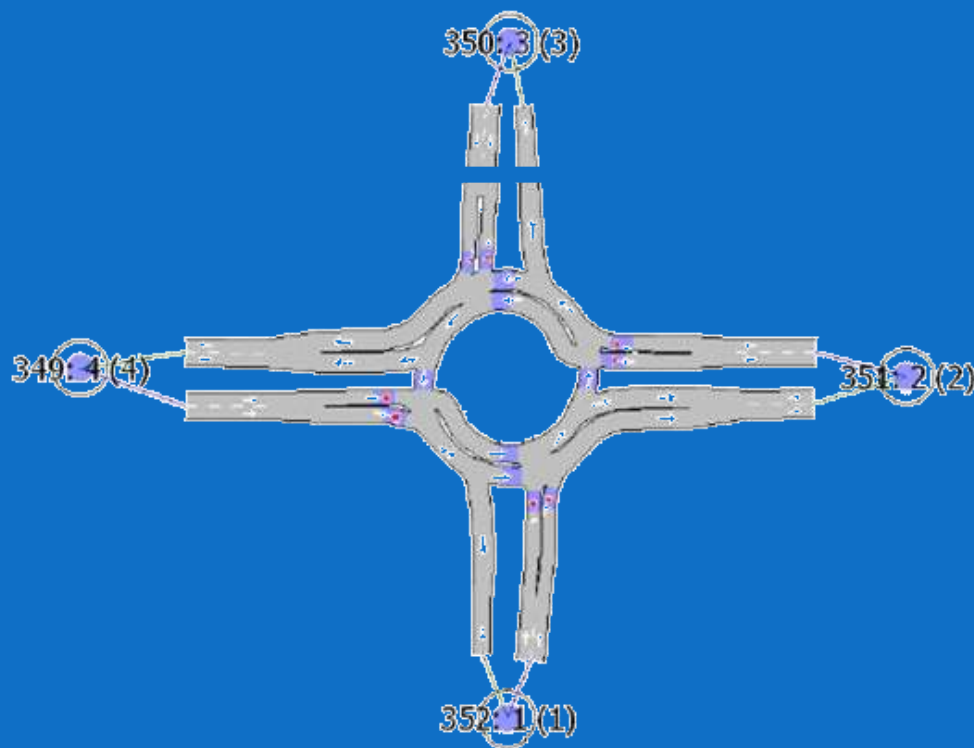


Designing Turbo-roundabouts



Anna Granà – DICAM
University of Palermo, Italy

outlines

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



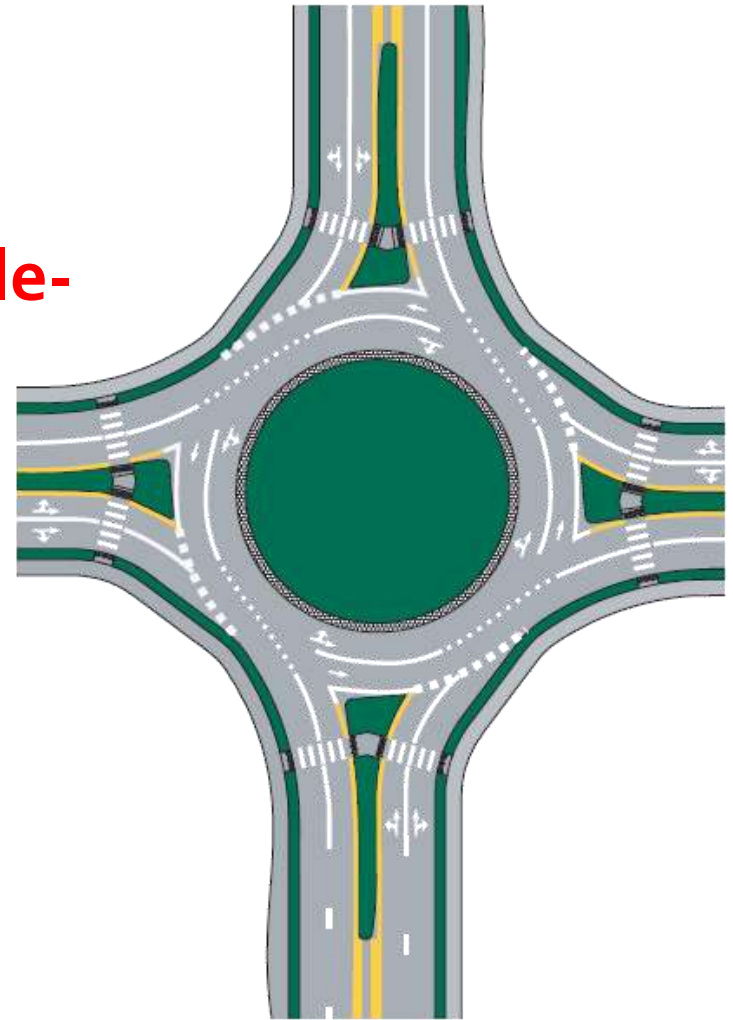
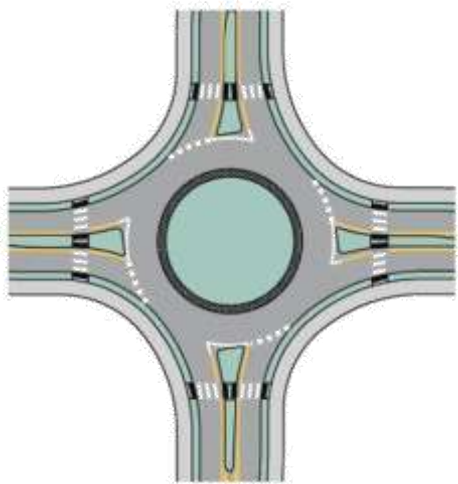
What's the turbo-roundabout?

- ✓ **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**.



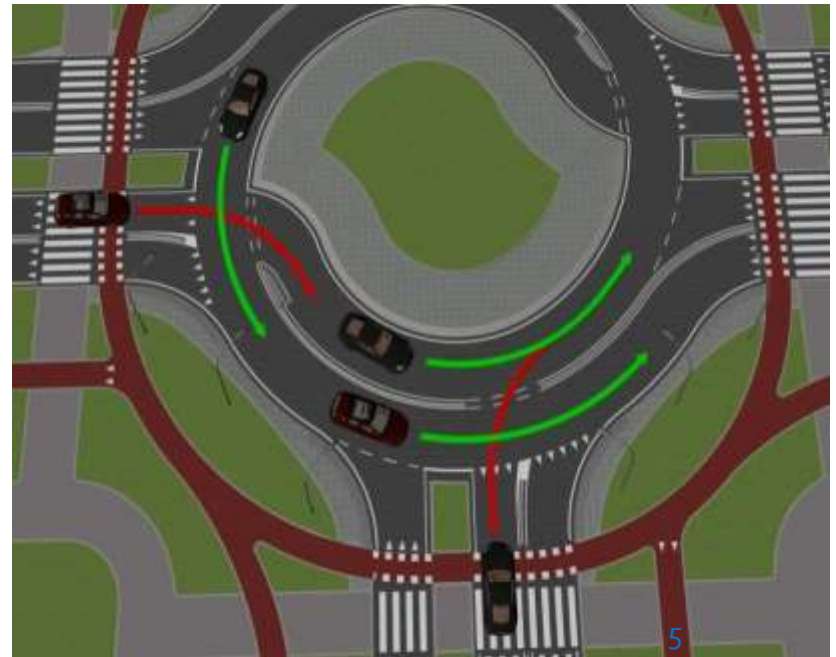
What's the turbo-roundabout?

- ✓ 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?

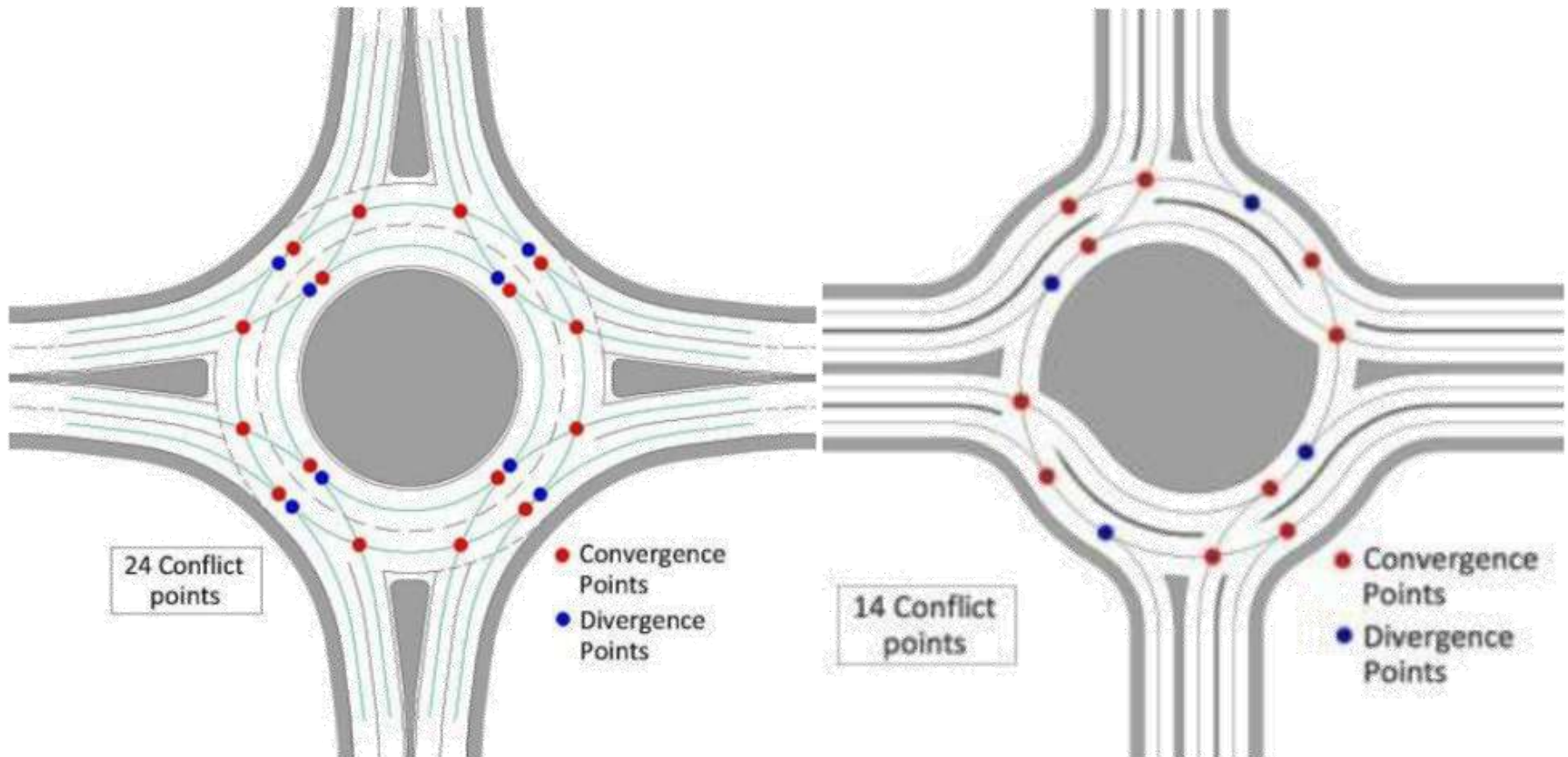
- ✓ The turbo-roundabout meets the following conditions:
 - ❖ no lane changing on the roundabout;
 - ❖ no need to yield to more than two lanes;
 - ❖ low driving speed through the roundabout.



What's the turbo-roundabout?

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

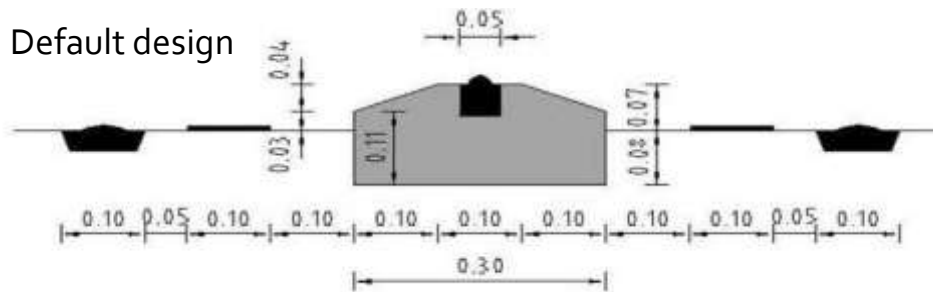
- ✓ reduction in the number of conflicts, eliminating weaving and cut-in conflicts;



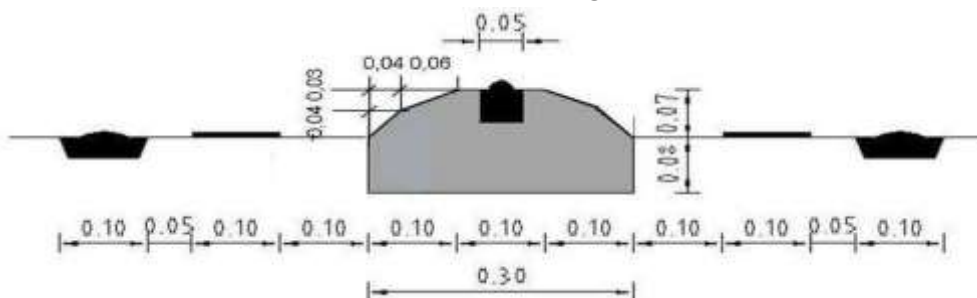
What's the turbo-roundabout?

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.



Modified to permit use for snow plough



What's the turbo-roundabout?

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



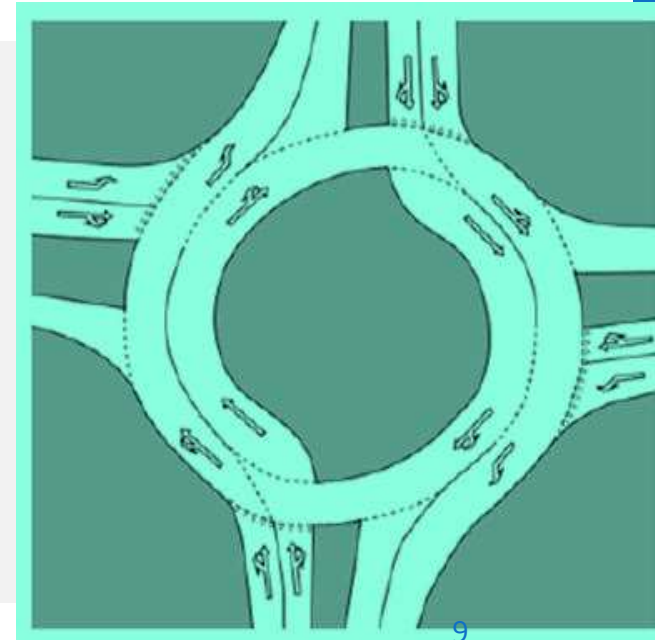
What's the turbo-roundabout?

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

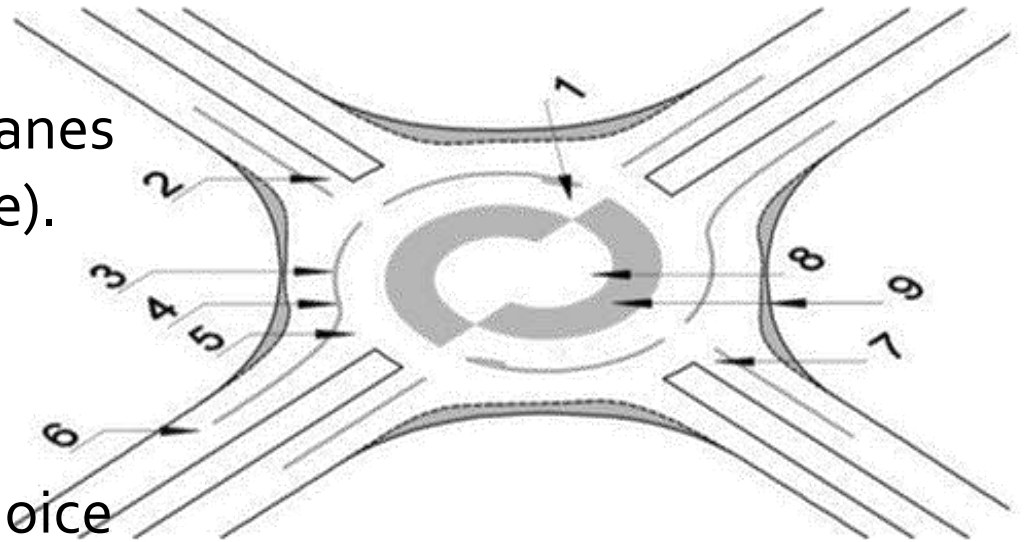
- I. there are usually **2 entering lanes** continuing into **2 circulating lanes**,
- II. the use of the **inner circulating lane** is more **attractive**, since there is no need for weaving,
- III. the entering flow is no longer **hesitant**, which increases the entry capacity.



What's the turbo-roundabout?

Features of a Turbo roundabout

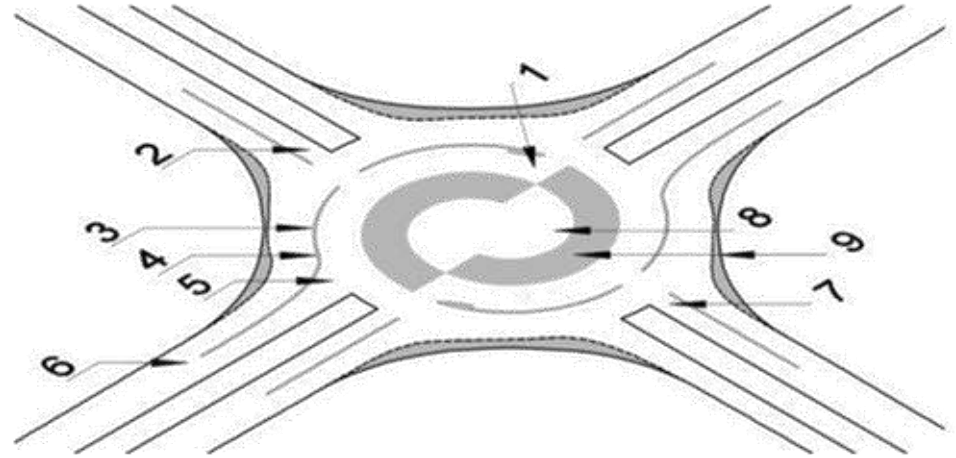
1. Nested spiral lane at one or more entries.
2. Yield to no more than two lanes (deviation might be possible).
3. Smooth spiral markings.
4. Raised and mountable lane dividers.
5. At least one lane offers a choice for direction.
6. At least two exit legs have two exit lanes.
7. Entry approach are at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

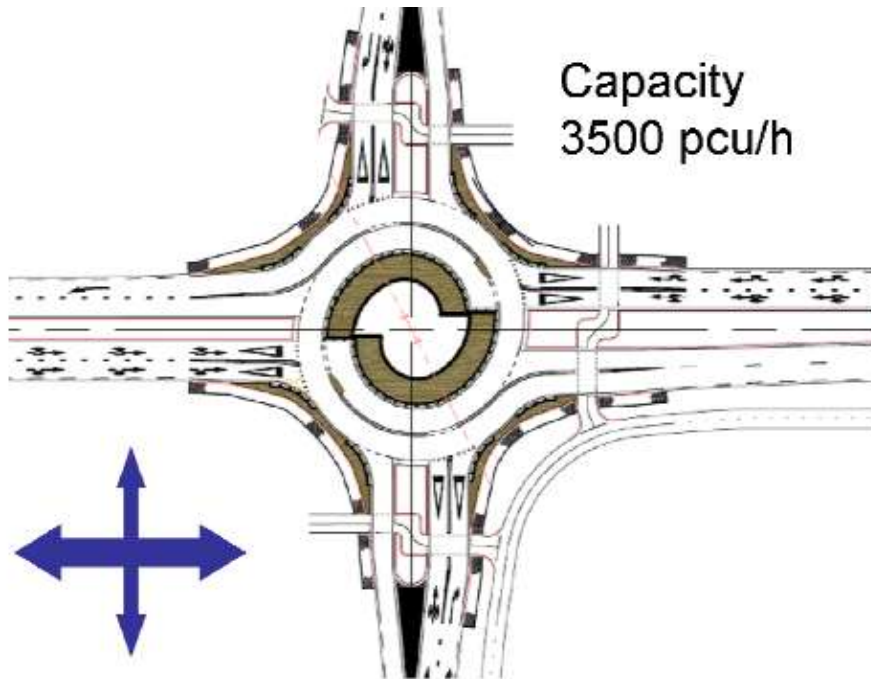
DIFFERENT VARIANTS OF THE TURBO ROUNDABOUT - Fortuijn (2009)

- ✓ 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

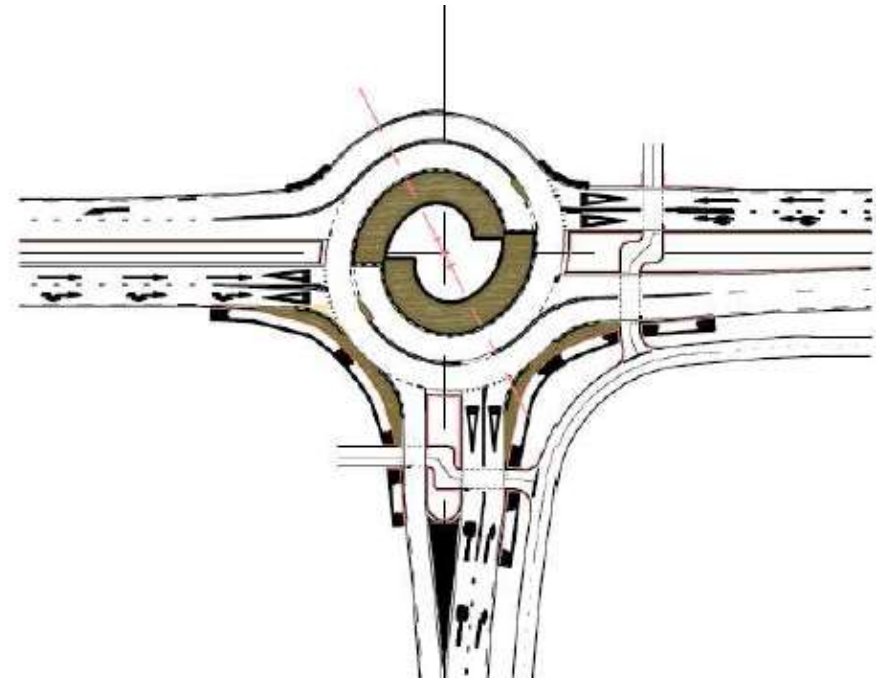


What's the turbo-roundabout?

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

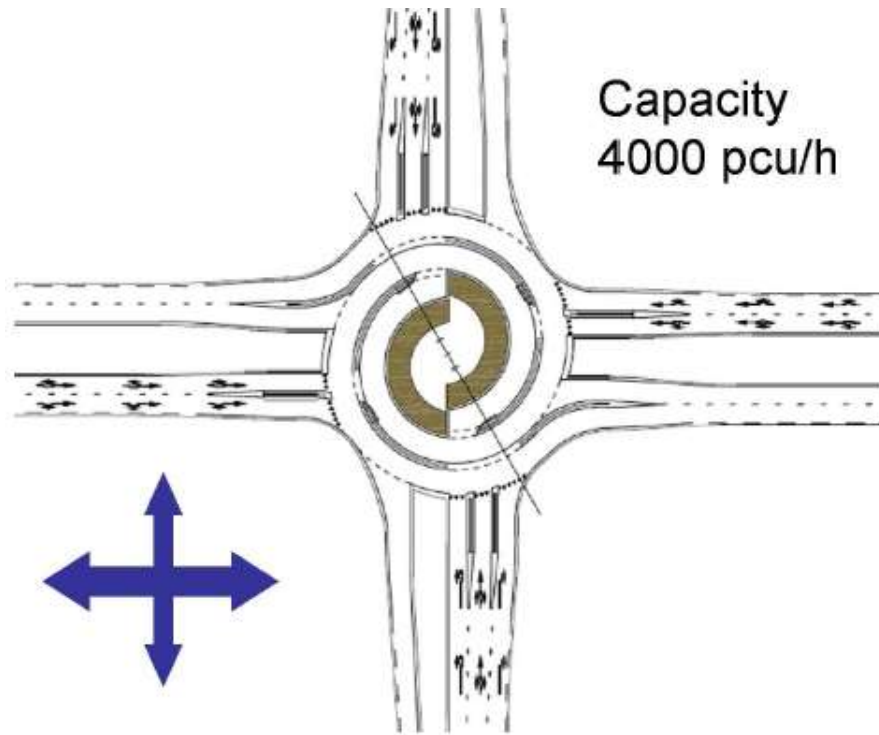


Basic turbo roundabout



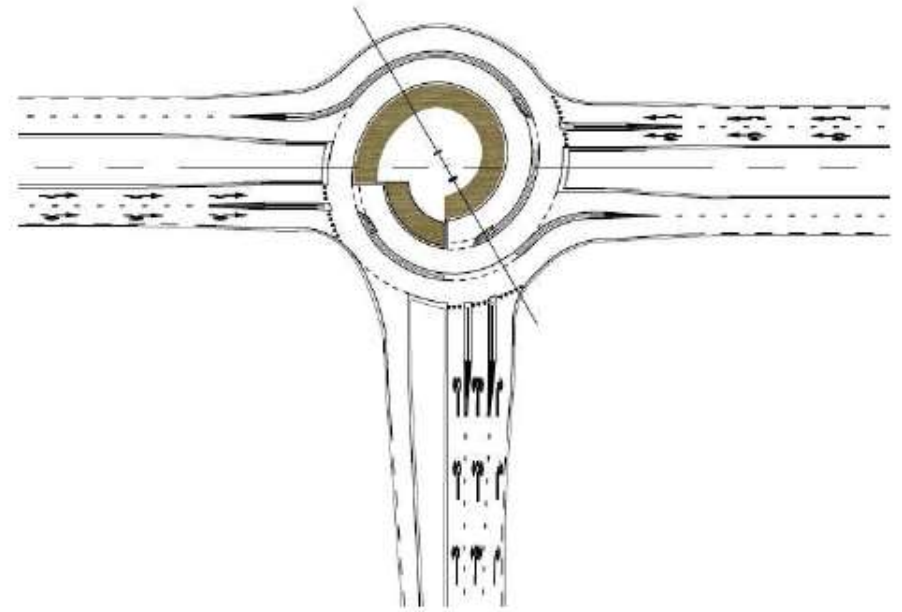
Three-leg Basic turbo roundabout

What's the turbo-roundabout?



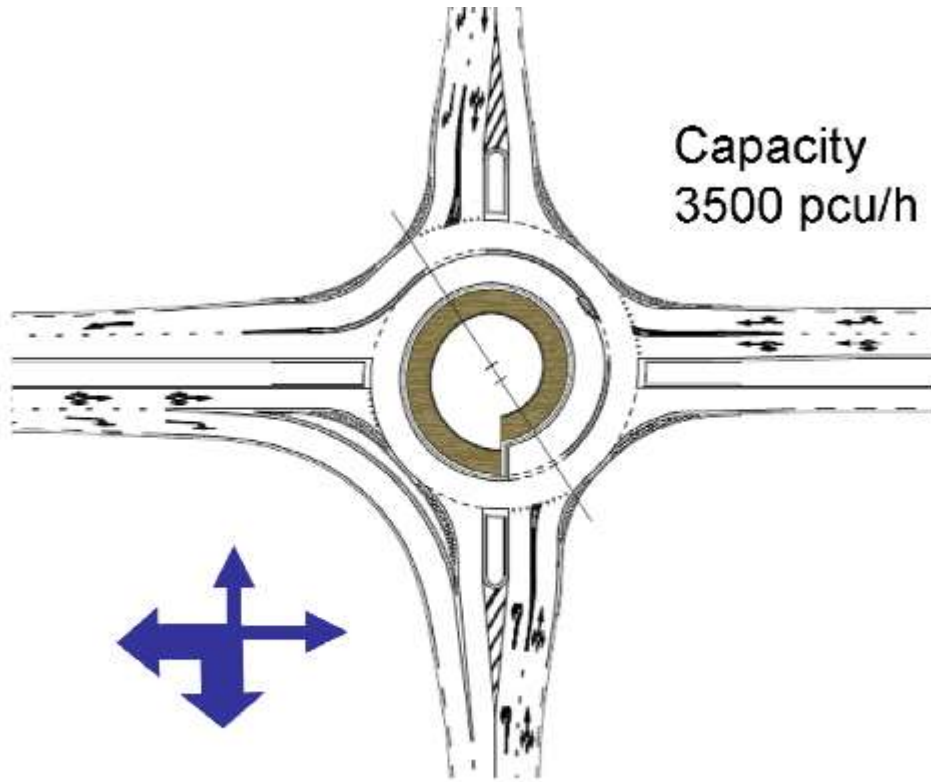
Capacity
4000 pcu/h

Spiral roundabout

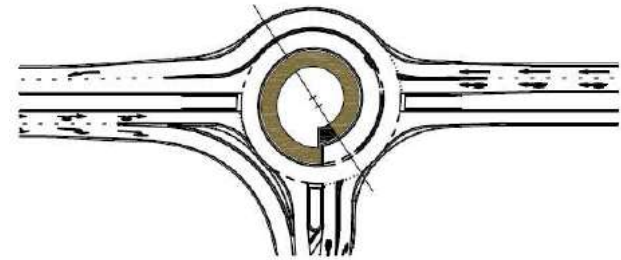
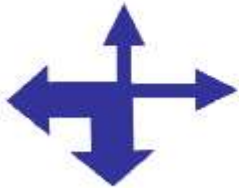


Three-leg Spiral roundabout

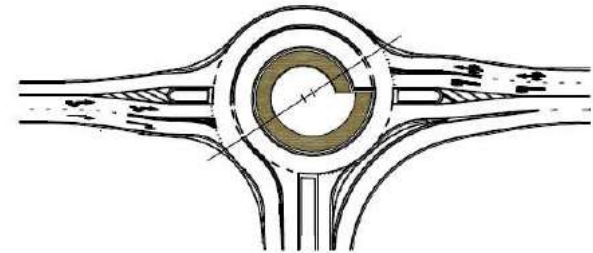
What's the turbo-roundabout?



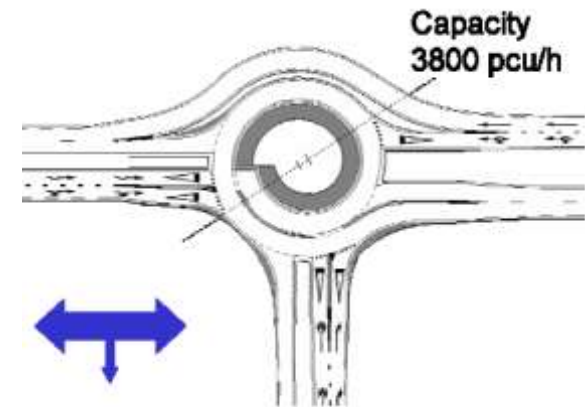
Knee roundabout



Three-leg Knee roundabout



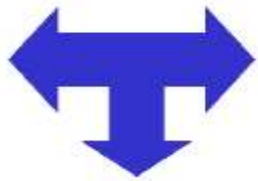
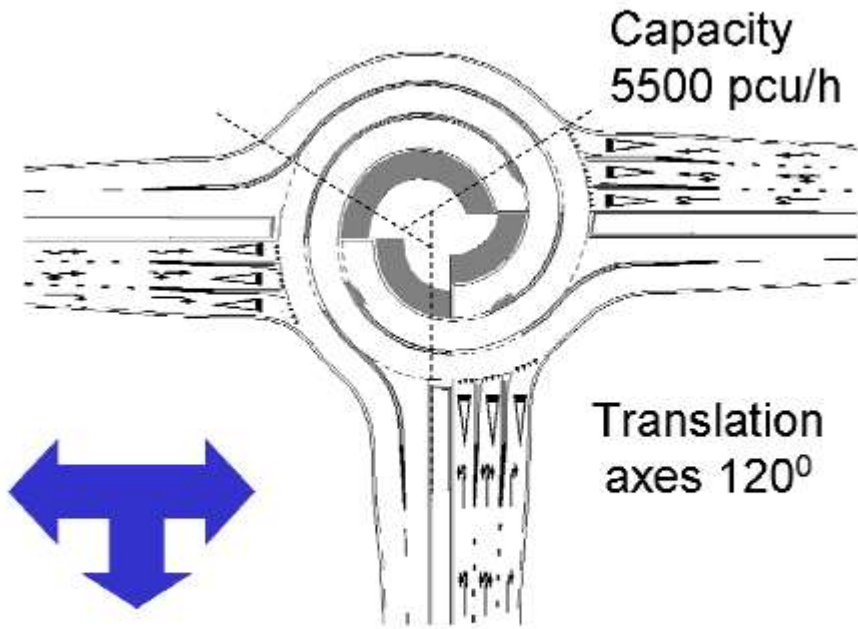
Three-leg Knee roundabout



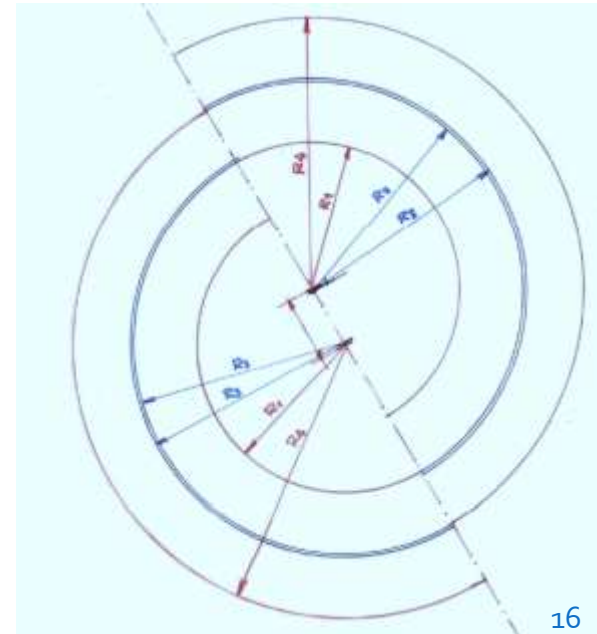
Three-leg Stretched Knee roundabout

What's the turbo-roundabout?

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

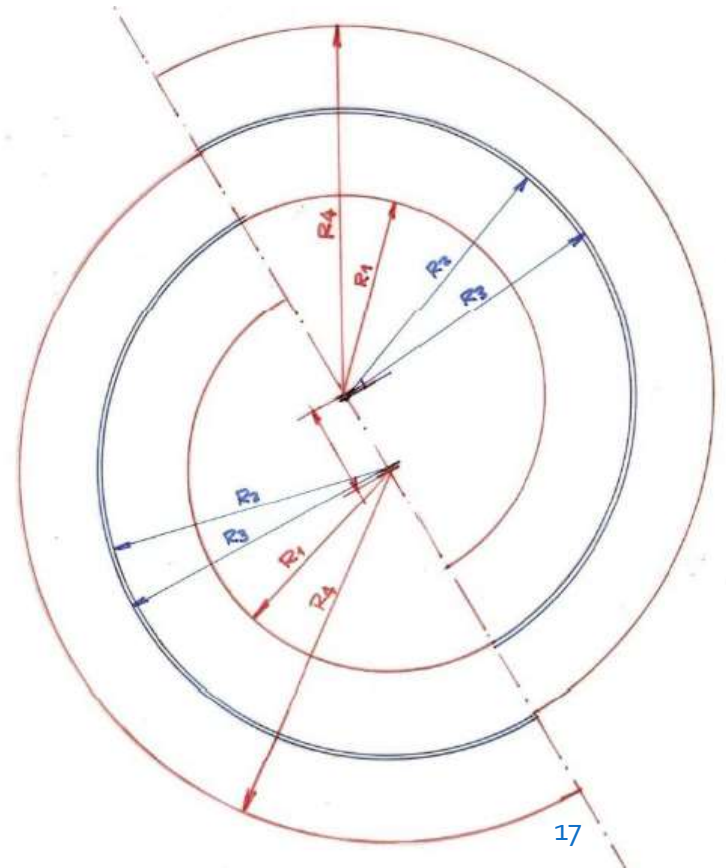


Star Roundabout
(three-leg)



What's the turbo-roundabout?

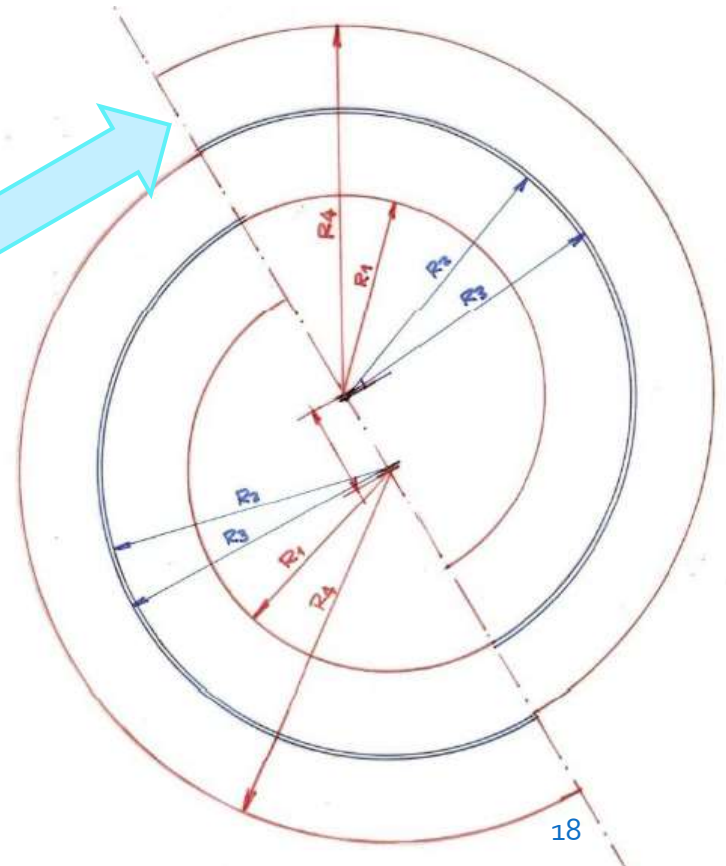
- ✓ The **geometrical form** of the turbo roundabout is formed by the so-called **"turbo block"** of all the necessary radii, which must be rotated in a certain way, thereby **obtaining traffic lanes**.
- ✓ The **dimensions of this turbo-block** must **ensure** that the **speed** does not exceed **40 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



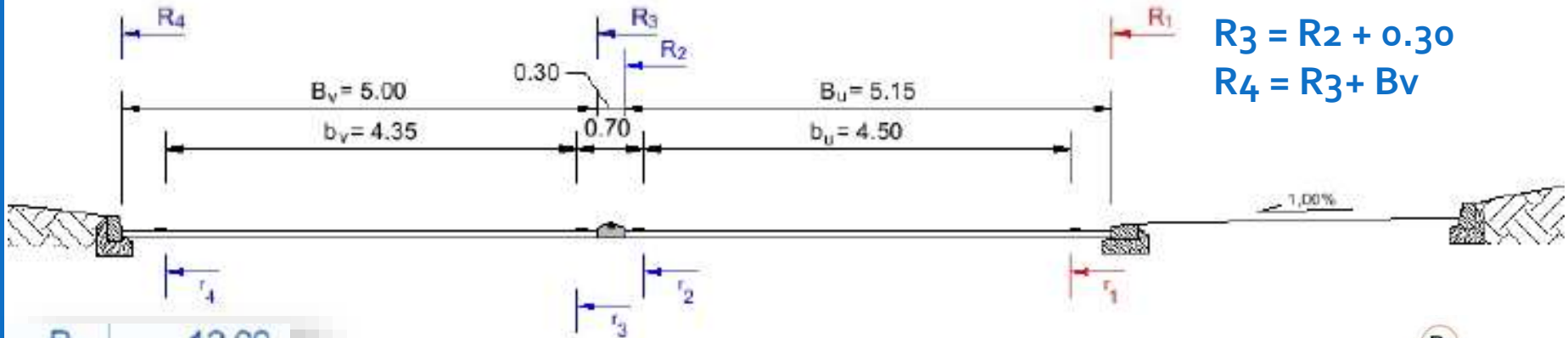
What's the turbo-roundabout?

R_1 : 10,50 m; 12 m;
15 m; 20 m

$$R_2 = R_1 + B_u$$

$$R_3 = R_2 + 0.30$$

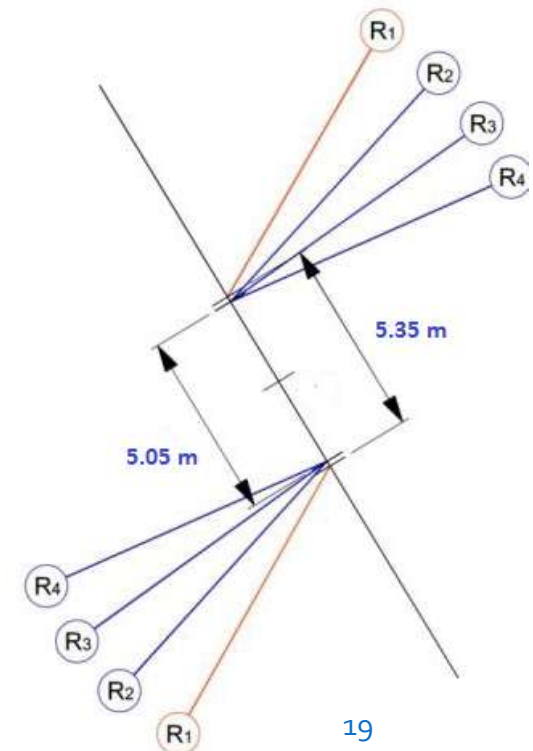
$$R_4 = R_3 + B_v$$



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
B_u	5.15
b_v	4.35
b_u	4.50
D_v	5.35
D_u	5.05

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

- the inner radius of the inner lane - R_1 ;
- the width of the traffic (inner and outer) lanes;
- the width of the lane divider;



“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

Tomaž Tollazzi

Alternative Types of Roundabouts

An Informational Guide

 Springer



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).....»

The second turbo roundabout in the city Koper



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

		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 - 1.800.000,00

Tomaž Tollazzi

Alternative Types of Roundabouts

An Informational Guide



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.

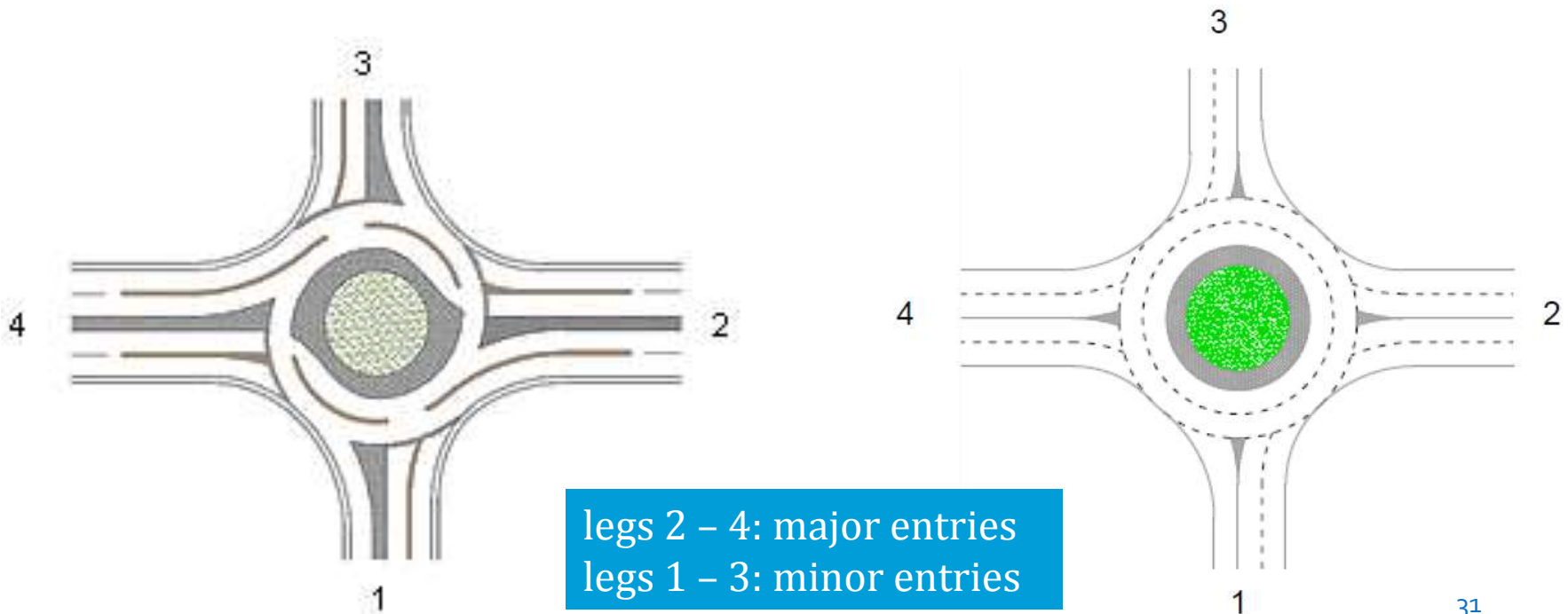
What's the matter?

- ✓ 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.



Turboroundabouts vs roundabouts in brief

Capacity models based on gap-acceptance theory

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

✓ 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).

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

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

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

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

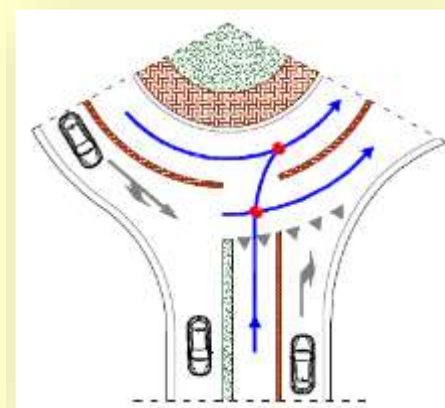
λ : scale parameter where the conflicting flow rate (Q_C) is in pcu/h;
 Δ : the minimum headway between vehicles moving along the opposing lane [s]
 T_c : Critical gap [s]; T_f : Follow-up time, [s];

Assumptions on Entry Capacity Evaluations

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

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

- C_e: entry lane capacity [pcu/h];
- φ₋: Cowan's M3 parameter representing the **proportion of free traffic** within the major stream;
- Q_{c,-}: conflicting traffic flow [pcu/h];
- T_{c,-}: critical gap for circulating lane [s];
- T_{f,-}: 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 T_c, T_f, 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 Hagrind 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 ($Q_{c,e}$) 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 ($Q_{c,e}$) and in the inner circle lane ($Q_{c,i}$); 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

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

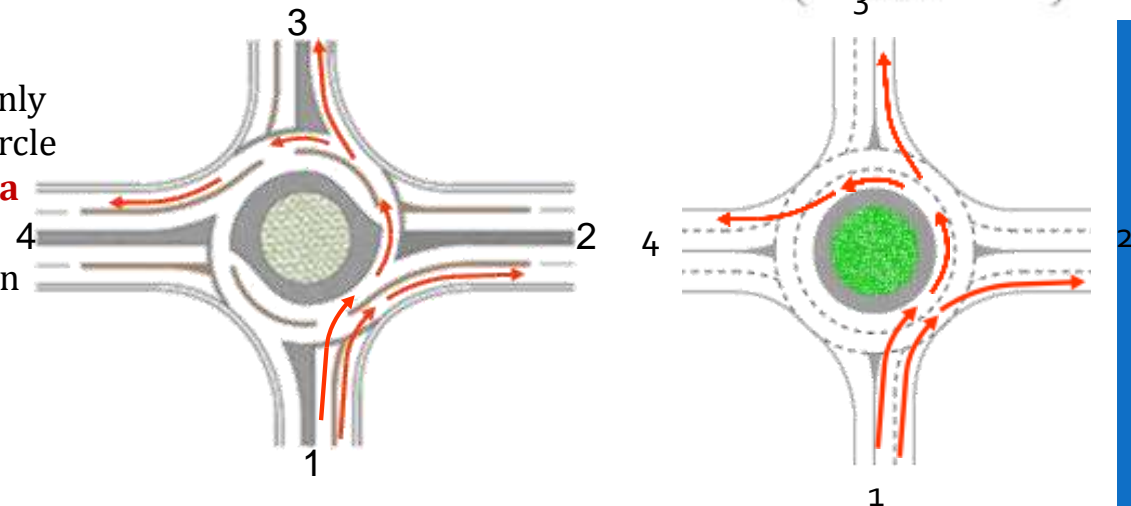
At double-lane roundabouts

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

$$\phi = 1 - \Delta q_c \quad \text{eq. Tanner, 1962}$$

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 [*]:

T_c and T_f the values assumed for **turbo-roundabout**

T_c and T_f 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;

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

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 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

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

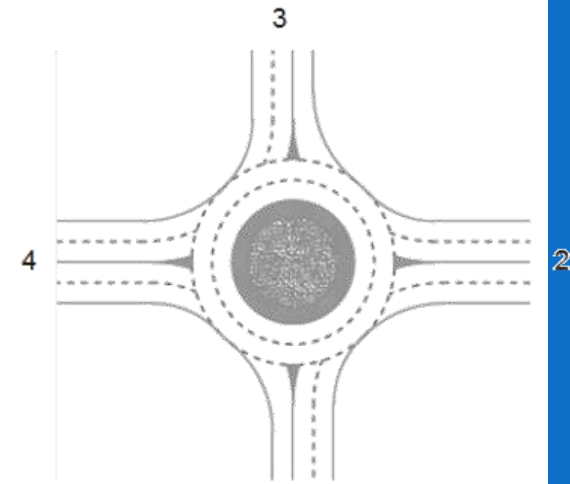
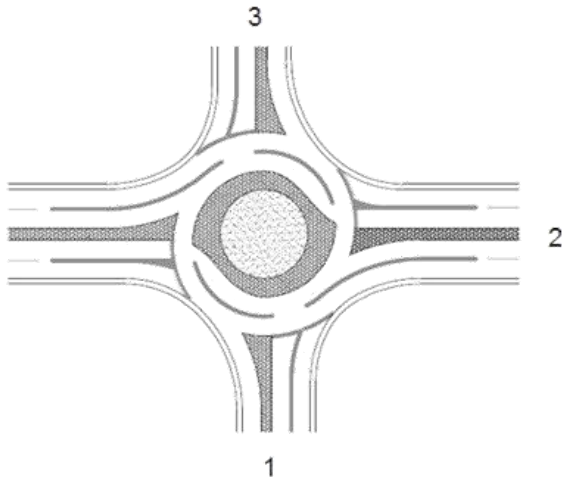
↻ **Case c:** similar to case b but percentages of left and right turning movements from minor to major entries are inverted.

- ✓ 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



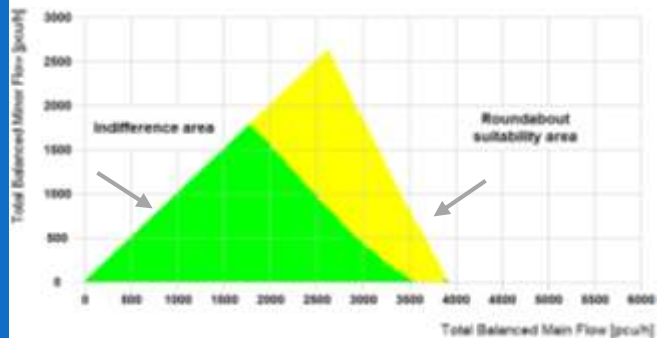
- ✓ the **control delay** was computed as the weighted mean value of the mean control delay d_i at each entry lane i ;

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

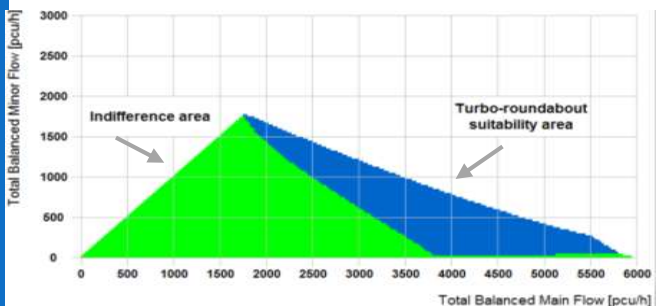
- ✓ At double-lane roundabout, the mean control delay d_i is the control delay at the whole entry i .

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

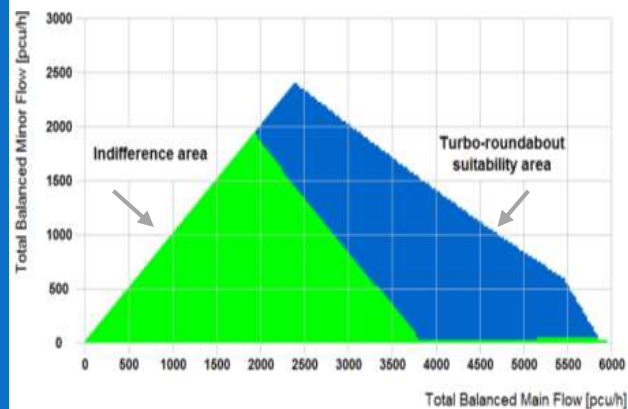
Comparing Basic Turbo-roundabouts and Double-lane Roundabouts to Evaluate Operational Benefits



x-axis represents the variable (Qe_2+Qe_4) ;
y-axis represents the variable (Qe_1+Qe_3) ;
*these variables are the basis for **suitability domains** in **undersaturated flow conditions** having the distinction between suitability areas:*



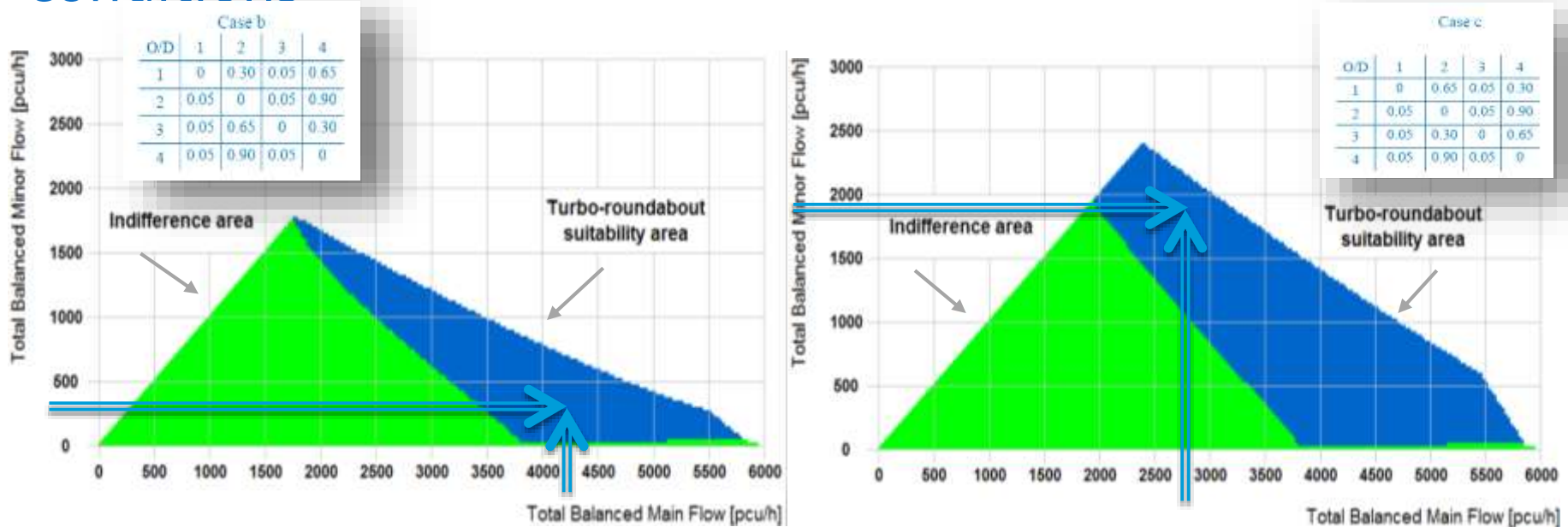
The **yellow area** is the roundabout suitability area (delays at roundabouts are less than 50% of those experienced at turbo-roundabouts);



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



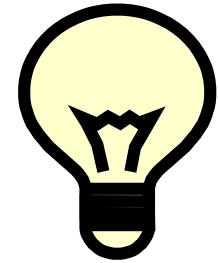
- ✓ *turbo-roundabouts perform better than double-lane roundabouts* when **high traffic flows enter from major roads** and *low traffic flows enter from minor roads*.
- ✓ **Case c** allows significantly **larger minor traffic flows** than **case b** because in case c **right turning movements from minor roads** are prevalent on the others.

conclusions

- ✓ **Applications of Hagrind 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

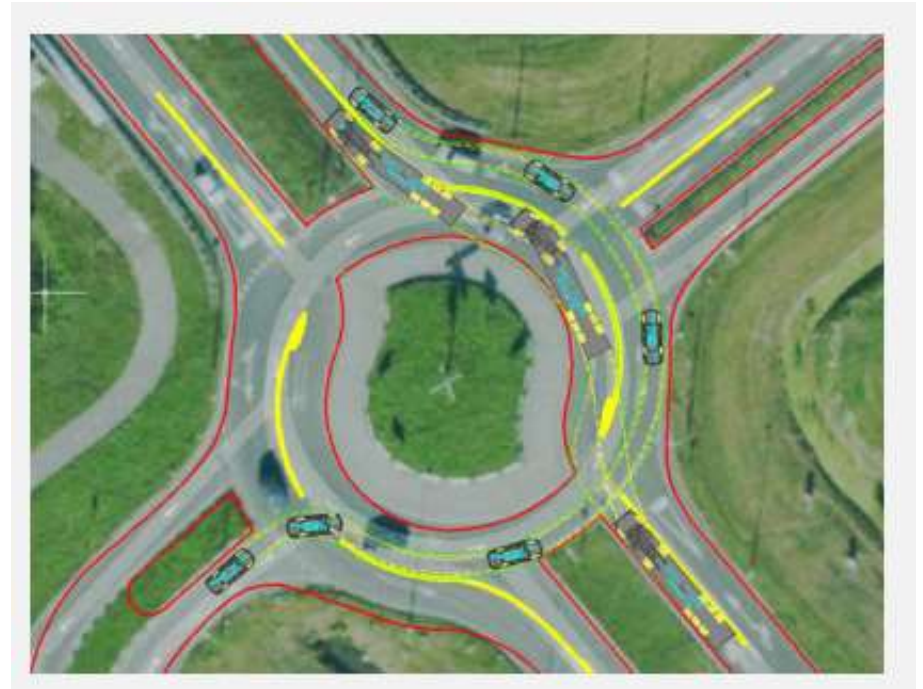


- Introduction
- Step 1: construction of the network model for the turbo-roundabout
- Step 2: calibration of the software
- Step 3: experimental design and data acquisition
- Step 4: statistical regression of the data obtained by microsimulation and analysis of the results
- Step 5: calculating passenger 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).**



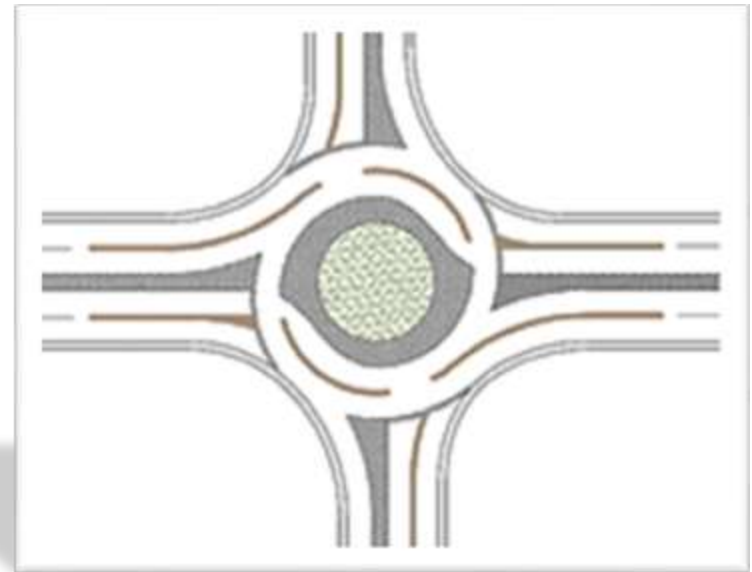
- ✓ The **microsimulation** can be a useful tool when the **variation of the traffic quality** in roundabout **should be evaluated**, in the presence of a **traffic demand** characterized by **different percentages of trucks**.



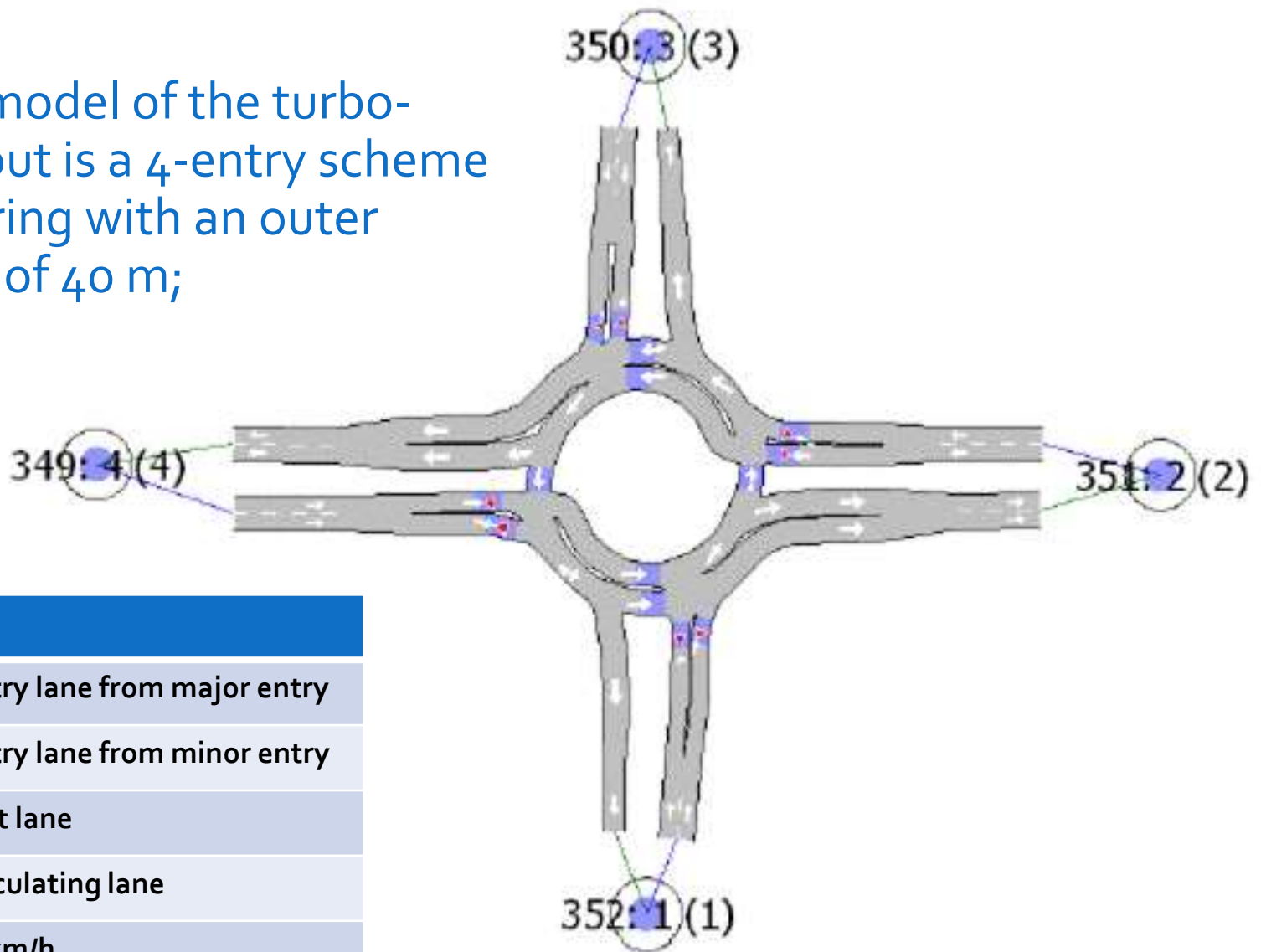
- ✓ By micro-simulation it is possible to **isolate traffic conditions** difficult to observe on field and **replicate** them to have a number of data as much as possible numerous.
- ✓ In simulation it is possible to **obtain capacity values** varying the percentage of trucks at entries and in the circulating 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);



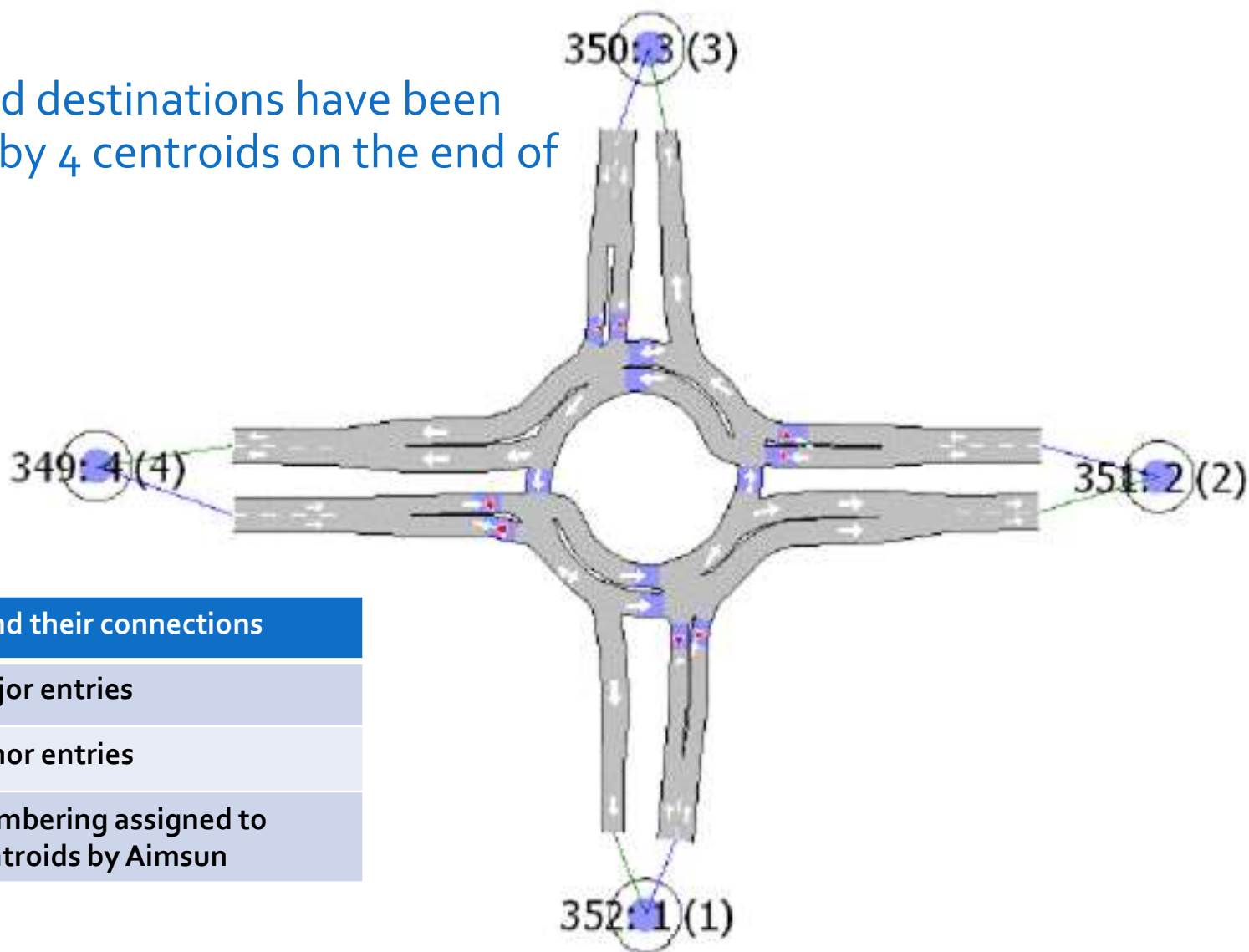
- ✓ Aimsun model of the turbo-roundabout is a 4-entry scheme having a ring with an outer diameter of 40 m;



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	



- ✓ 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

introduction

Step 1

Step 2

Step 3

Step 4

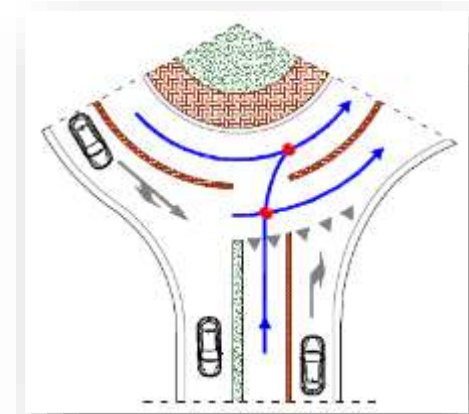
- ✓ according to Barcelo (2011), **calibration of a traffic microsimulation model** is an **iterative process** consisting in **changing and adjusting** numerous model parameters and **comparing model outputs with a set of empirical data until a predefined level of agreement between the two data sets 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 Haging model (1998) using the times obtained by Fortuijn (2009).

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

C_e : entry lane capacity [pcu/h];
 φ : Cowan's M3 parameter representing the **proportion of free traffic** within the major stream;
 $Q_{c,-}$: conflicting traffic flow [pcu/h];
 $T_{c,-}$: critical gap for circulating lane [s];
 $T_{f,-}$: 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).



introduction

Step 1

Step 2

Step 3

Step 4

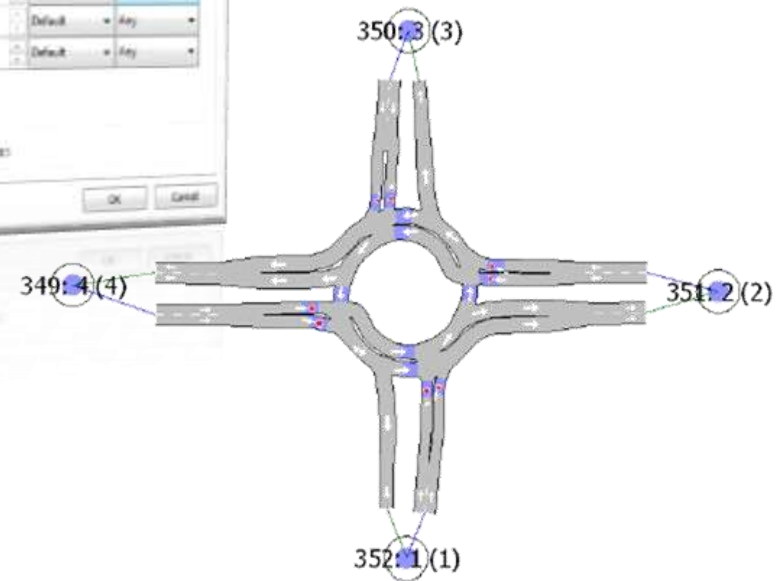
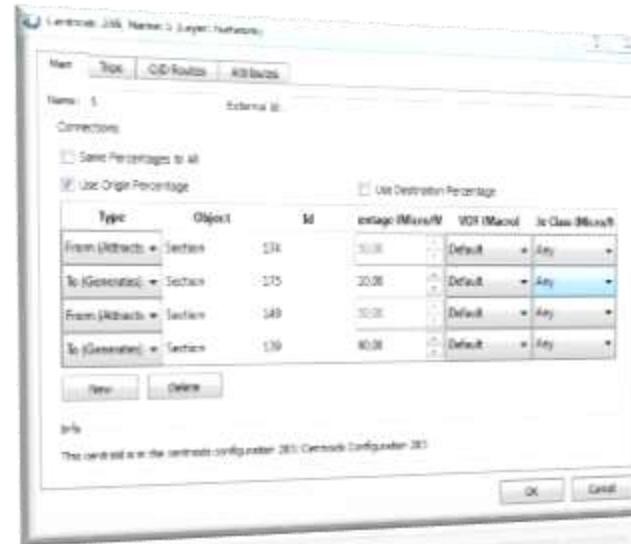
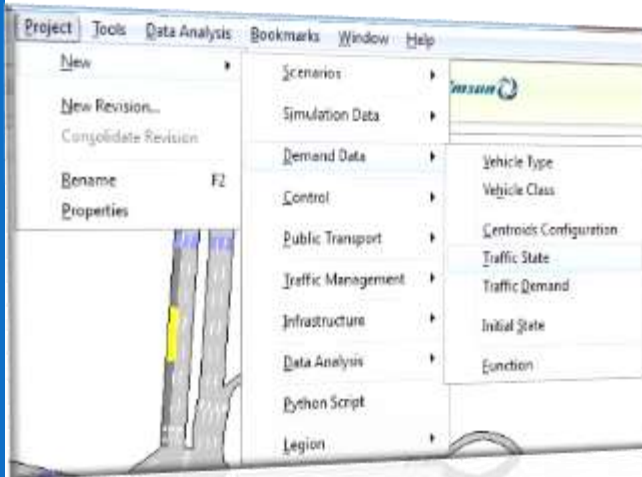
Step 5

✓ 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 Haging 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;

O/D Matrix: 309, Name: Total Matrix

Main | Path Assignment | Parameters

Name: Total Matrix External Id:

Vehicle Type: 8: car Purpose: None

Headers: Id : Name Initial Time: 8:00:00 Duration: 1:00:00

	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

Operation: Split Copy Paste

Operation Parameters

	Percentage
1	95
2	5

Automatic Factor Split Duration

New Delete Execute

OK Cancel

- ✓ 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 iterations 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 Hagrings 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 ($Q_{c,e}$) in the outer circle lane; see eq. a

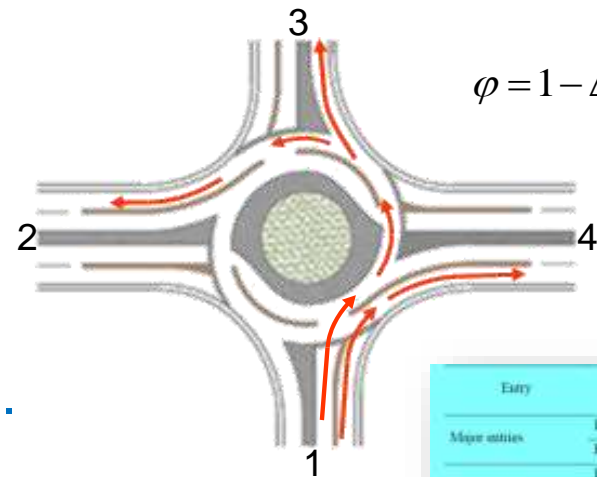
Left-lane capacity of entries 1-3 as a function of circulating traffic flows in the outer ($Q_{c,e}$) and in the inner circle lane ($Q_{c,i}$); see eq. b;

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

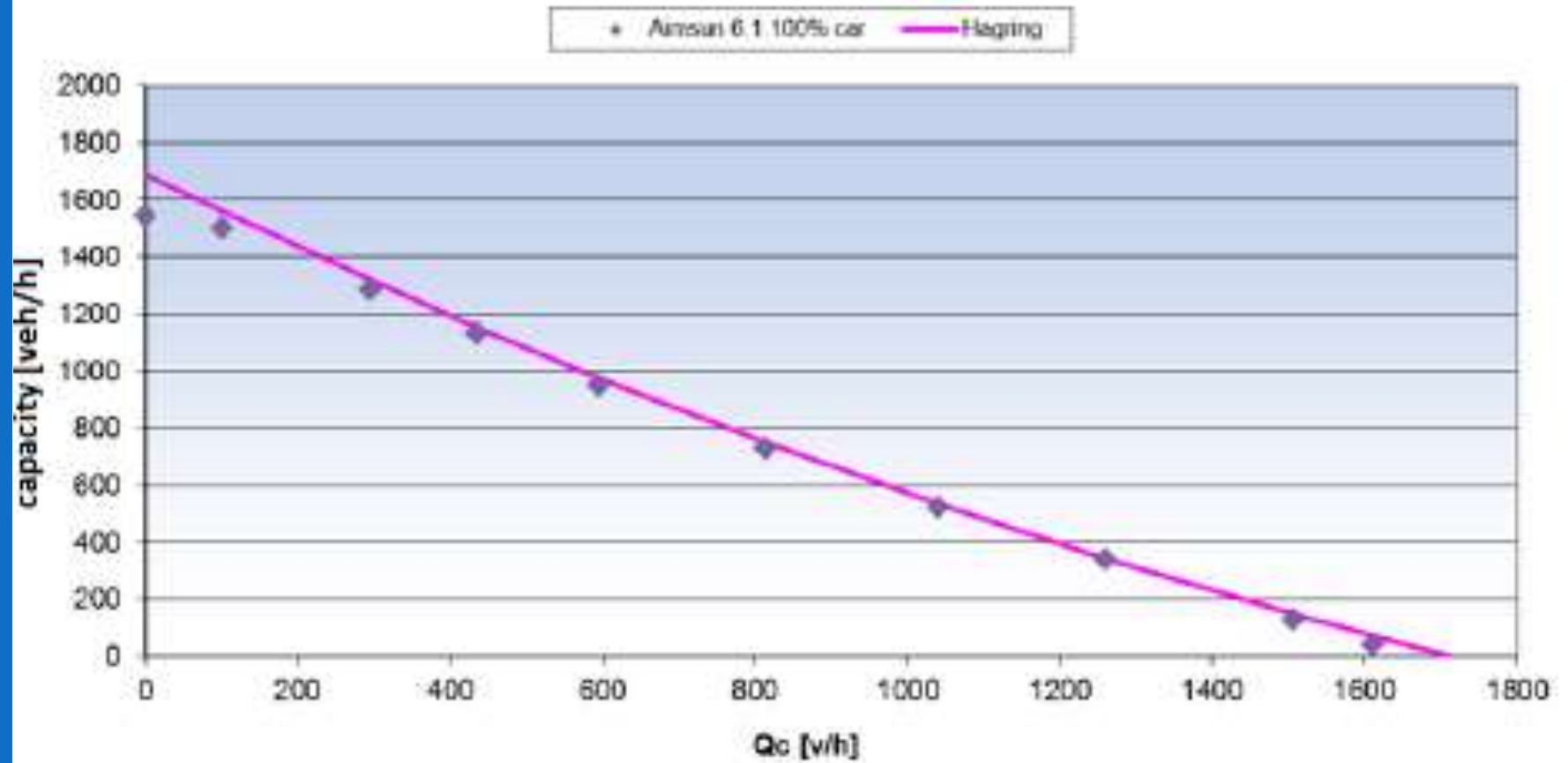
$$C_e = (Q_{c,e} + Q_{c,i}) \cdot \left(1 - \frac{\Delta \cdot Q_{c,e}}{3600}\right) \cdot \left(1 - \frac{\Delta \cdot Q_{c,i}}{3600}\right) \cdot \frac{\exp\left(\frac{-Q_{c,e}}{3600} \cdot (T_{c,e} - \Delta)\right) \cdot \exp\left(\frac{-Q_{c,i}}{3600} \cdot (T_{c,i} - \Delta)\right)}{1 - \exp\left(\frac{-(Q_{c,e}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



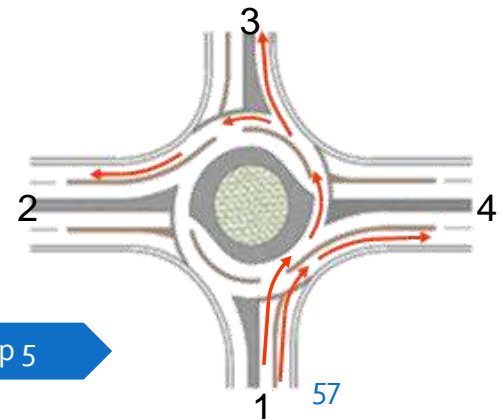
$\phi = 1 - \Delta q_c$ Tanner, 1962

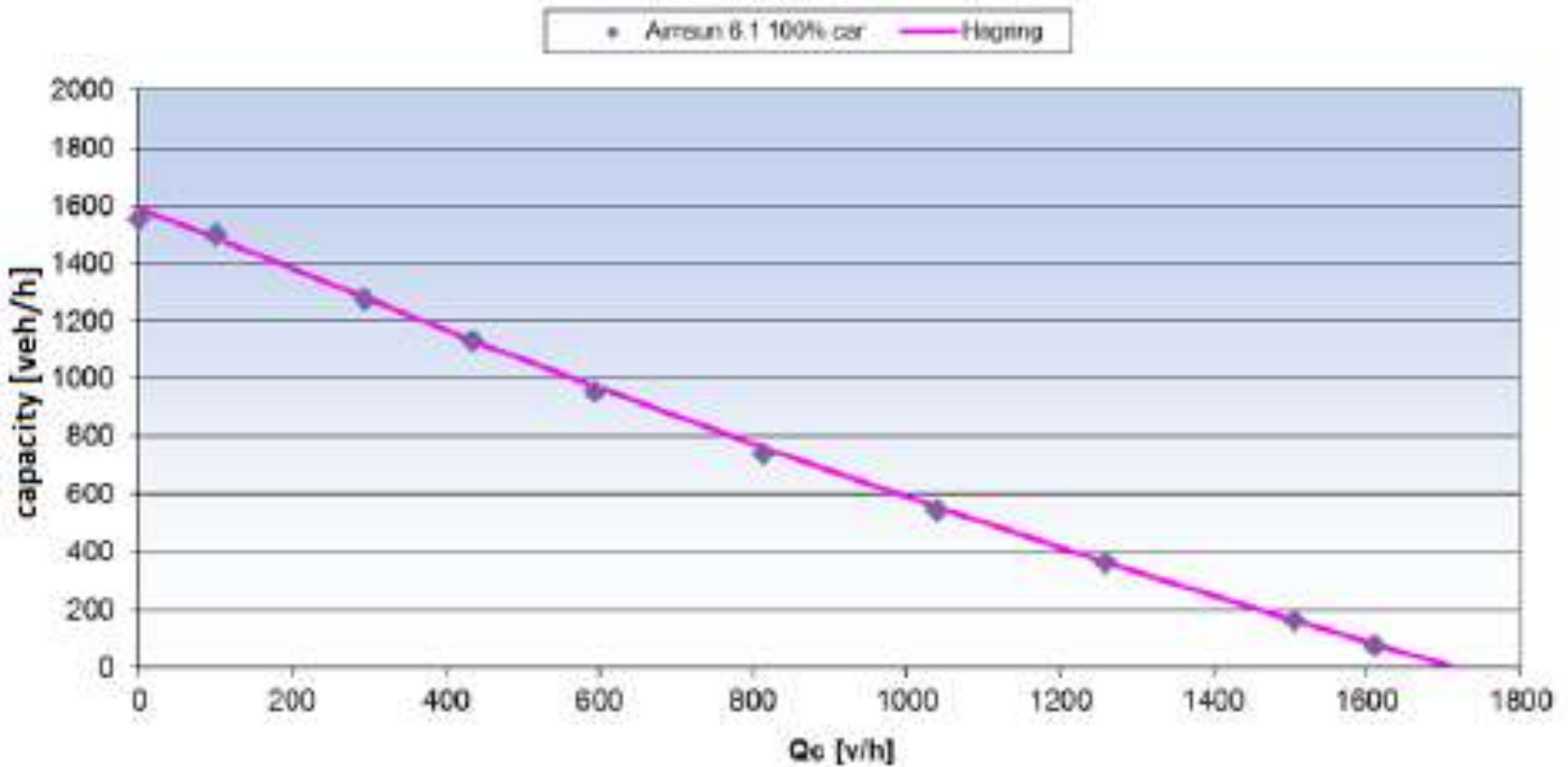
- ✓ **Gap acceptance parameters (T_c and T_f) for basic turbo-roundabouts were already presented in the previous section.**

Entry	Lane	T_c		$T_f [s]$	$\Delta [s]$
		$T_{c,l} [s]$	$T_{c,r} [s]$		
Major entries	Left	-	3.60	2.20	2.10
	Right	-	3.87	2.13	2.10
Minor entries	Left	3.19	3.03	2.20	2.10
	Right	-	3.74	2.13	2.10

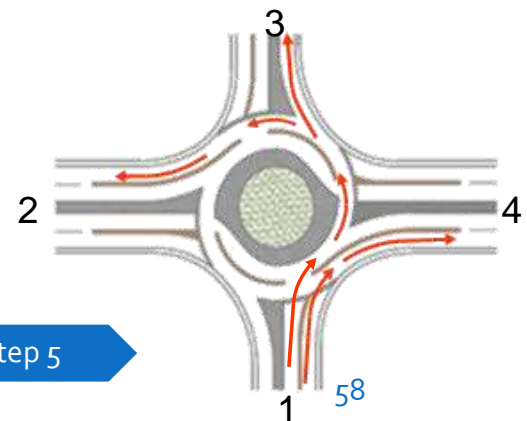


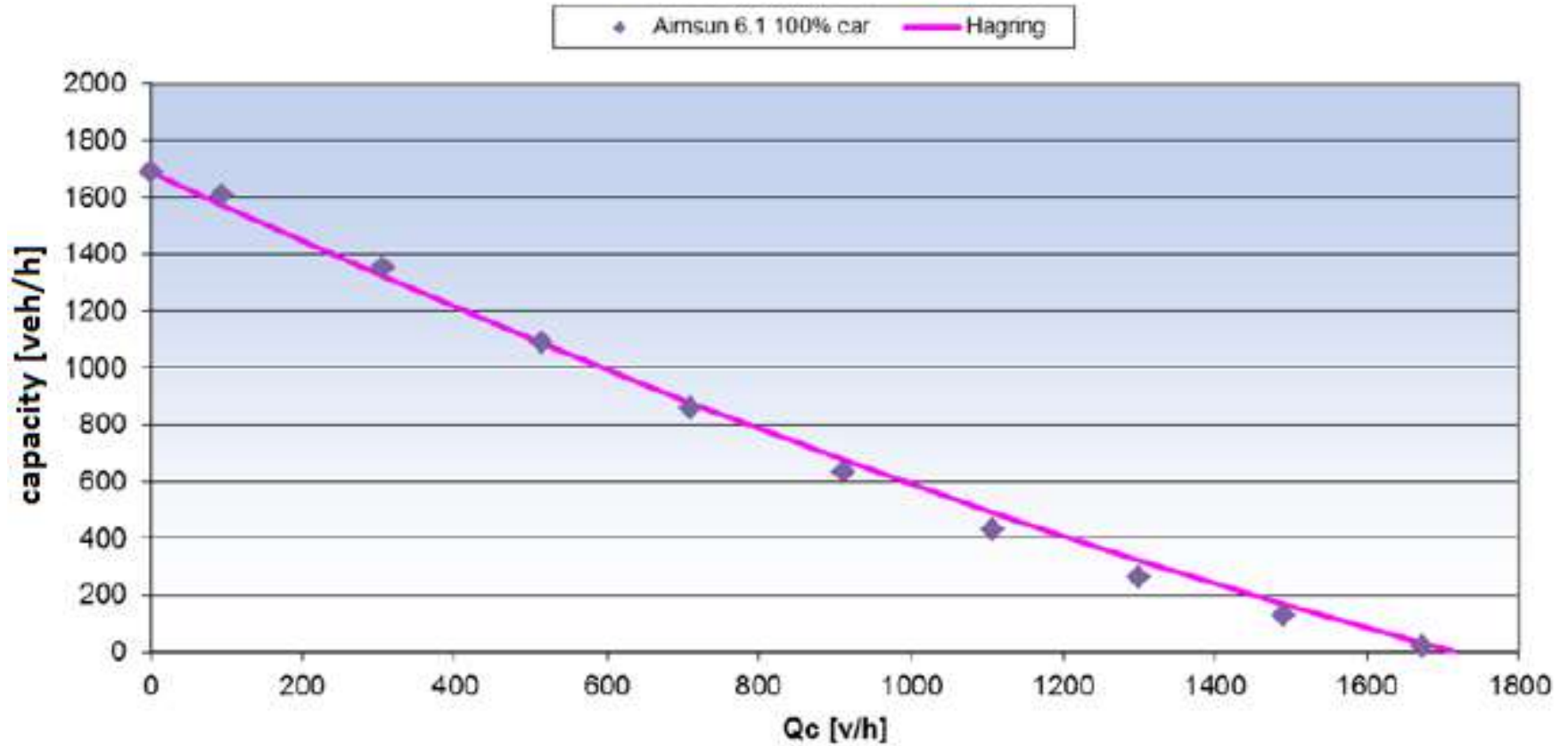
Right lane capacity on major entry
Simulation vs theoretical data



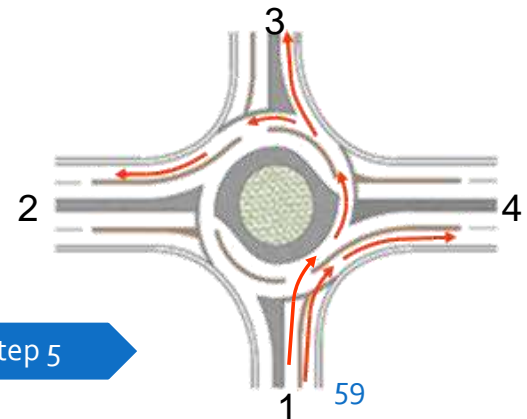


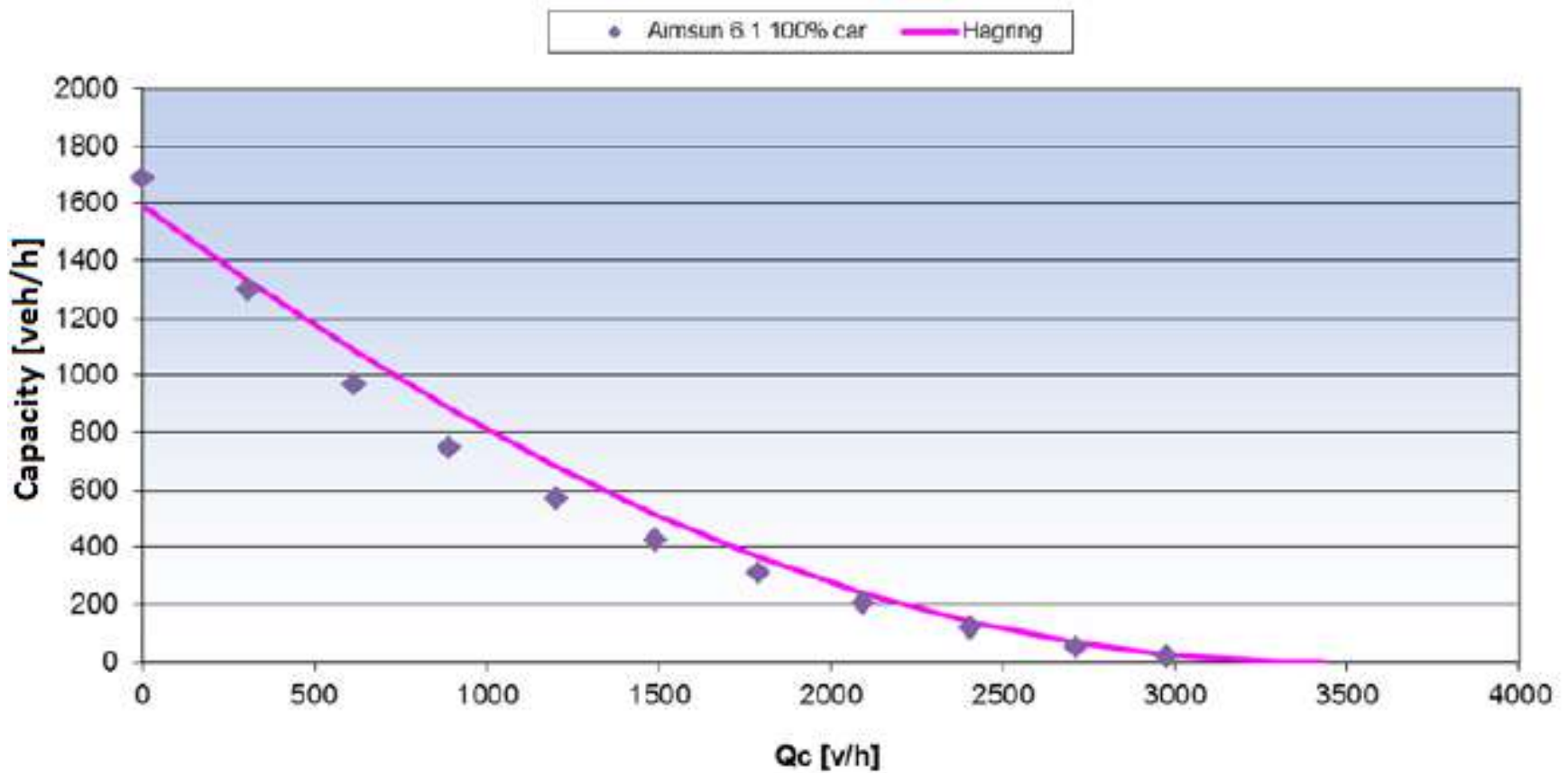
Left lane capacity on major entry
Simulation vs theoretical data



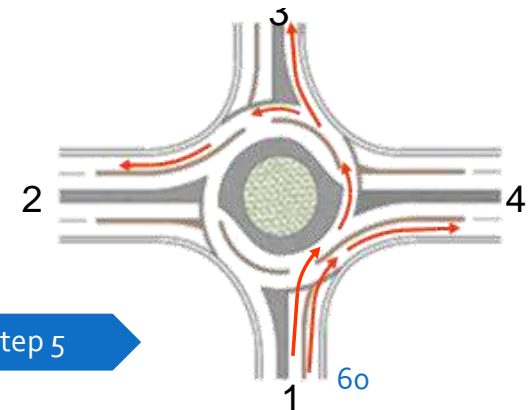


Right lane capacity on minor entry
Simulation vs theoretical data



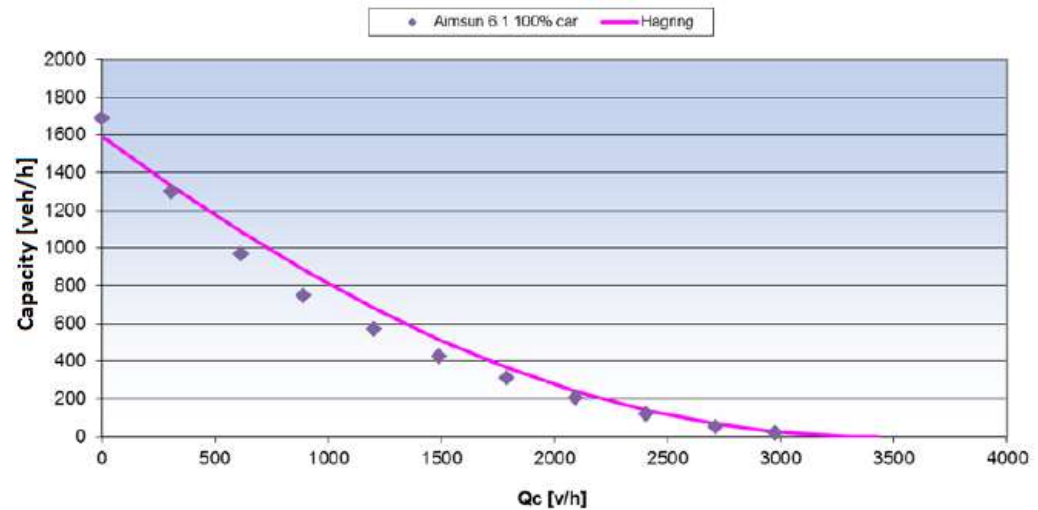


Left lane capacity on minor entry
 Simulation vs theoretical data
 NB: $Q_c = Q_{ce} + Q_{ci}$ and $Q_{ci}/Q_{ce} = 1$



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

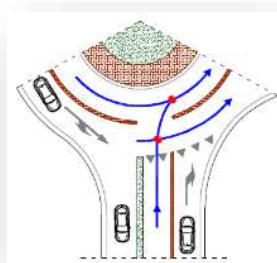
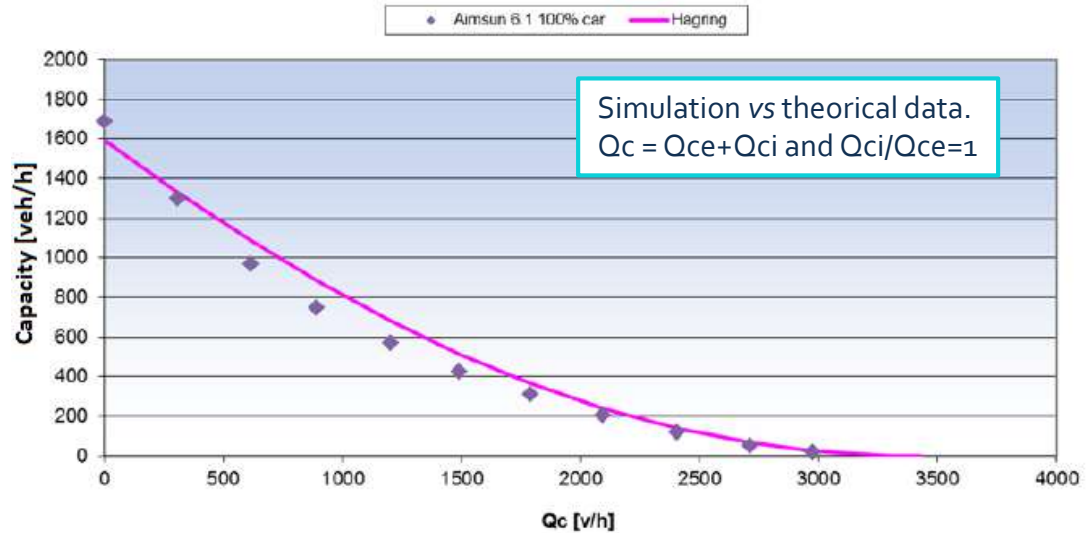
✓ **Maybe**, $T_{ce} = 3.03$ s and $T_{ci} = 3.19$ s were underestimated by Fortuijn for left turning movements;



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 T_{ce} is less than T_{ci} , **but** it should be the contrary;

✓ Mcdowell et al (1983) highlighted 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

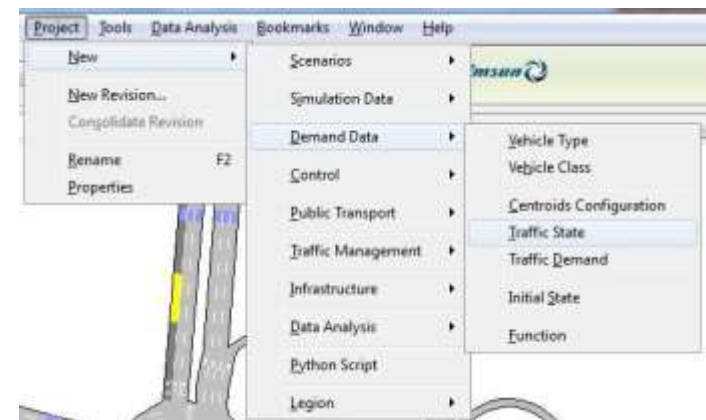
* Mcdowell et al (1983). Gap acceptance and traffic conflict simulation as a measure of risk. TRRL SR 776.



	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/s ²	3 m/s ²	3 m/s ²	3 m/s ²
Normal Deceleration	4 m/s ²	0,25 m/s ²	3,50 m/s ²	4,50 m/s ²
Max Deceleration	6 m/s ²	0,50 m/s ²	5 m/s ²	7 m/s ²
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"

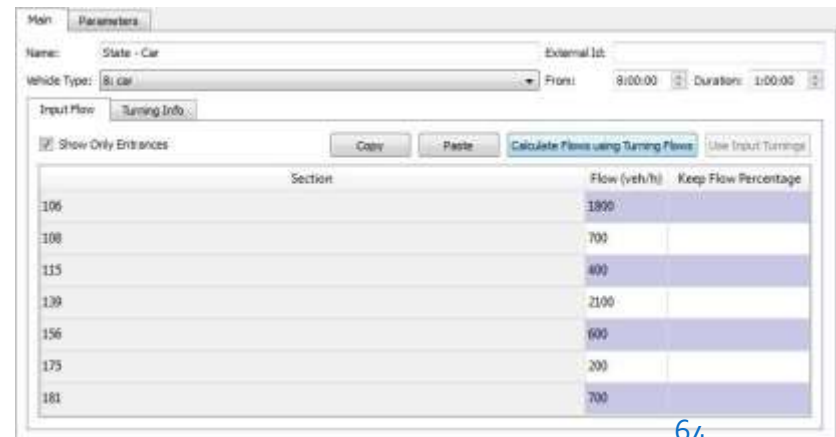
- ✓ they express the properties and cinematic performance attributed to the category vehicular "car"



	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/s ²	1 m/s ²	1 m/s ²	1 m/s ²
Normal Deceleration	3,50 m/s ²	1 m/s ²	2,50 m/s ²	4,80 m/s ²
Max Deceleration	5 m/s ²	0,50 m/s ²	4 m/s ²	6 m/s ²
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**.

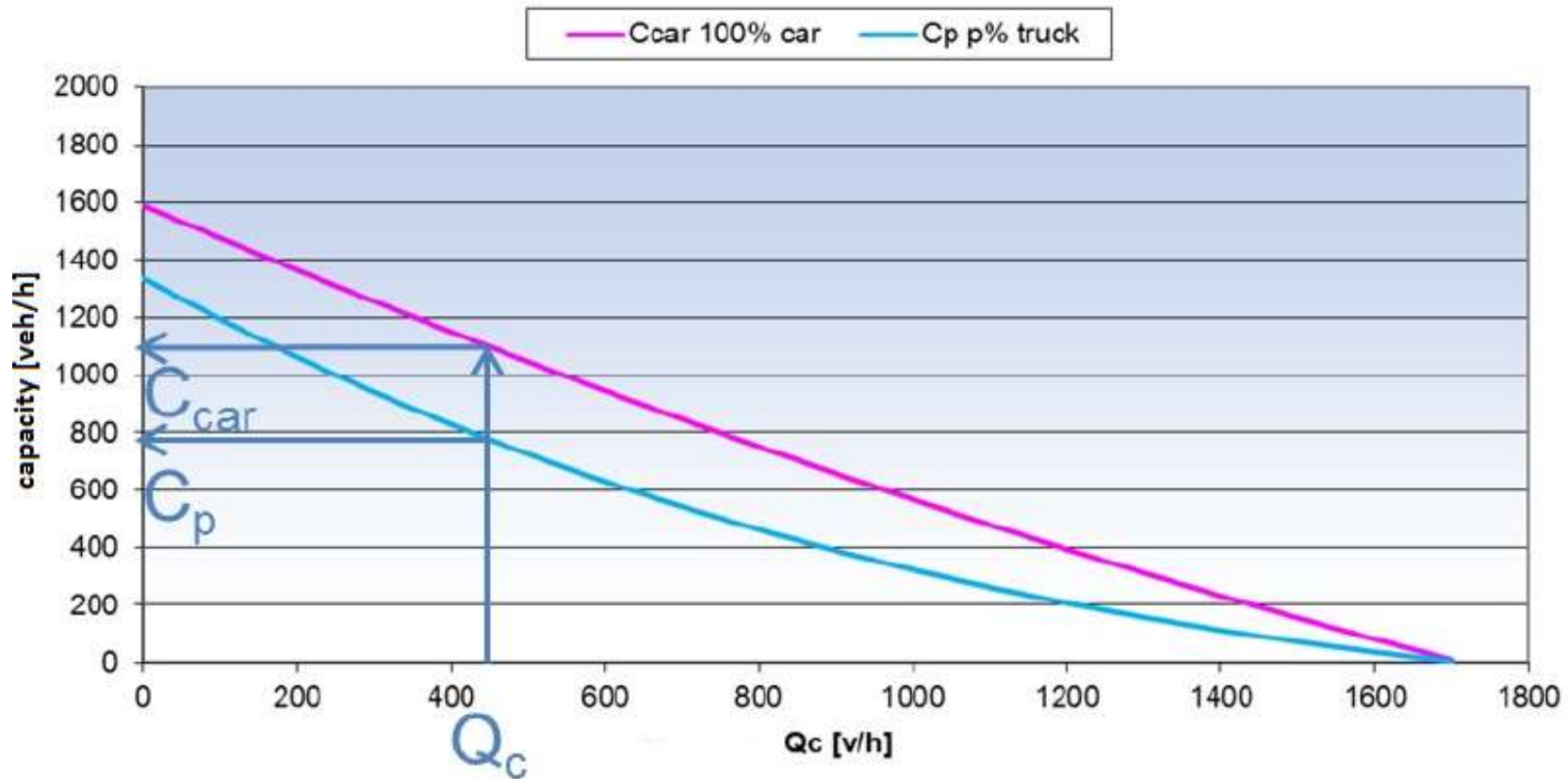


- ✓ Capacity functions for the **different entering lanes** in presence of **different percentages of trucks** were developed;
- ✓ O/D matrices were assigned to reproduce saturation conditions at entries.
 - ❖ So the **number of vehicles** entering the intersection **represents the capacity value for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

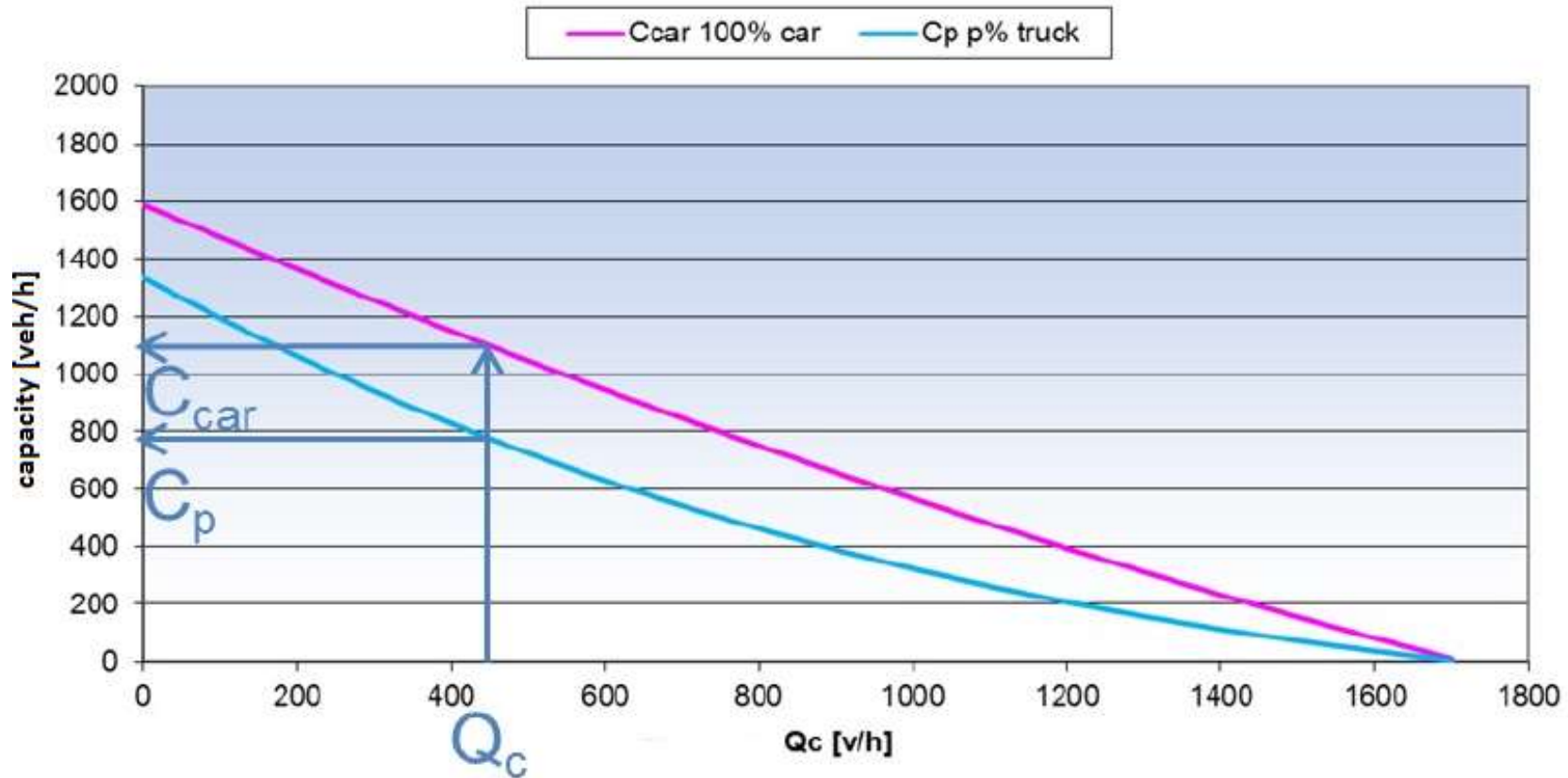


Estimation of passenger car equivalency factors for a given % of heavy vehicles (Et)



- ✓ This estimation was developed considering: $C_{car} = (1-p) C_p + p C_p E_t$
 C_p : a mixed flow including the **share** of passenger cars $(1-p) C_p$ and heavy vehicles ($p C_p$), multiplied by **Et** for homogeneity.

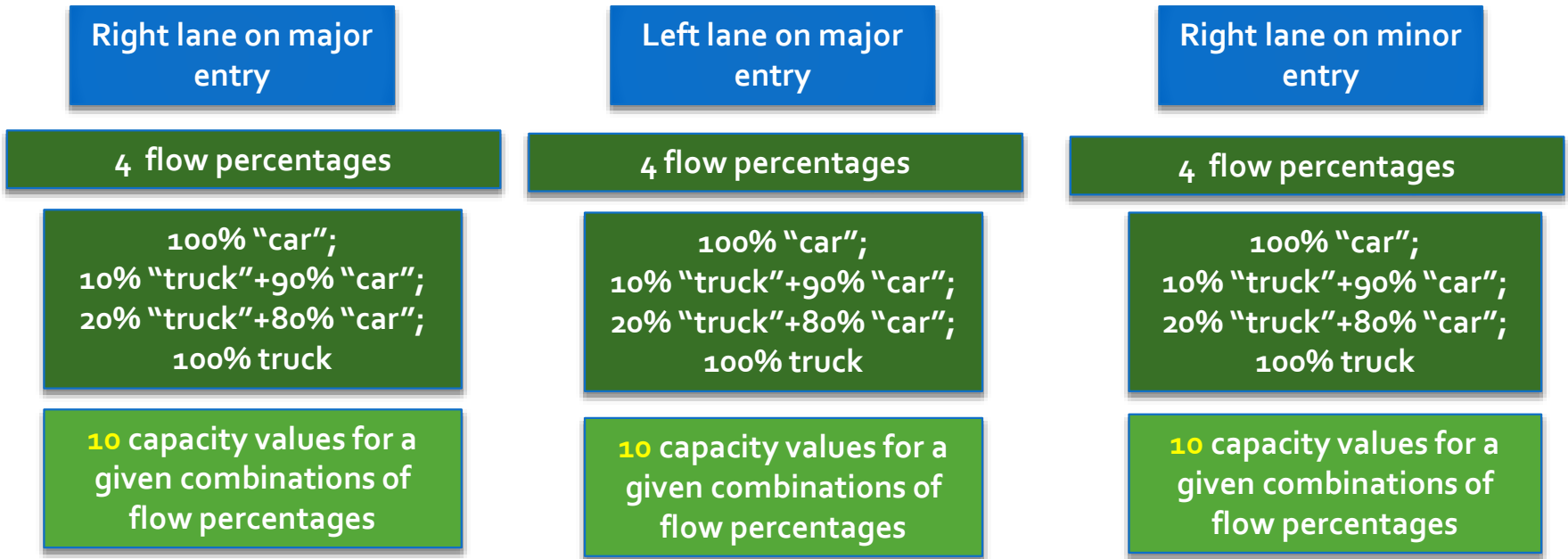
Estimation of passenger car equivalency factors for a given % of heavy vehicles (Et)



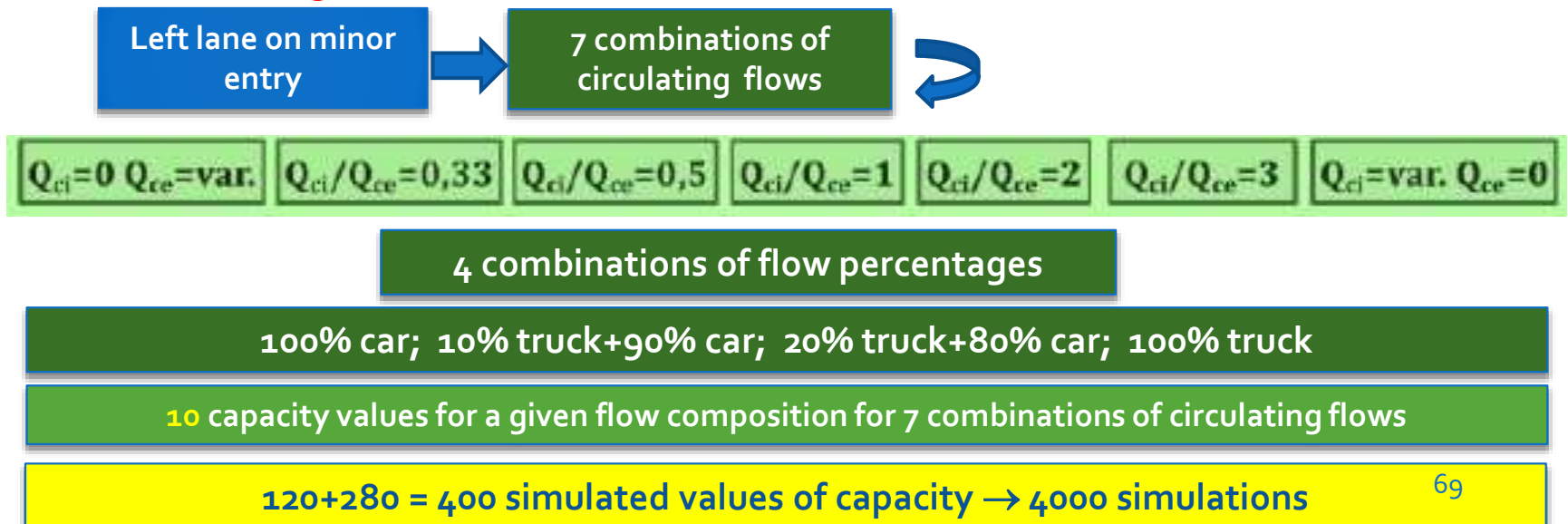
- ✓ Capacity functions for C_{car} and C_p for different schemes of flow percentages were developed;
- ✓ So: $E_t = [C_{car} - (1-p) C_p] / p C_p$
passenger car equivalency factors for a given % of heavy vehicles were estimated.

experimental plan for the estimation of passenger car equivalency factors

Lanes with one antagonist traffic flow



Lanes with two antagonist traffic flow



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

$$C^*(Q_{ci}/Q_{ce}=x) > C^*(Q_{ci}/Q_{ce}=1/x) \quad \text{for } x > 1$$

- ✓ **So Aimun outputs agree with** Mcdowell et al (1983) observations (**$T_{ce} > T_{ci}$**), but **disagree with T_c values** observed by Fortujin.



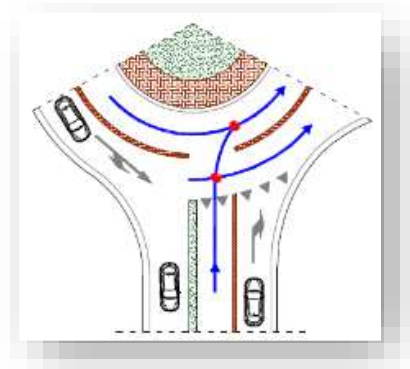
- ✓ **Statistical regressions** of the microsimulation outputs (C ; Q_c) and analysis of the results were then carried out;
- ✓ Non linear statistical regressions of the data obtained were developed using Mathematica 9.0; **Hagring model was specified again:**

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

→ 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 .



introduction

Step 1

Step 2

Step 3

Step 4

Step 5

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	1,28624×10 ⁻¹¹	5,10406 5,54906
		T _f	2,69525	0,0270715	99,5604	1,15681×10 ⁻¹³	2,63282 2,75768
20% truck 80%car	0,999755	T _c	4,08475	0,0630056	64,8316	3,56411×10 ⁻¹²	3,93946 4,23004
		T _f	2,35396	0,017734	132,738	1,16025×10 ⁻¹⁴	2,31307 2,39486
10% truck 90%car	0,999706	T _c	3,90996	0,0674909	57,9332	8,75134×10 ⁻¹²	3,75433 4,0656
		T _f	2,30904	0,0191305	120,7	2,48147×10 ⁻¹⁴	2,26493 2,35316
100% car	0,999428	T _c	3,73143	0,092694	40,2553	1,59563×10 ⁻¹⁰	3,51767 3,94518
		T _f	2,26604	0,0264516	85,6673	3,84587×10 ⁻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	4,65326×10 ⁻¹²	5,02047 5,40385
		T _f	2,74204	0,024255	113,051	4,18844×10 ⁻¹⁴	2,68611 2,79797
20% truck 80%car	0,999962	T _c	3,99916	0,0245052	163,197	2,22362×10 ⁻¹⁵	3,94265 4,05567
		T _f	2,36964	0,00704609	336,306	6,8427×10 ⁻¹⁸	2,3534 2,38589
10% truck 90%car	0,999822	T _c	3,77777	0,0516165	73,1892	1,35303×10 ⁻¹²	3,65874 3,89679
		T _f	2,33173	0,0151171	154,244	3,49154×10 ⁻¹⁵	2,29687 2,36659
100% car	0,999787	T _c	3,62675	0,0558058	64,9888	3,49585×10 ⁻¹²	3,49806 3,75544
		T _f	2,28131	0,0163185	139,799	7,66559×10 ⁻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**, T_c is close 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	2,05503×10 ⁻⁸	6,11269 7,55761
		T _f	2,7624	0,0720031	38,365	2,34022×10 ⁻¹⁰	2,59636 2,92844
20% truck 80%car	0,999934	T _c	4,91513	0,0344126	142,829	6,45751×10 ⁻¹⁵	4,83578 4,99449
		T _f	2,20238	0,00808662	272,349	3,69864×10 ⁻¹⁷	2,18374 2,22103
10% truck 90%car	0,999743	T _c	4,54072	0,0651728	69,6721	2,00528×10 ⁻¹²	4,39044 4,69101
		T _f	2,14082	0,01572	136,185	9,45183×10 ⁻¹⁵	2,10457 2,17707
100% car	0,999305	T _c	4,02581	0,100879	39,9072	1,7099×10 ⁻¹⁰	3,79318 4,25844
		T _f	2,08169	0,0255953	81,3312	5,82469×10 ⁻¹³	2,02267 2,14071

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



* 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	1,32323×10 ⁻³⁶	4,87705 5,65925
		T _{ce}	5,63962	0,204802	27,537	3,3981×10 ⁻³⁷	5,23048 6,04876
		T _f	3,22537	0,0777851	41,4652	5,7937×10 ⁻⁴⁸	3,06998 3,38076
20% truck 80% car	0,996322	T _{ci}	4,19798	0,0978292	42,9113	2,06056×10 ⁻⁴⁹	4,0026 4,39336
		T _{ce}	4,49392	0,101208	44,4029	2,40324×10 ⁻⁵⁰	4,2918 4,69605
		T _f	2,39767	0,0310105	77,3181	1,05895×10 ⁻⁶⁵	2,33574 2,4596
10% truck 90% car	0,998326	T _{ci}	3,97144	0,0647749	61,3115	3,05426×10 ⁻⁵⁹	3,84208 4,10081
		T _{ce}	4,23483	0,0666998	63,4908	3,27244×10 ⁻⁶⁰	4,10162 4,36803
		T _f	2,30234	0,0201487	114,268	1,20079×10 ⁻⁷⁶	2,2621 2,34258
100% car	0,999064	T _{ci}	3,6684	0,0465887	78,7402	5,45744×10 ⁻⁶⁷	3,57538 3,76142
		T _{ce}	3,94255	0,0481695	81,8474	4,35206×10 ⁻⁶⁸	3,84637 4,03872
		T _f	2,19418	0,0143212	153,212	5,84016×10 ⁻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.

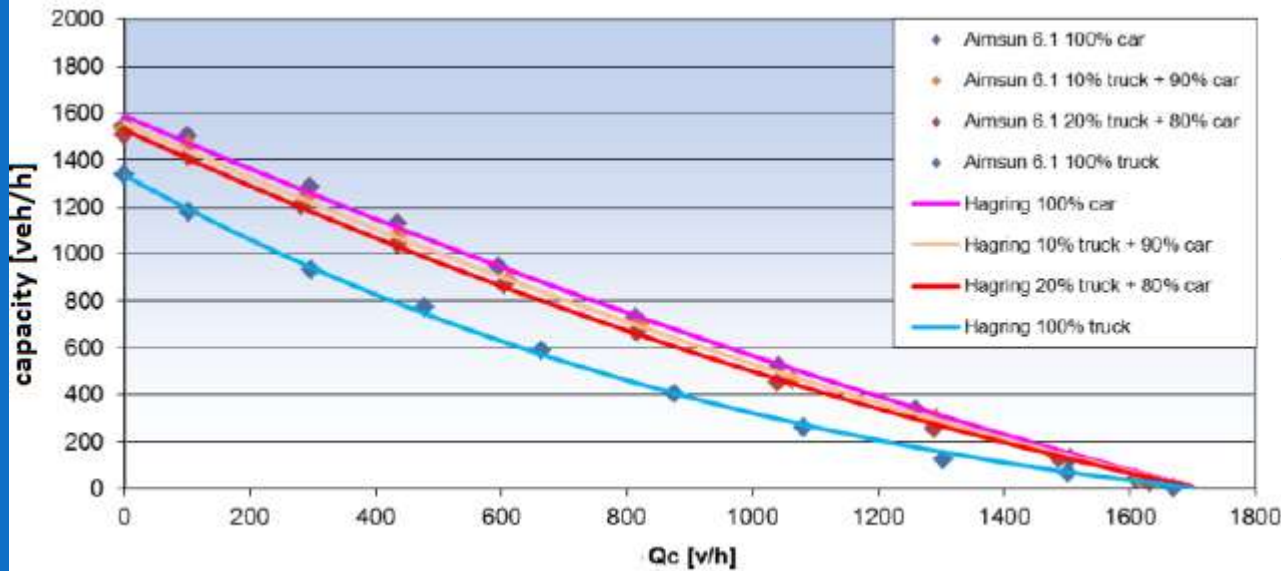
Why?

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

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

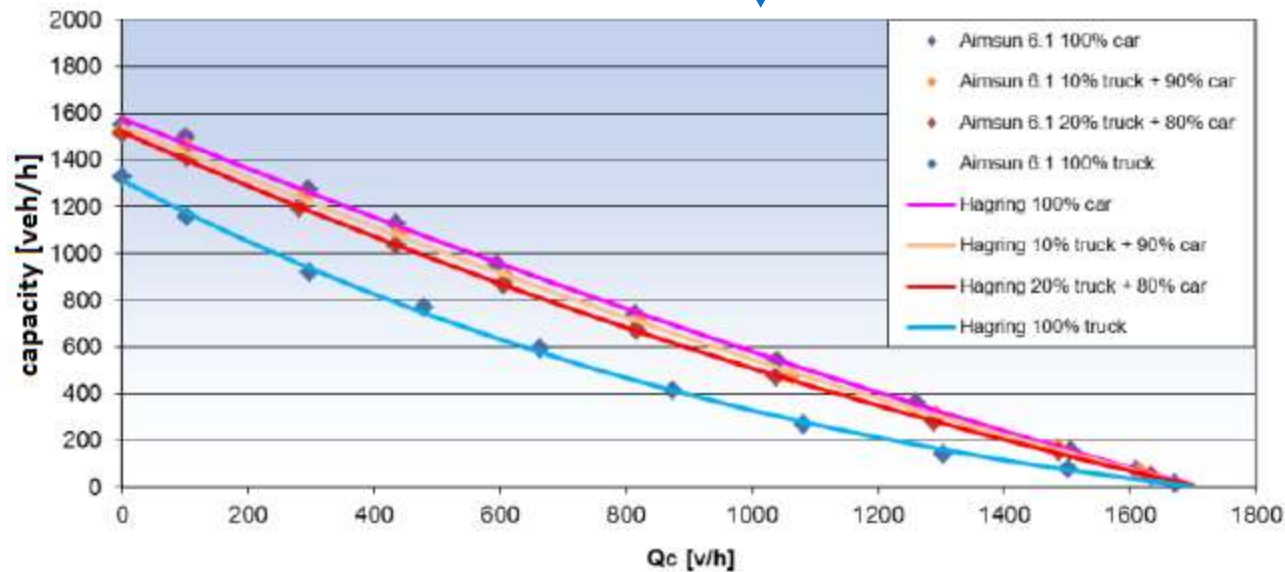
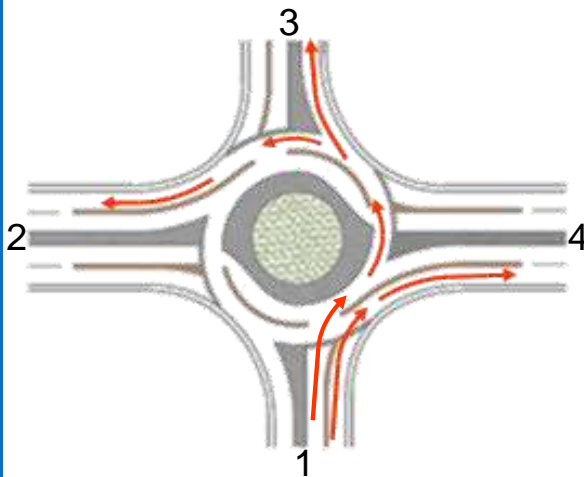
They are shown in the following slides.



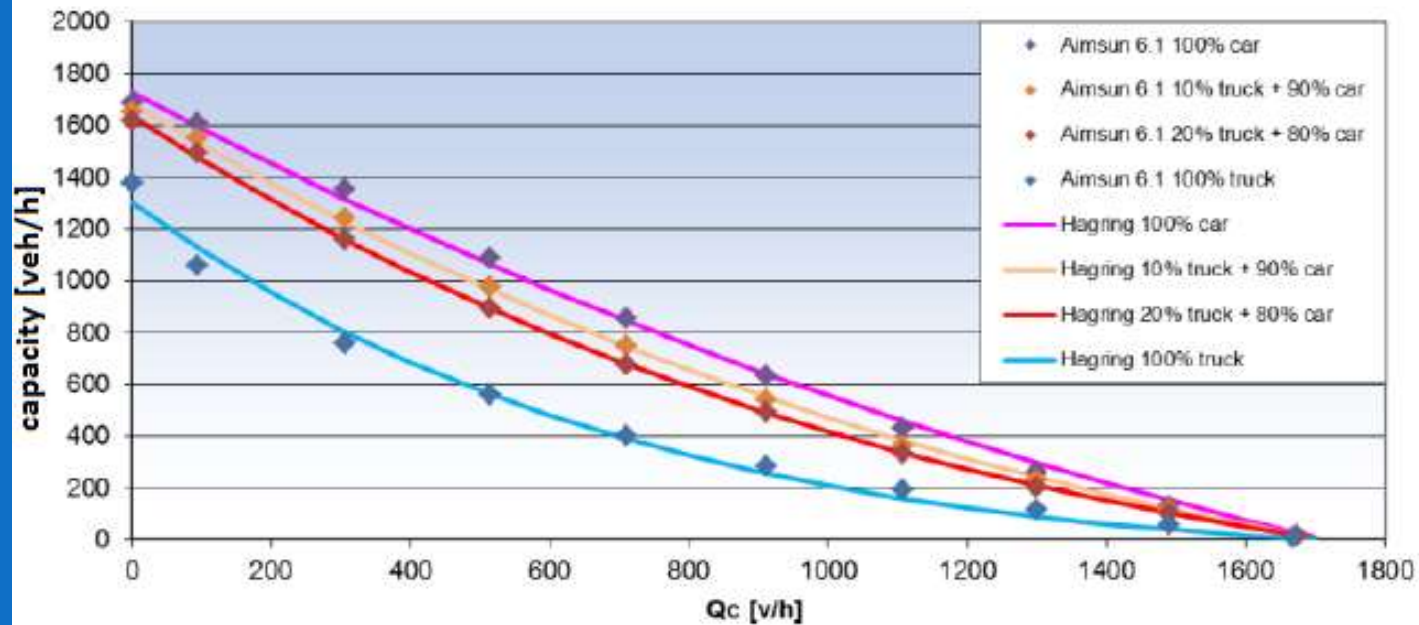


Simulated data and regressions for the **right lane on major entry**

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



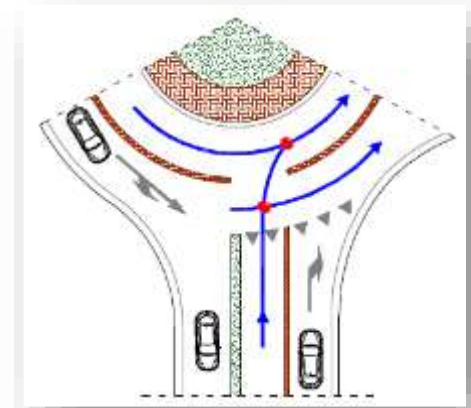
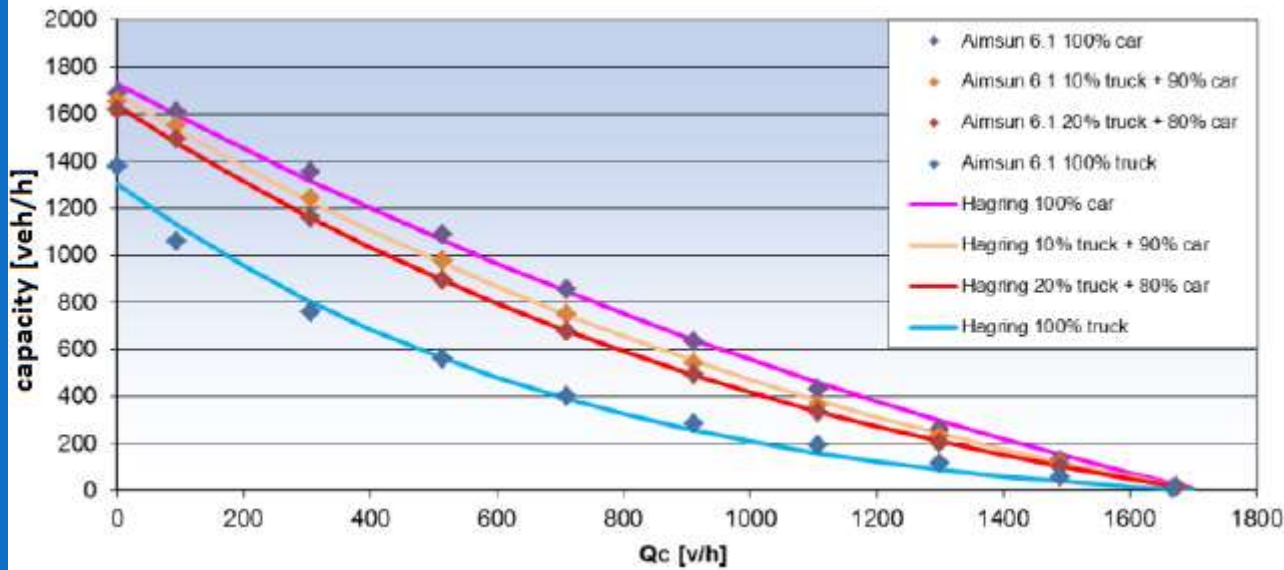
The functions are the same because the behavioral parameters were similar for each truck percentage



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

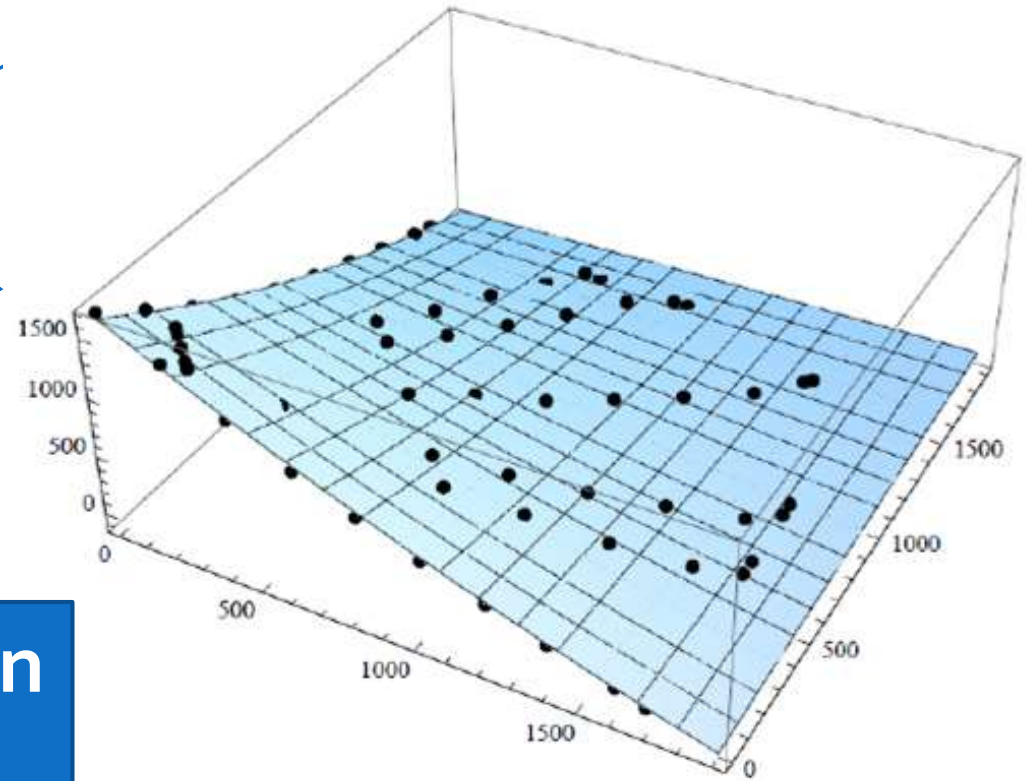
✓ Increasing Q_c , capacity values decrease, especially when truck percentages increase;





- ✓ for the **right lane** on **minor entry**, T_c 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
 Q_{ce} and Q_{ci}

introduction

Step 1

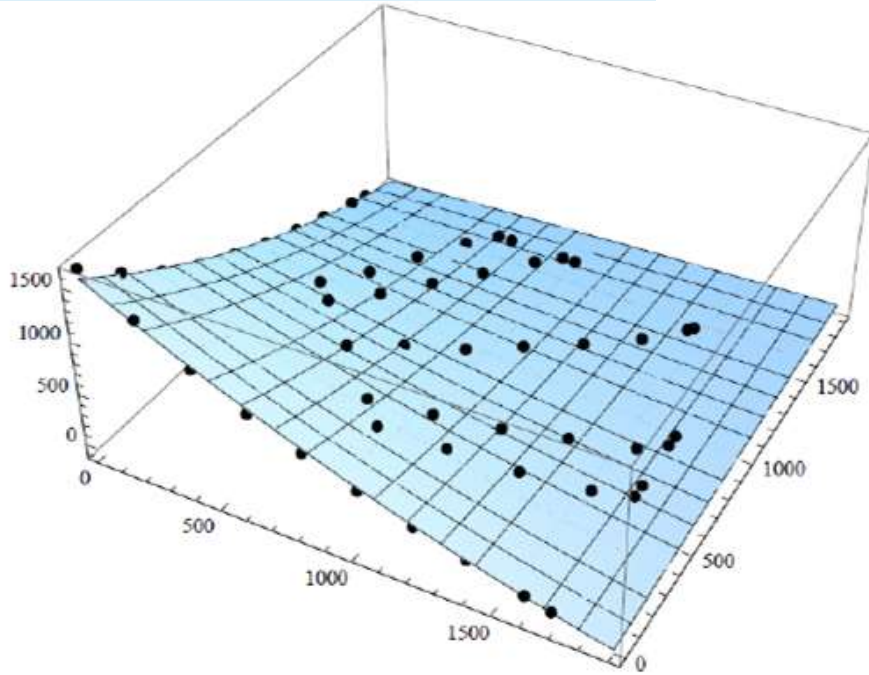
Step 2

Step 3

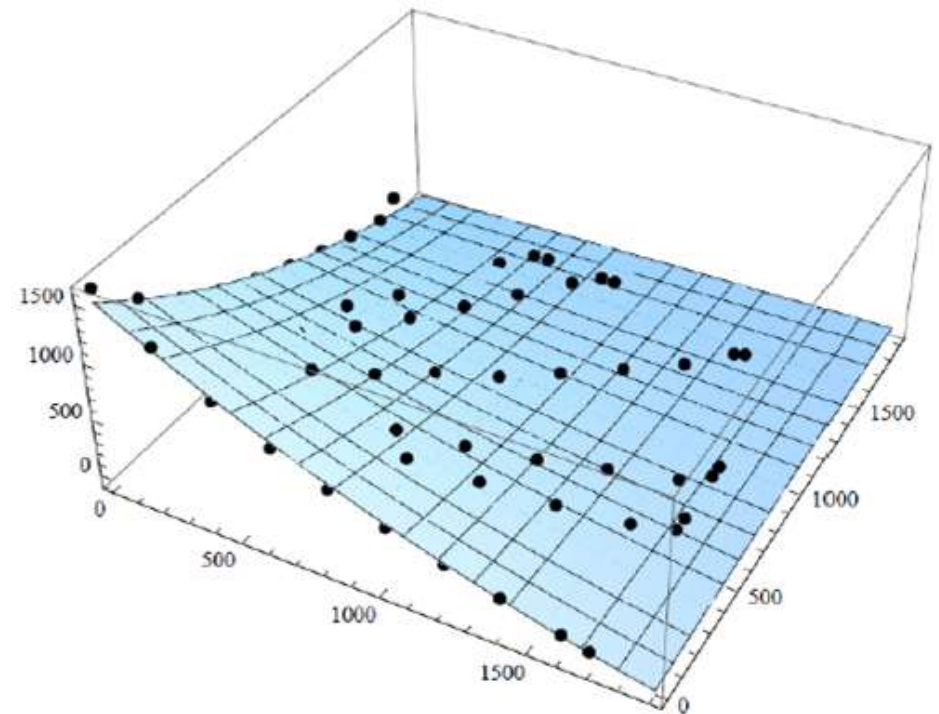
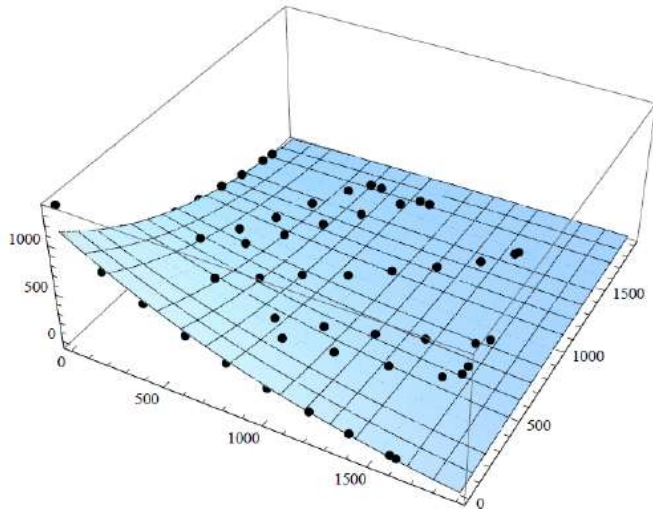
Step 4

Step 5

entry demand: 90% cars+ 10% 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: 100% truck

entry demand: 80% cars+ 20% truck

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

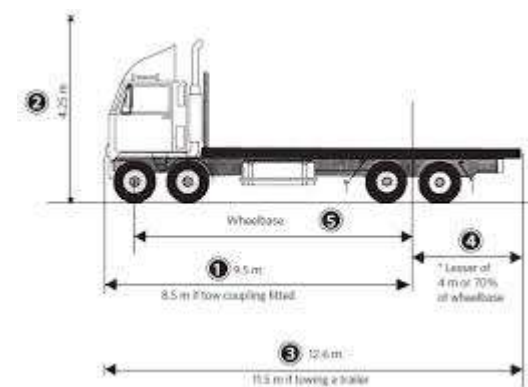
$$E_t = [C_{car} - (1-p) C_p] / p C_p$$

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

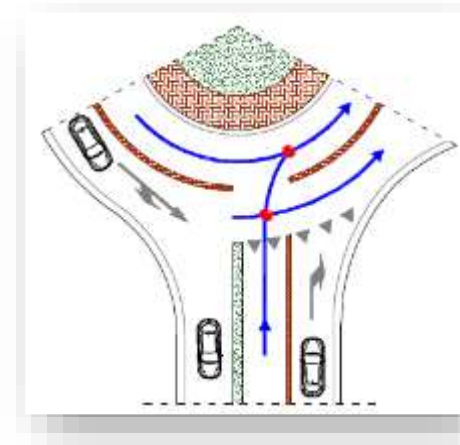
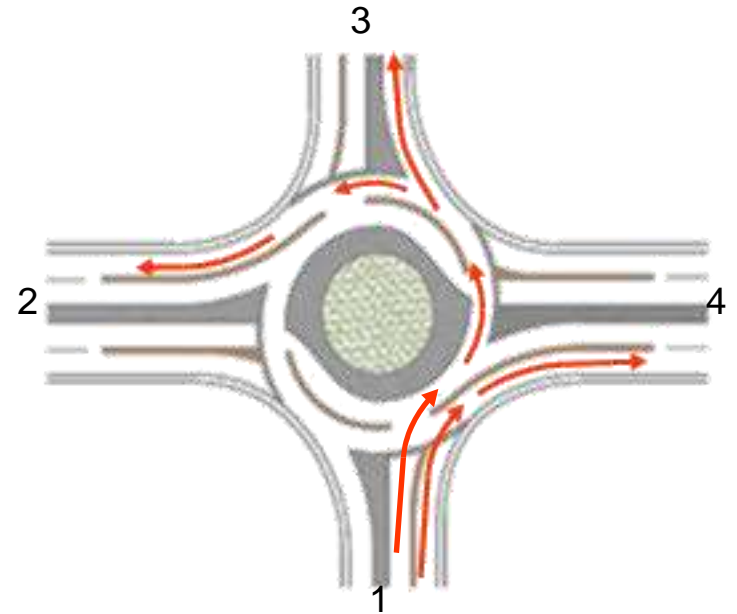
Step 2

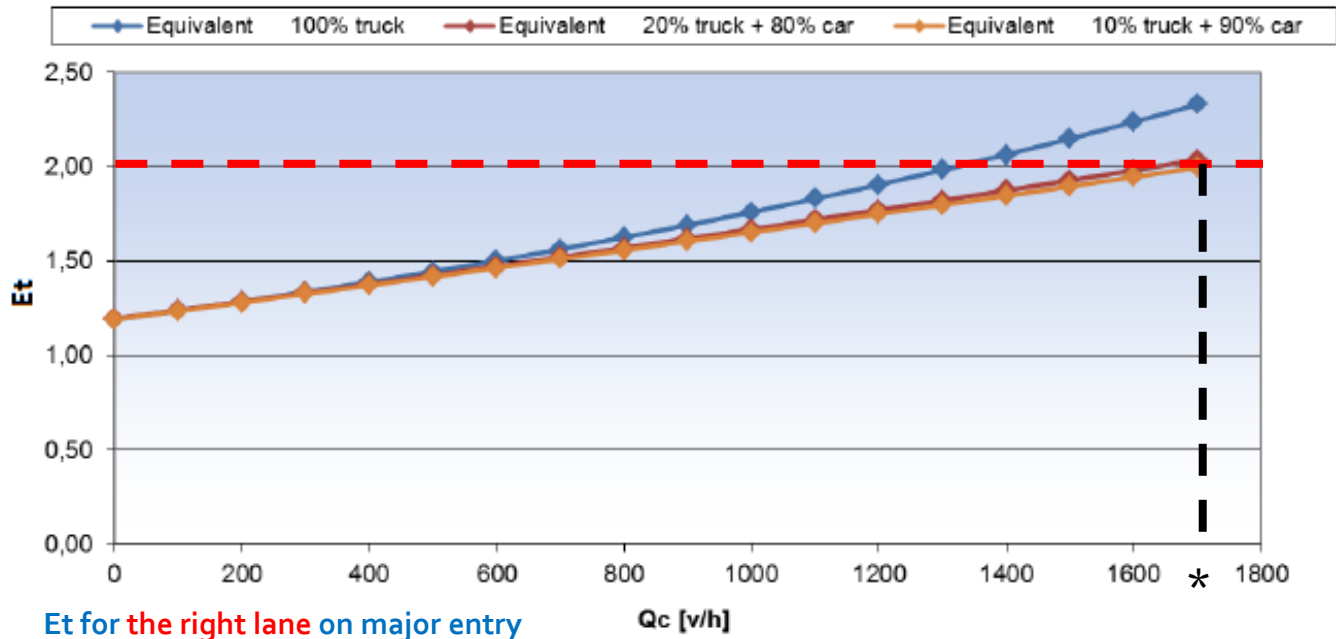
Step 3

Step 4

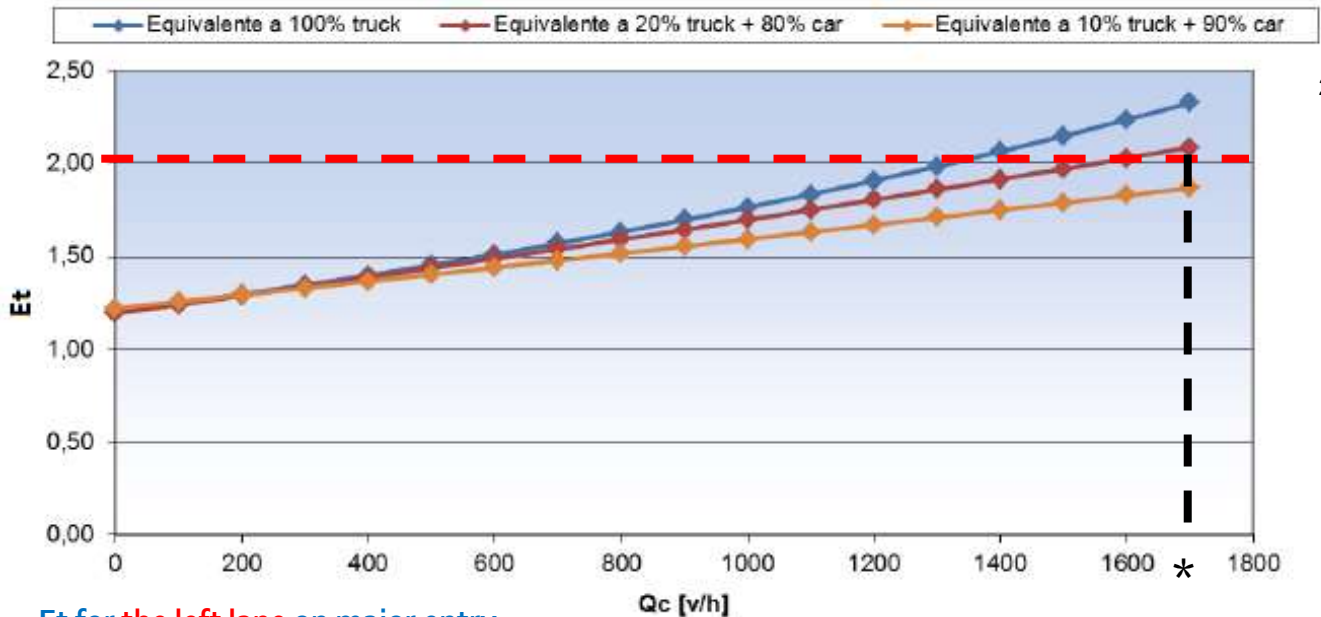
Step 5

- ✓ C_{car} and C_p depend on Q_c ;
- ✓ As a consequence **Et** depends on **Q_c** ;
- ✓ So **Et** is depending on one antagonist traffic flow (Q_{ce}) for **left- and right lane** at major entries and **right-lane** at minor entries;
- ✓ **Et** is depending on two antagonist traffic flows (Q_{ce} and Q_{ci}) for **left-lane** at minor entries.



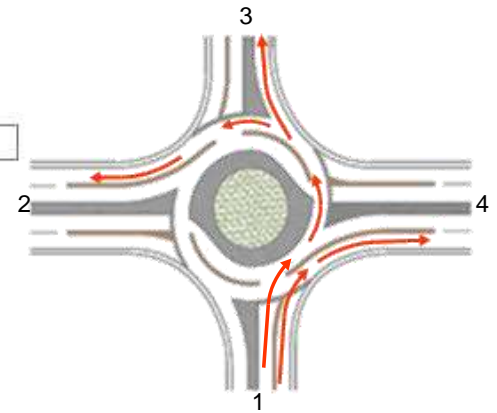


Et for the right lane on major entry



Et for the left lane on major entry

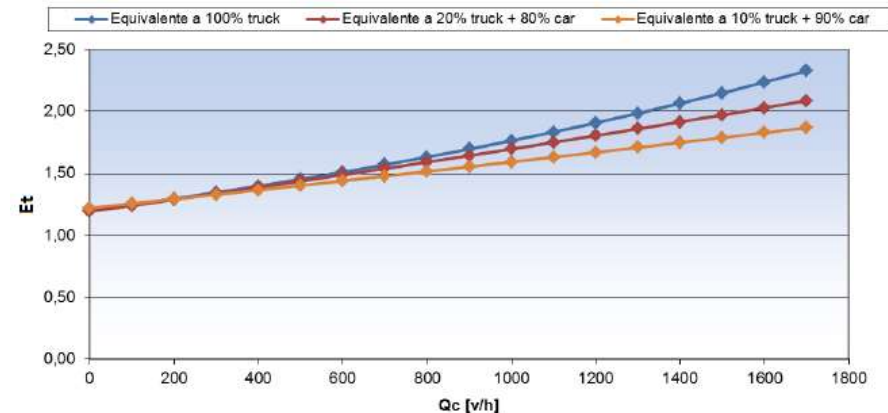
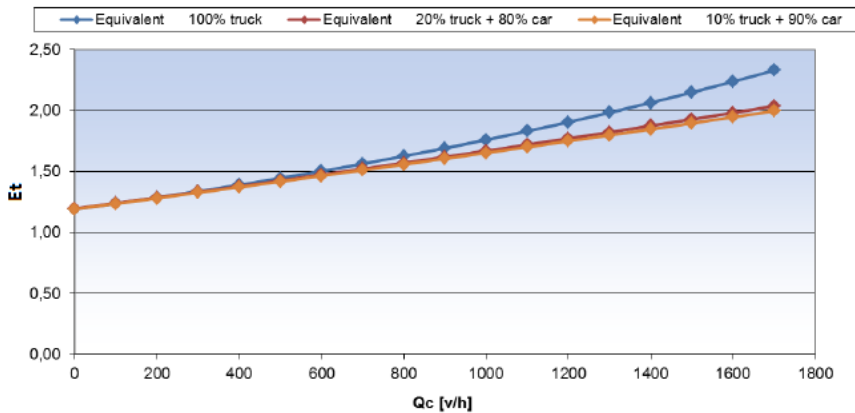
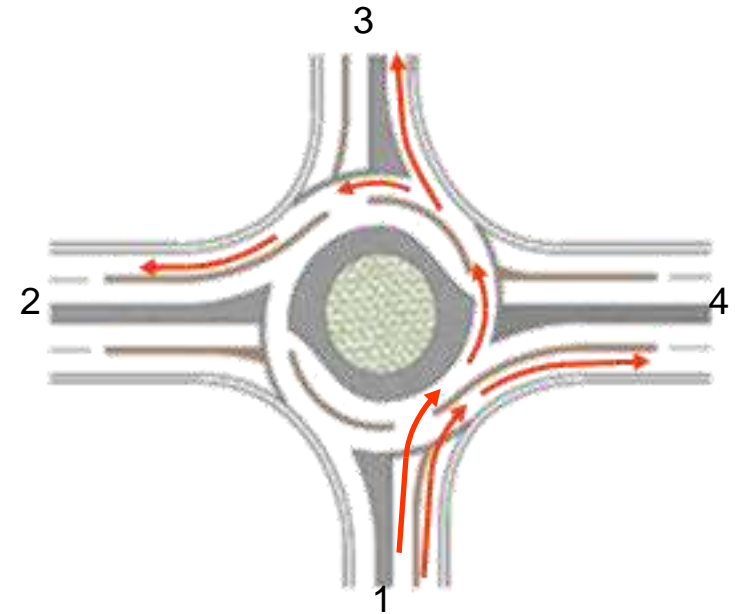
✓ For 20 % and 10 % of trucks the two functions are **overlapped** (you can see a good matching of the two functions);



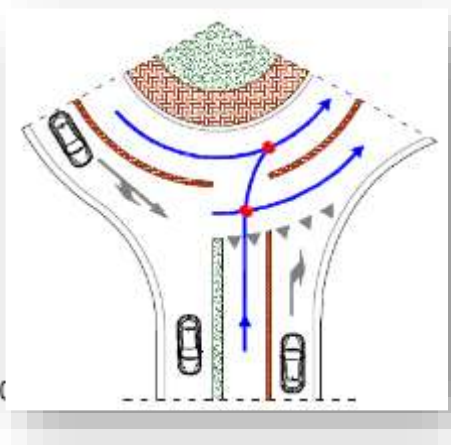
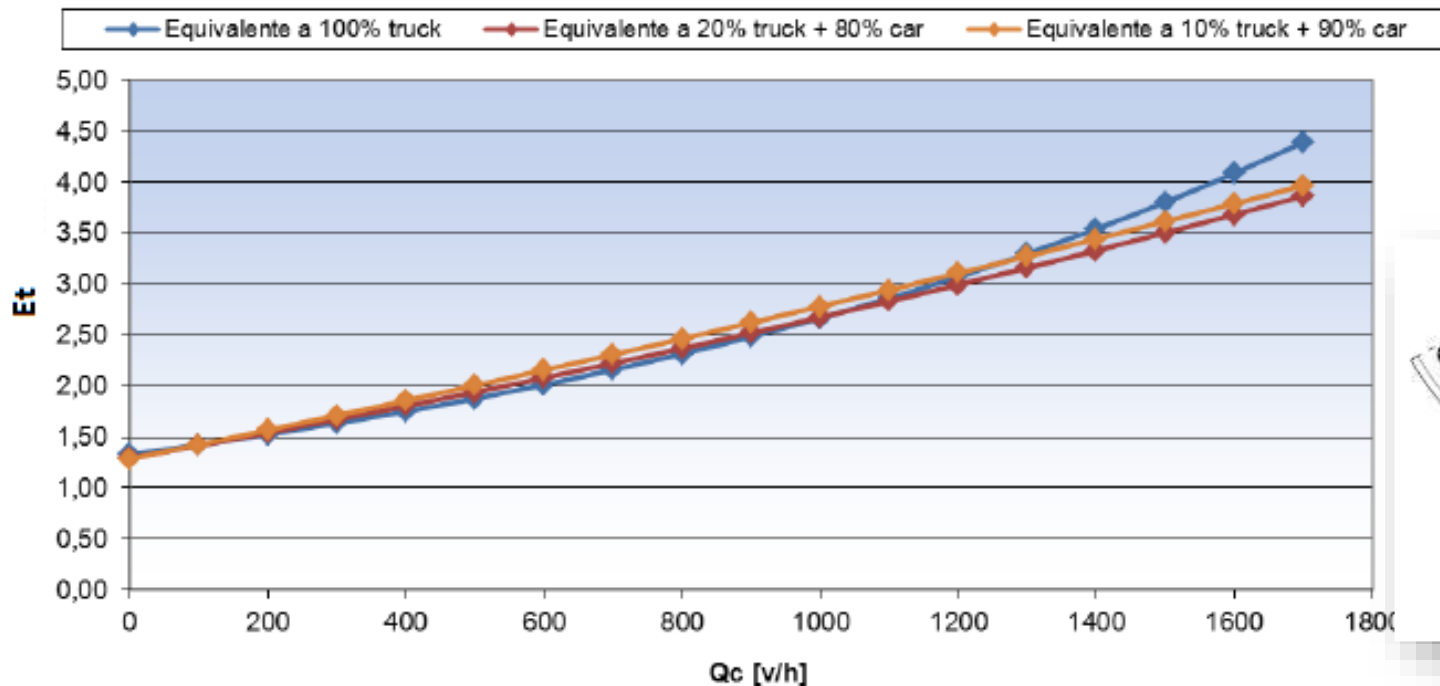
✓ In usual operations $E_t < 2$;

* $Q_c = 1700$ veh/h

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



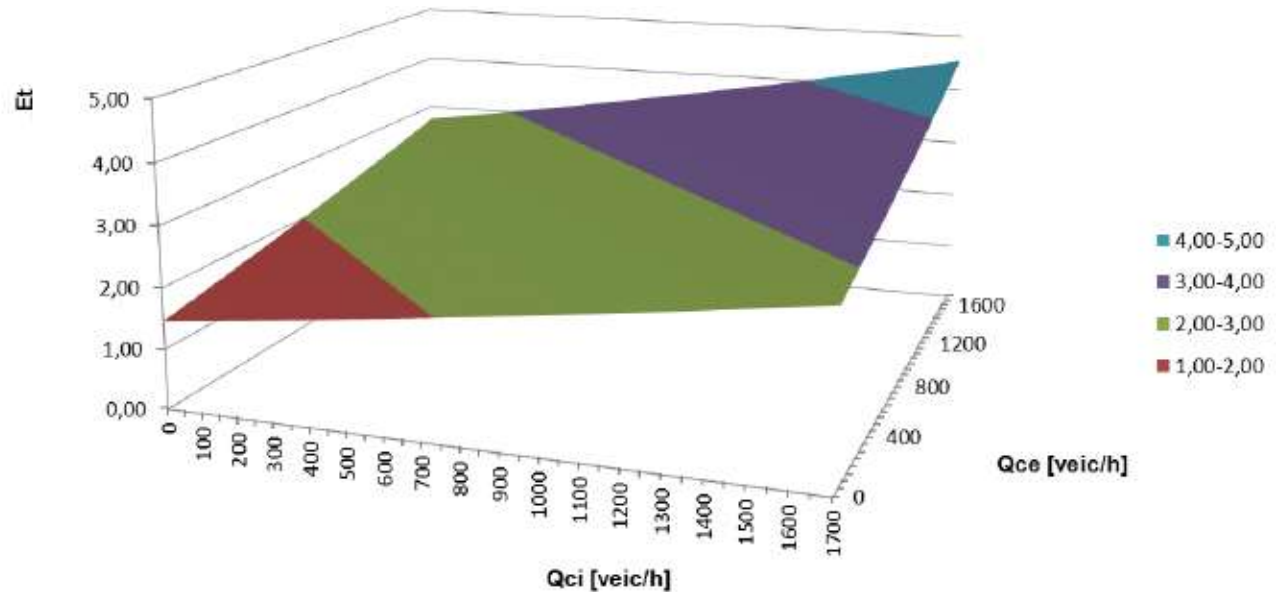
- ✓ $E_t = 2$ is early reached and exceeded when Q_c increases;
- ✓ In usual operations $E_t = 4$ is reached;
- ✓ Assuming $E_t = 2$ for **right lane at minor entries** as HCM 2010 suggests, underestimation of the impact of trucks on the quality of the traffic flow happens.



Equivalent factors for the **right lane** on minor entry

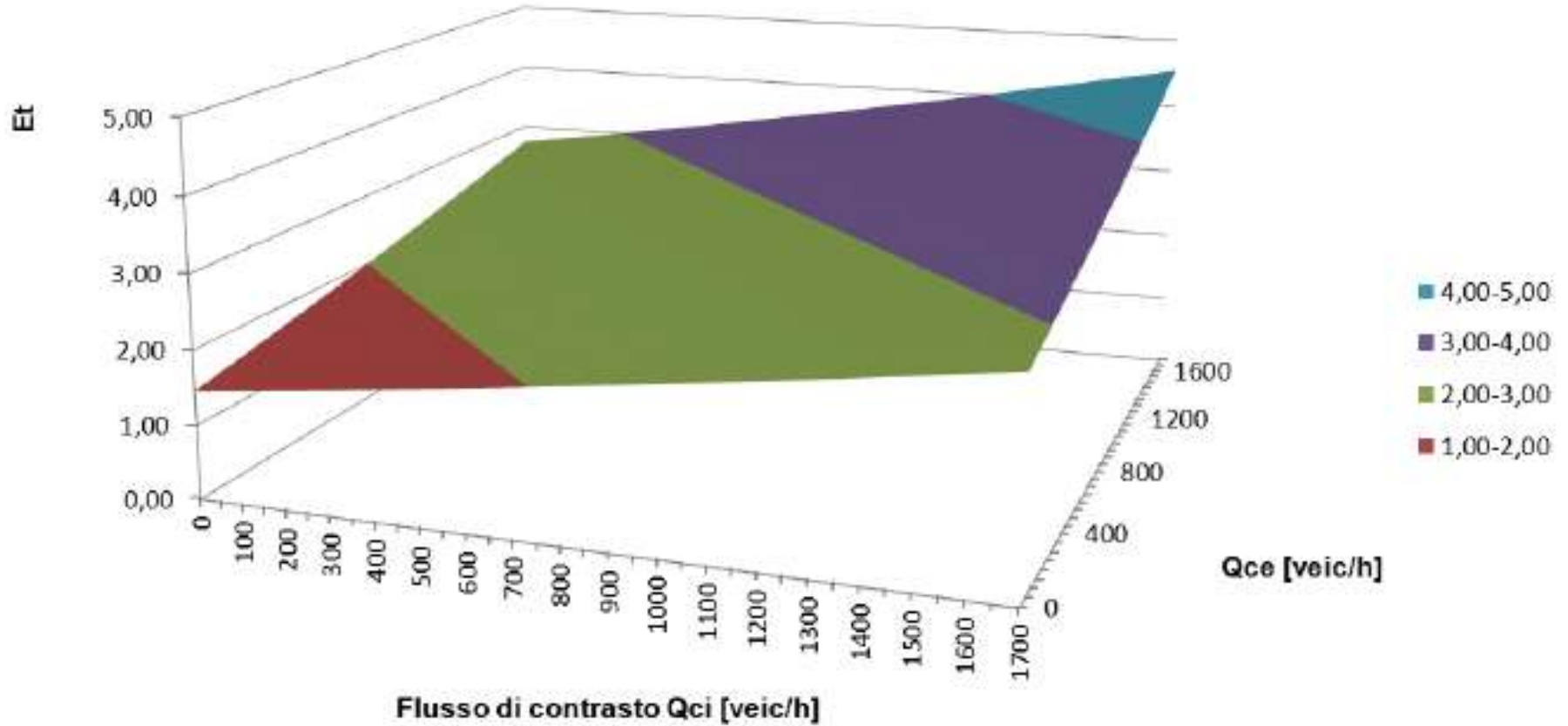


entry demand: 90%
cars+ 10% truck



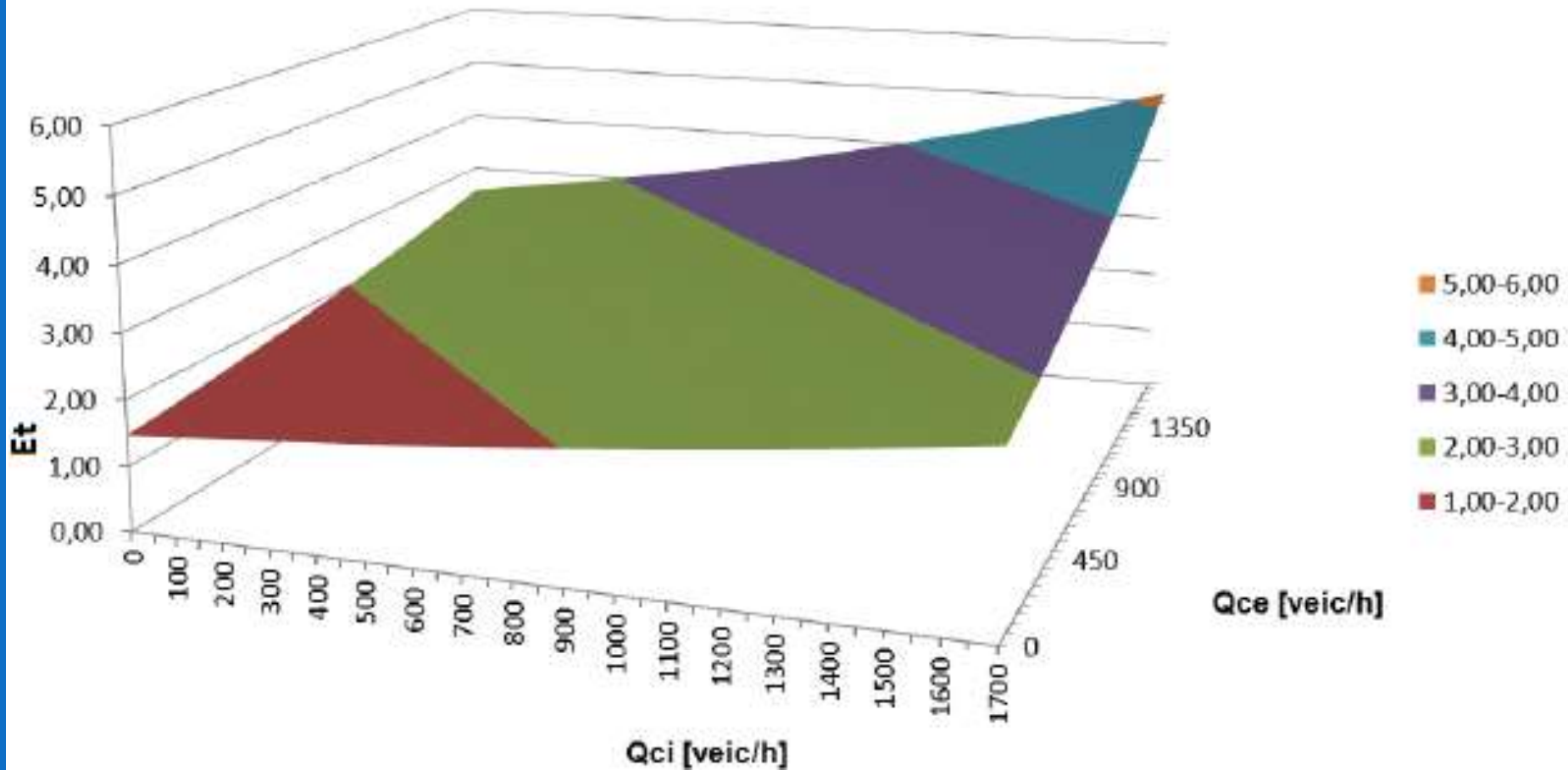
Equivalent factors for the left lane on minor entry

- ✓ 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

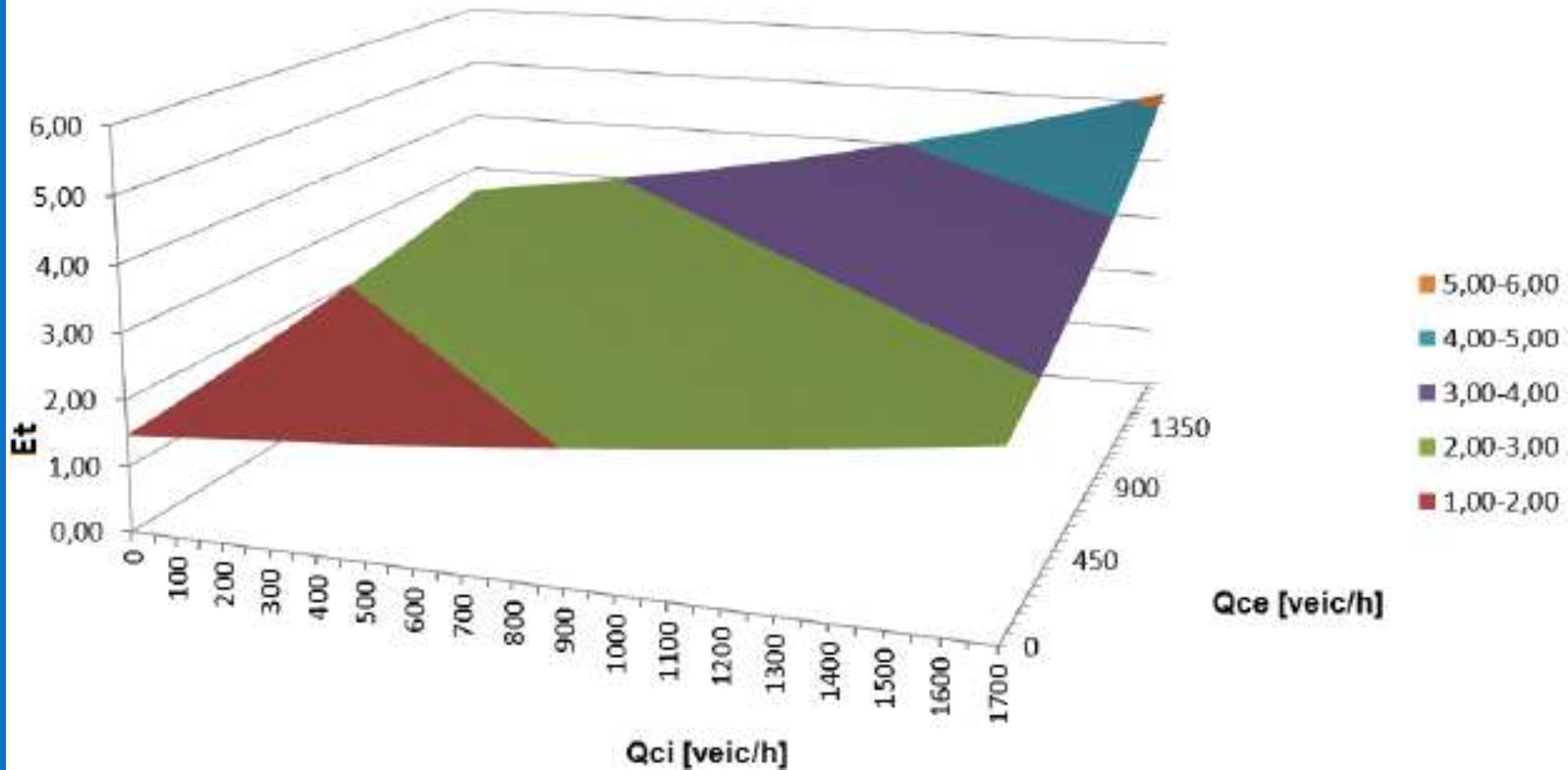
entry demand: 80% cars+ 20% truck



Equivalent factors for the left lane on minor entry

entry demand: 100%
truck

- ✓ in the usual traffic conditions (10% and 20% trucks), values $E_t=4.5$ is reached, ie slightly higher than the most value ($E_t = 4$) 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 $E_t = 2$ (HCM 2010) as for modern roundabouts, **underestimation** of the impact of trucks on the quality of traffic flow could happen;



Grazie per l'attenzione

Zuid-Holland province.

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

References: see eg....

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- Livelli prestazionali di rotonde 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)