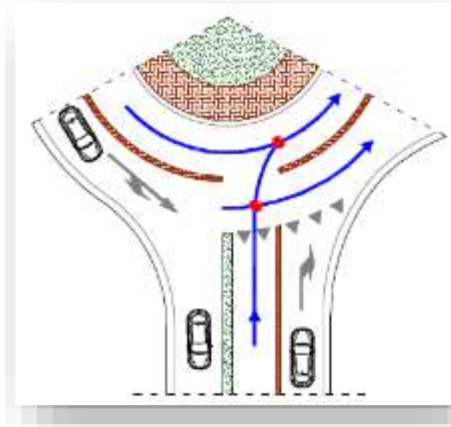


Simulated data and regressions for the **right lane on minor entry**

✓ **Increasing Qc, capacity values decrease, especially when truck percentages increase;**

introduction | Step 1 | Step 2 | Step 3 | Step 4 | Step 5



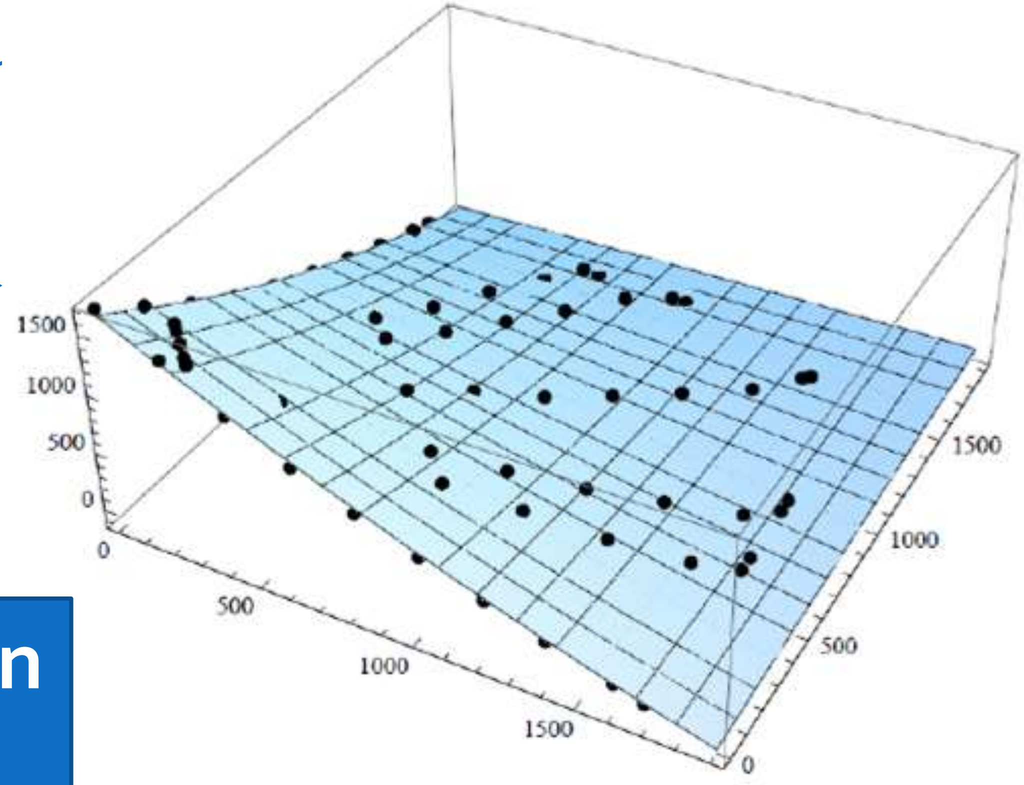


- for the **right lane** on **minor entry**, Tc was higher than that on major entries;
  - Aimsun gives **simulated capacity values less than those obtained for left- and right lane on major entries** even if the conflicting scheme is the same (**one antagonist traffic flow**);

I. This situation is due to the influence caused by **left-turning vehicles from minor entry**, facing two antagonist traffic flows;

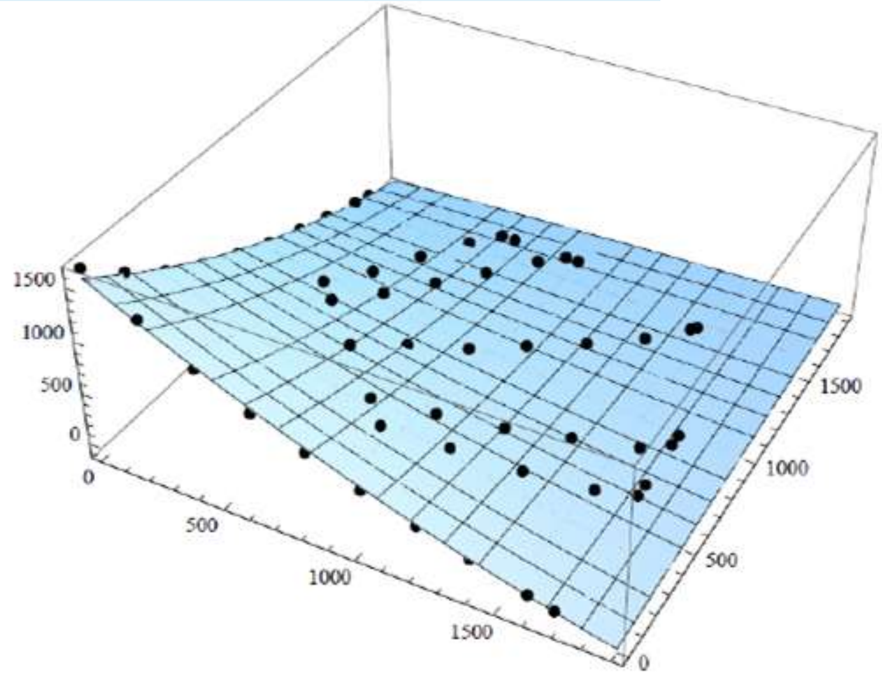
II. the **interference** with left-turning vehicles from minor entries **is higher when** truck percentages increase.

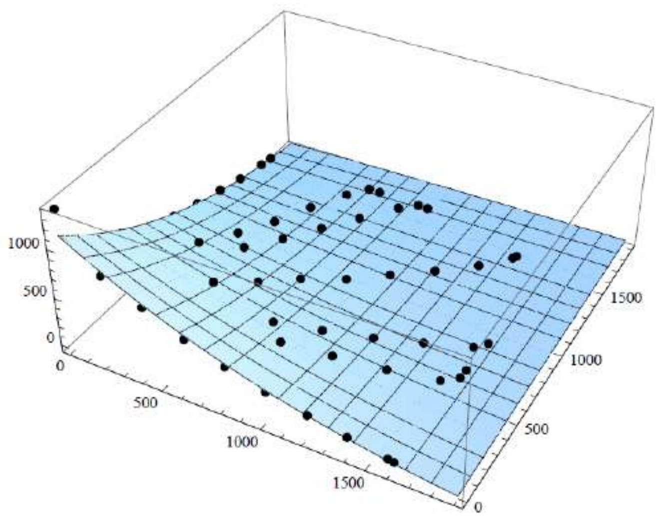
Fitted model and simulated data for
the left lane on minor entry
(entry demand: 100% cars)



the capacity function is in this case a surface, since the capacity depends on Qce and Qci

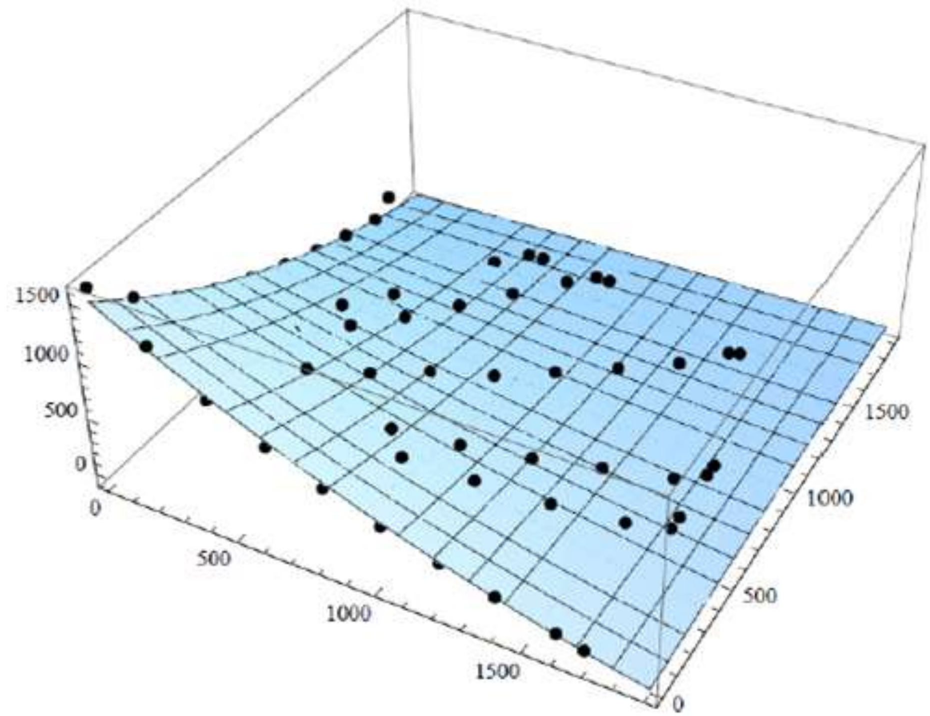
entry demand: 90% cars+ 10% truck





entry demand: 100% truck

- ✓ Capacity regression functions and simulated data for every truck percentage are shown;
- ✓ the **simulated points** corresponding to capacity values **higher than those** obtained **from the regression model** are visible;



entry demand: 80% cars+ 20% truck

- ✓ **Calculation** of the equivalent factors for a given percentage of trucks (Et) **was made by using**:

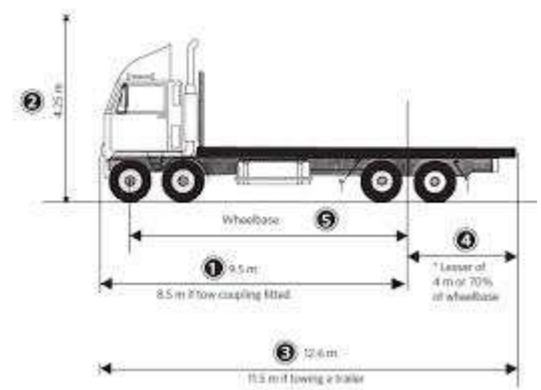
$$E_t = [C_{car} - (1-p)\, C_p\,] / \, p\, C_p$$

Where:

C_{car} : capacity with a traffic demand of cars only;

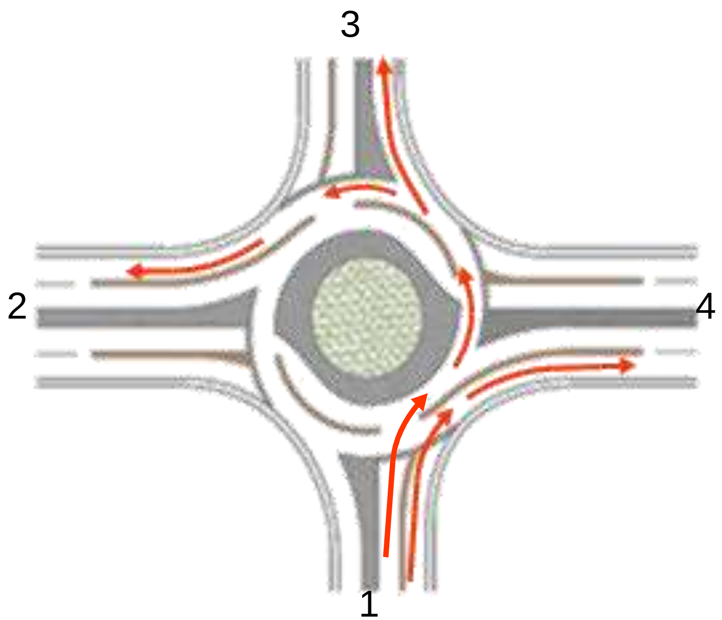
p : share of trucks

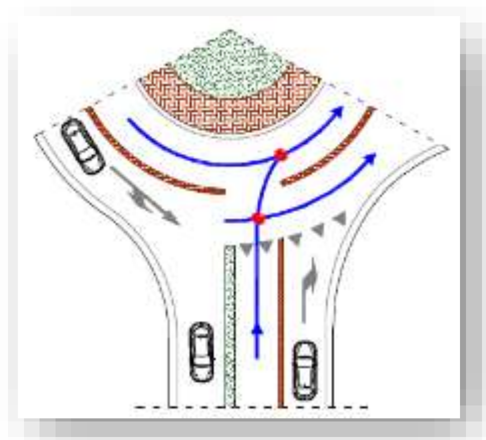
C_p : capacity with a **mixed traffic demand** characterized by **p** trucks.

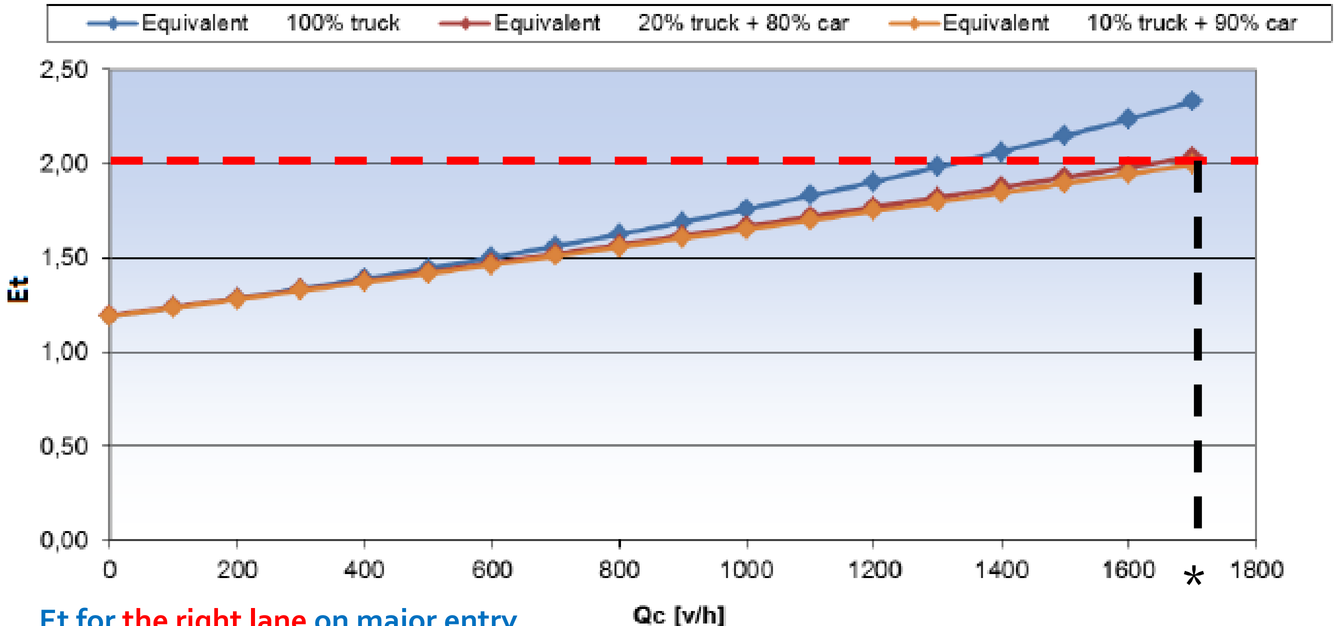


introduction | Step 1 | Step 2 | Step 3 | Step 4 | Step 5

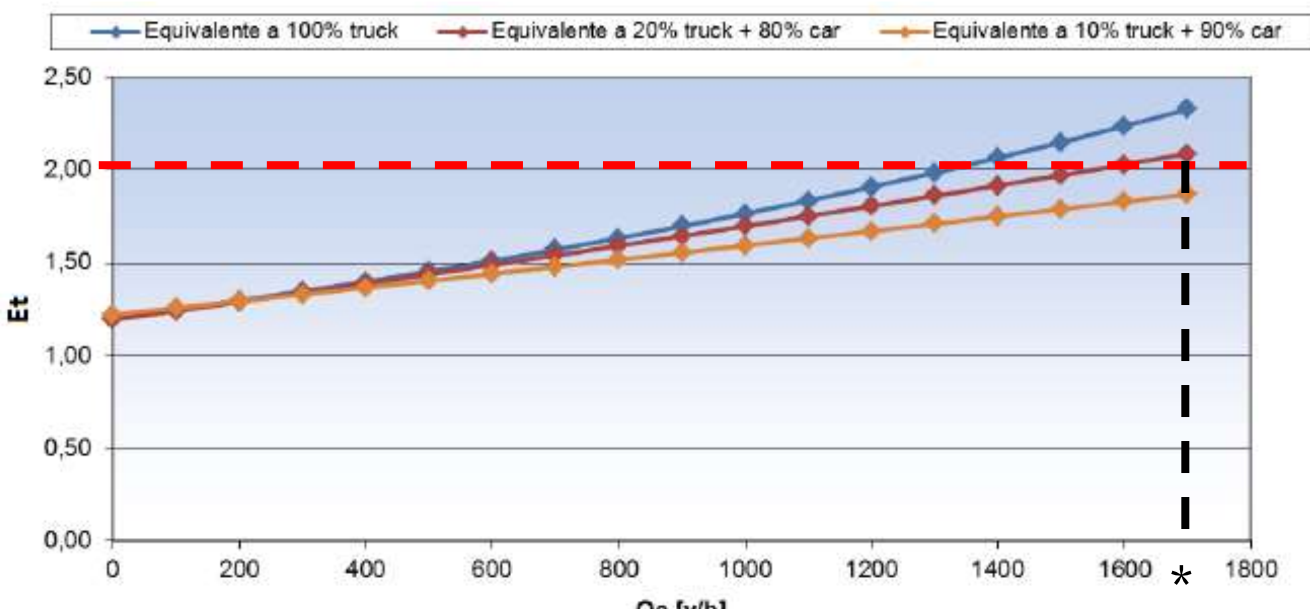
- **C_{car}** and **C_p** depend on *Qc*;
- As a consequence **Et** depends on **Qc**;
- So **Et** is depending on <u>one</u> antagonist traffic flow (Qce) for **left- and right lane** at **major entries** and **right-lane** at **minor entries**;
- **Et** is depending on <u>two</u> antagonist traffic flows (Qce and Qci) for **left-lane** at **minor entries**.





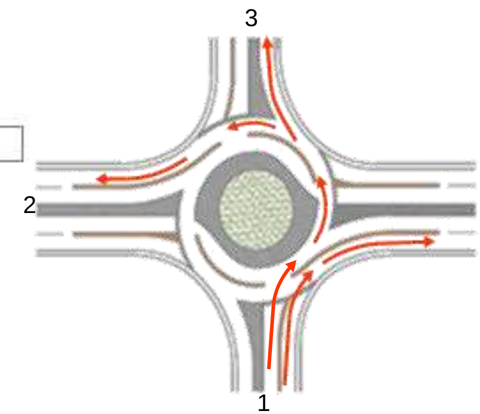


Et for **the right lane** on major entry



Et for **the left lane** on major entry

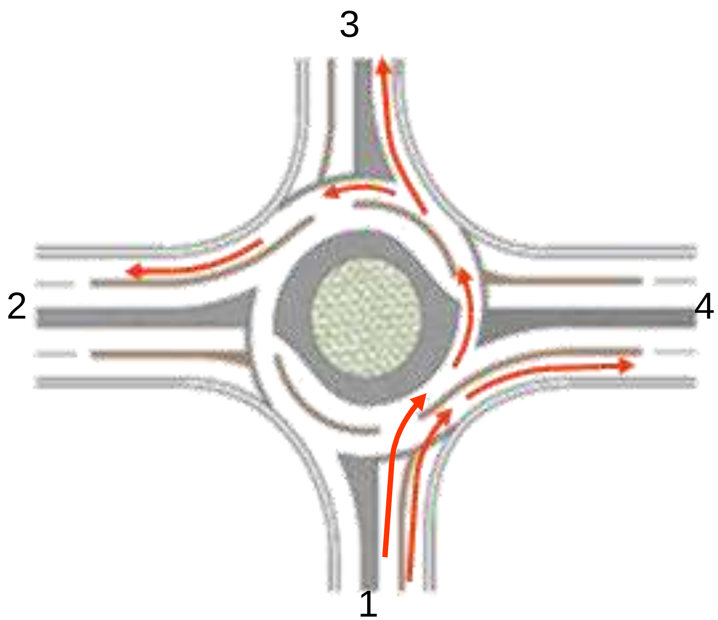
- ✓ For **20 %** and **10 %** of trucks the two functions are **overlapped** (you can see a good matching of the two functions);

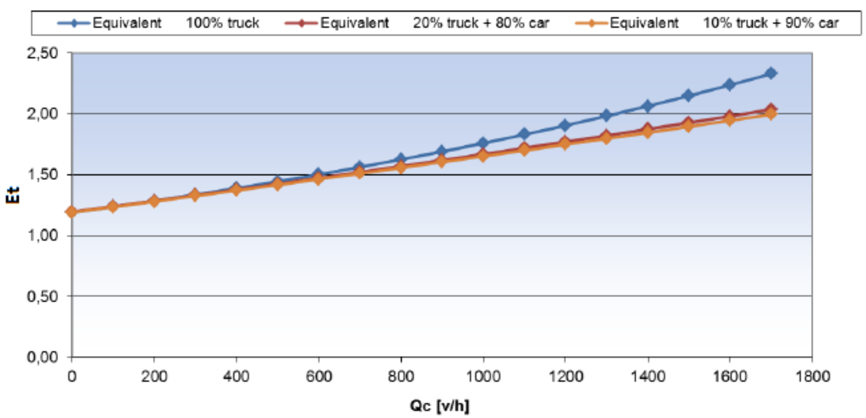


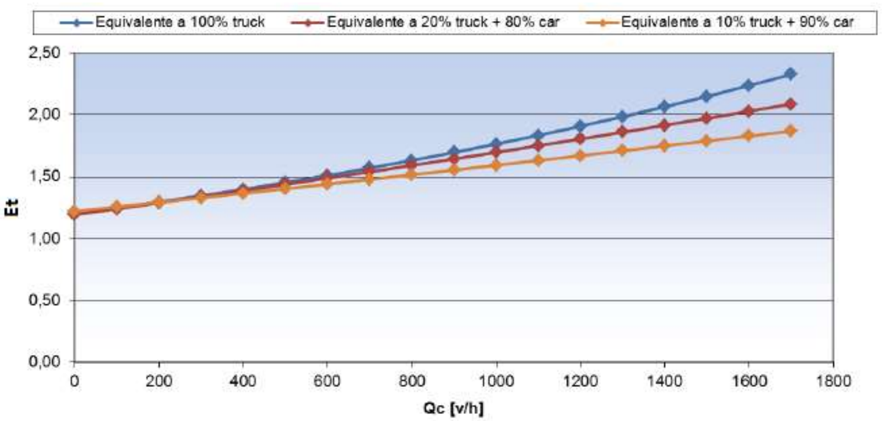
- ✓ In usual operations Et< 2;

* Qc = 1700 veh/h

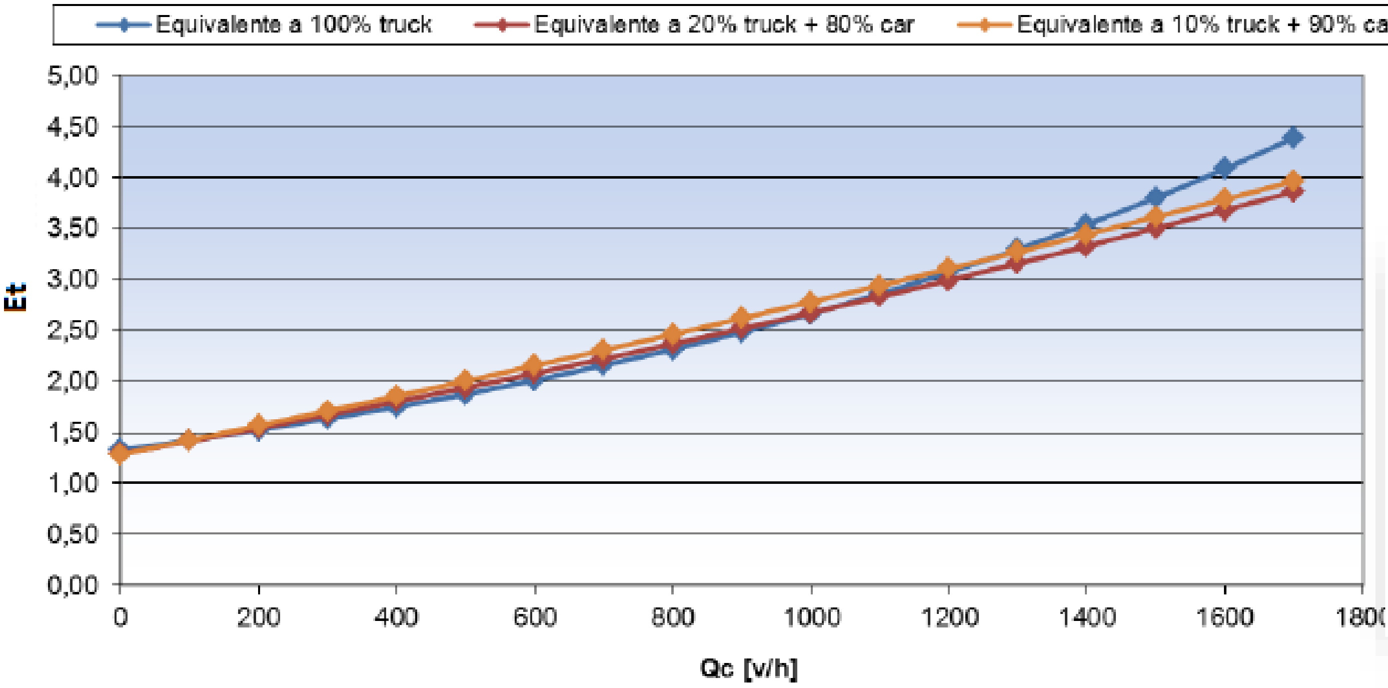
✓ Assuming **Et =2 for left- and right lane at major entries** (as HCM 2010 suggests), **<u>overestimation</u> of the impact of trucks** on the quality of the traffic flow **happens**.

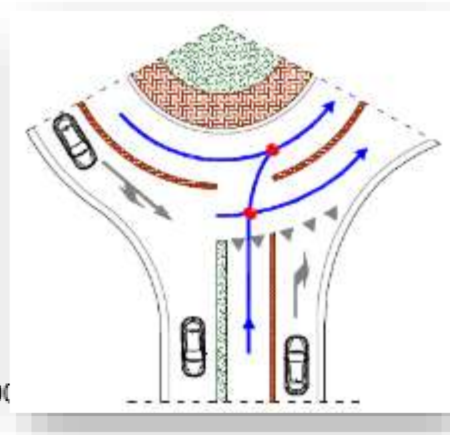






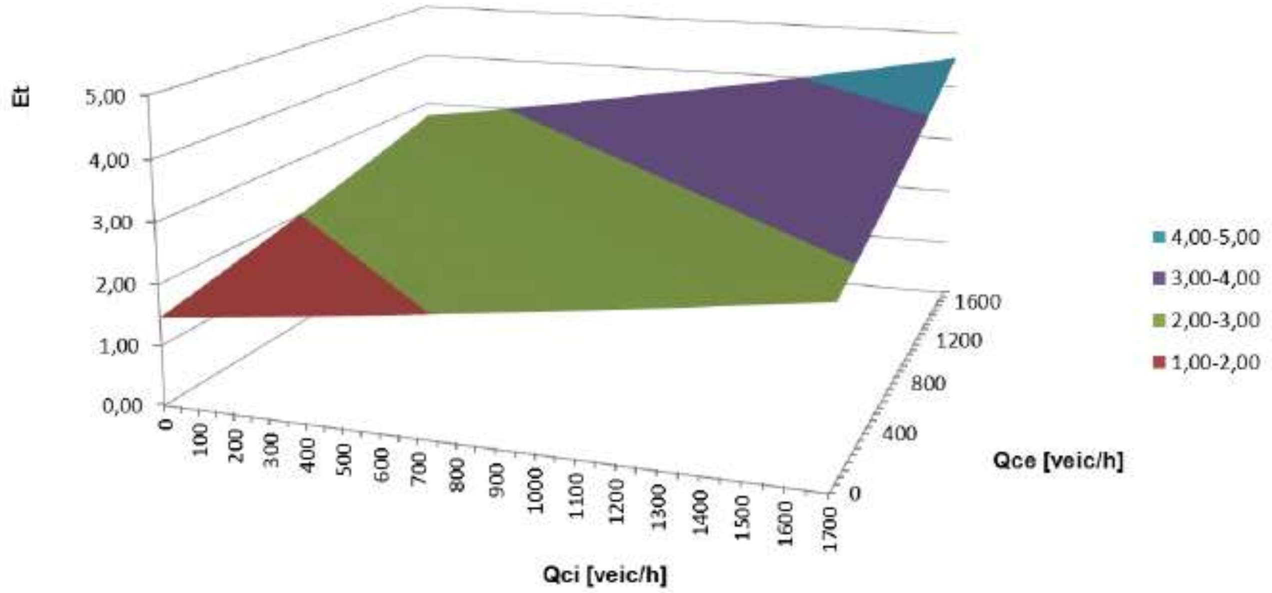
- **Et = 2** is early reached and exceeded when Qc increases;
- In usual operations **Et = 4** is reached;
- Assuming **Et =2** for **right lane at minor entries** as HCM 2010 suggests, **underestimation** of the impact of trucks on the quality of the traffic flow happens.





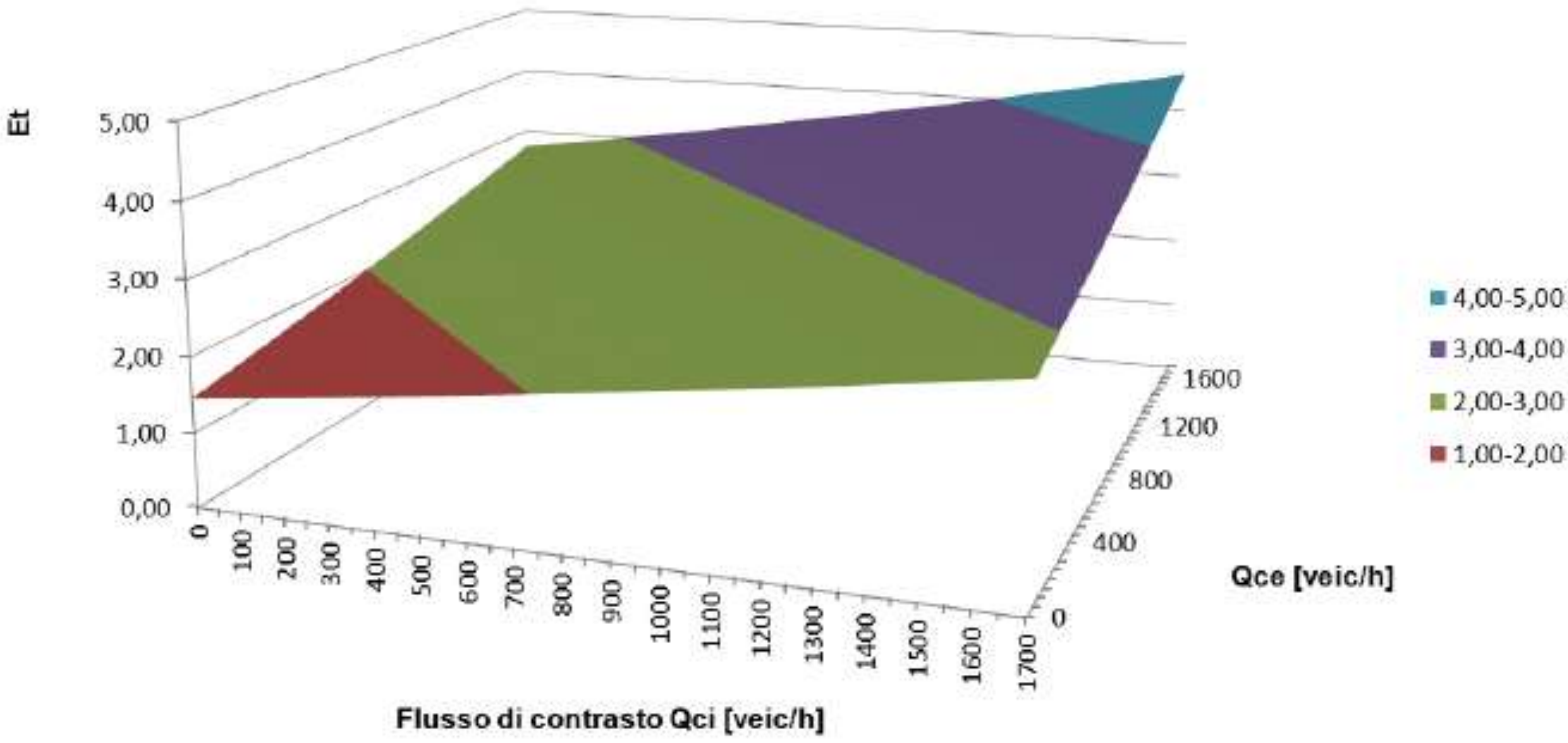
Equivalent factors for the right lane on minor entry

entry demand: 90% cars+ 10% truck



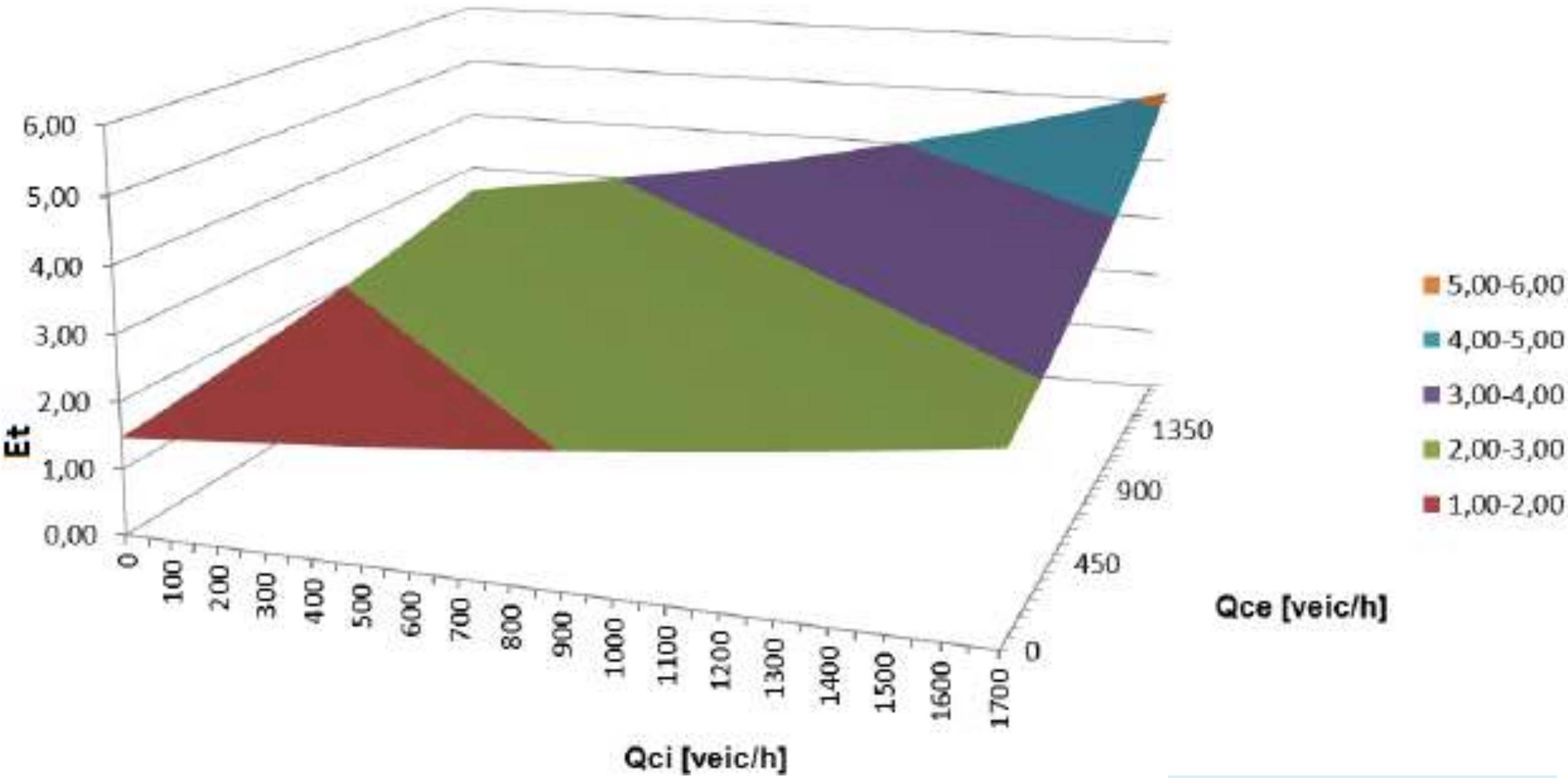
Equivalent factors for the left lane on minor entry

- ✓ E_t as a function of Q_{CE} and Q_{CI} for different percentages of trucks are *surfaces* and their overlapping in a single diagram would be illegible.



Equivalent factors for the left lane on minor entry

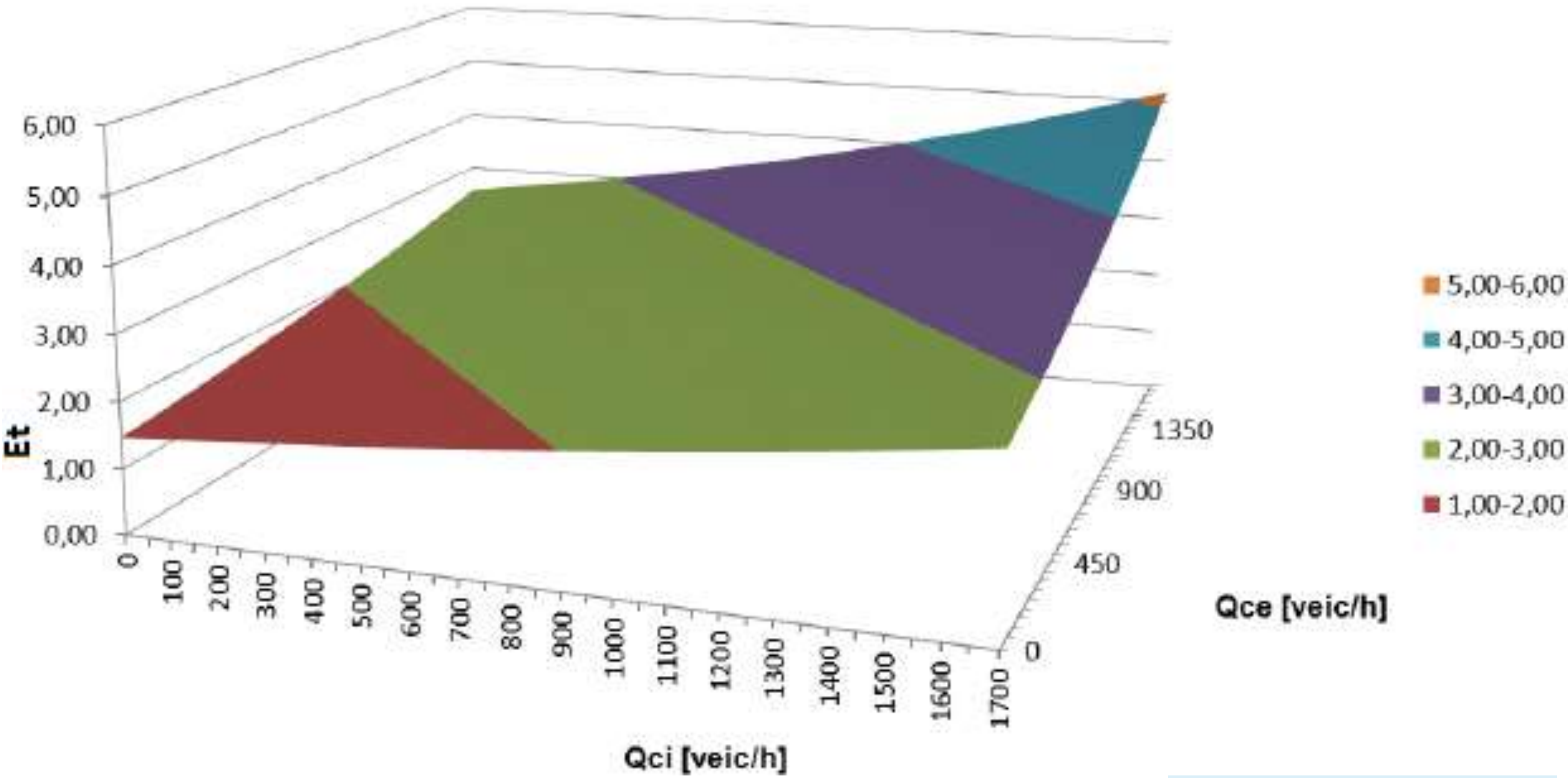
entry demand: 80% cars+ 20% truck



Equivalent factors for the left lane on minor entry

entry demand: 100% truck

- ✓ in the usual traffic conditions (10% and 20% trucks), values Et=4.5 is reached, ie slightly higher than the most value (Et = 4) obtained for the right lane on minor entries;



Equivalent factors for the left lane on minor entry

entry demand: 100% truck

- ✓ In addition, for this entry lane, assuming Et = 2 (HCM 2010) as for modern roundabouts, underestimation of the impact of trucks on the quality of traffic flow could happen;

Zuid-Holland province.

http://www.skyscrapercity.com/showthread.php?t=413067&page=496

References: see eg….

- L.G.H. Fortuijn, 2009, Turbo Roundabouts: Design Principles and Safety Performance.

  Transportation Research Record, 2096: 16-24

- Rodegerdts et al., 2010, Roundabouts: An Informational Guide *Second Edition*, NCHRP REPORT 672, http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_672.pdf

- CROW (2008). Turbo roundabouts. Publication No. 257, Ede (in Dutch).

- Ana Bastos Silva, Luís Vasconcelos, Sílvia Santosa, 2014, Moving from Conventional Roundabouts to Turbo-Roundabouts, EWGT2013 – 16th Meeting of the EURO Working Group on Transportation, Procedia - Social and Behavioral Sciences 111 (2014) 137 – 146.

- Giuffrè O, Guerrieri M, Granà A (2010) “Turbo-Roundabout General Design Criteria and Functional Principles: Case Studies from Real World”, 4th International Symposium on Highway Geometric Design. Valencia, Spain.

- Mauro R, Branco F (2010) “Comparative Analysis of Compact Multilane Roundabouts and Turboroundabouts”, Journal of Transportation Engineering 136, 316–322.

- Livelli prestazionali d rotatorie tradizionali e innovative a confronto. L’impatto dei veicoli pesanti. Tesi di Dottorato in Ingegneria delle Infrastrutture viarie –ciclo XXIV, Febbraio 2014 (allievo S. Marino; tutor O. Giuffrè, A. Granà)