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.

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.
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).
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)
What’s the turbo-roundabout?

Capacity
4000 pcu/h

Spiral roundabout

Three-leg Spiral roundabout
What's the turbo-roundabout?

Knee roundabout

Capacity 3500 pcu/h

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.

Fortujin, 2009
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;

[Diagram of a turbo-roundabout]

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?

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;

$R_1$: 10.50 m; 12 m; 15 m; 20 m
$R_2 = R_1 + Bu$
$R_3 = R_2 + 0.30$
$R_4 = R_3 + Bv$

The shift of the centre points...
“Today we count about 300 turbo-roundabouts worldwide”

http://www.turboroundabout.com/turbo-roundabout.html
Sassenheim - The Netherlands
Monster - The Netherlands
Dutch turbo roundabout, from SWOV publication
Rotterdam - The Netherlands
Oud Beijerland - The Netherlands
Szolnok - Hungary
Tollazzi, 2014 «The Netherlands (about 80); Slovenia (11); Germany (1); Hungary (1); Belgium (1); Indiana USA (2)…….»
“this comparation is stupid because every case is unique” Tollazzi, 2014

<table>
<thead>
<tr>
<th></th>
<th>2008-2009</th>
<th>2010 - 2012</th>
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<td>the duration of</td>
<td>4-5 months</td>
</tr>
<tr>
<td></td>
<td>construction</td>
<td>4-5 months</td>
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<tr>
<td></td>
<td>indicative price</td>
<td>800.000 - 1.500.000,00</td>
</tr>
<tr>
<td>Turbo roundabout</td>
<td>the duration of</td>
<td>5 months</td>
</tr>
<tr>
<td></td>
<td>construction</td>
<td>5 – 6 months</td>
</tr>
<tr>
<td></td>
<td>indicative price</td>
<td>800.000 - 1.650.000,00</td>
</tr>
</tbody>
</table>

The second turbo roundabout in the city Koper
The second Slovenian Turbo Roundabout – under construction; city Maribor 2008

The first turbo roundabout in the city Maribor; 2010

Springer Tracts on Transportation and Traffic STTT

Tomaž Tollazzi

Alternative Types of Roundabouts
An Informational Guide

Springer
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
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).

\[ f(\tau) = 1 - \varphi \quad \tau = \Delta \]

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

\[ \lambda = \frac{\varphi \cdot Q_c}{1 - \Delta Q_c} \]

Step function, Tanner 1962
Linear function, Jacobs, 1979

Cowan’s Distribution – Shifted Negative Exponential Distribution – M3

\( \lambda \): scale parameter where the conflicting flow rate (Qc) is in pcu/h;
\( \Delta \): 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:

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

- Ce: entry lane capacity [pcu/h];
- \( \varphi \): 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];
- \( \Delta \): 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, \( \Delta \) 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 ($Q_{c,e}$) 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

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

\[ \varphi = 1 - \Delta q_c \quad \text{eq. Tanner, 1962} \]

$q_c$ : the conflicting flow rate [pcu/s]
$\Delta$: the average intrabunch headway [s]
Assumptions on $T_c$, $T_f$ and $\Delta$

✓ 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 [*]:

<table>
<thead>
<tr>
<th>Entry</th>
<th>Lane</th>
<th>$T_c$</th>
<th>$T_f$</th>
<th>$\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$T_c$ [s]</td>
<td>$T_f$ [s]</td>
<td>$\Delta$ [s]</td>
</tr>
<tr>
<td>Major entries</td>
<td>Left</td>
<td>-</td>
<td>3.60</td>
<td>2.26</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-</td>
<td>3.87</td>
<td>2.13</td>
</tr>
<tr>
<td>Minor entries</td>
<td>Left</td>
<td>3.19</td>
<td>3.03</td>
<td>2.26</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-</td>
<td>3.74</td>
<td>2.13</td>
</tr>
</tbody>
</table>

Traffic situations

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

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.

Lane selection percentages performed by turning vehicles from entries
• 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 $i$.

\[
d_i = \frac{3600}{C_{e,i}} + 900T \left[ \frac{Q_{e,i}}{C_{e,i}} - 1 + \sqrt{\left( \frac{Q_{e,i}}{C_{e,i}} - 1 \right)^2 + \frac{3600}{450T} \left( \frac{Q_{e,i}}{C_{e,i}} \right)} \right] + 5
\]
Comparing Basic Turbo-roundabouts and Double-lane Roundabouts to Evaluate Operational Benefits

**x-axis** represents the variable \((Q_{e2}+Q_{e4})\);

**y-axis** represents the variable \((Q_{e1}+Q_{e3})\);

*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

- **Turboroundabouts 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).
✓ 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;

<table>
<thead>
<tr>
<th>the centroids and their connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-4</td>
</tr>
<tr>
<td>1-3</td>
</tr>
<tr>
<td>349, 350, 351, 352</td>
</tr>
</tbody>
</table>
✓ 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).

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

Ce: entry lane capacity [pcu/h];
\( \varphi \): 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];
\( \Delta \): minimum headway of circulating traffic [s];
j, k, l, m: indices for conflicting lanes (differing in mathematical form, but repeatedly representing the same lanes).

✓ 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 (*)).

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>definition</th>
<th>Default</th>
<th>Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum headway [s]</td>
<td>the time between the leader and the follower vehicle</td>
<td>2.10</td>
<td>1.70</td>
</tr>
<tr>
<td>reaction time [s]</td>
<td>the time a driver takes for reacting to speed changes in the preceding vehicle</td>
<td>1.35</td>
<td>1.00</td>
</tr>
</tbody>
</table>

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%;

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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 ($Q_{c,e}$) 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;

**Gap acceptance parameters** ($T_c$ and $T_f$) for basic turbo-roundabouts were already presented in the previous section.
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, Tce =3.03 s and Tci =3.19 s were underestimated by Fortuiijn for left turning movements;

<table>
<thead>
<tr>
<th>Entry</th>
<th>Lane</th>
<th>$T_c$ [s]</th>
<th>$T_i$ [s]</th>
<th>$\Delta$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major entries</td>
<td>Left</td>
<td>3.60</td>
<td>2.26</td>
<td>2.10</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>3.87</td>
<td>2.13</td>
<td>2.10</td>
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<td></td>
<td>Right</td>
<td>3.74</td>
<td>2.13</td>
<td>2.10</td>
</tr>
</tbody>
</table>
Moreover Tce is less than Tci, 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.

Default values in Aimsun for traffic state “car”

✓ they express the properties and cinematic performance attributed to the category vehicular “car”
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 \( C_{\text{car}} \) with the capacity values \( C_p \) corresponding to a traffic demand characterized by a percentage \( p \) of heavy vehicles.
This estimation was developed considering: $C_{\text{car}} = (1-p) C_p + p C_p E_t$

$C_p$: a mixed flow including the share of passenger cars $(1-p) C_p$ and heavy vehicles $(p C_p)$, multiplied by $E_t$ 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: $E_t = \frac{C_{car} - (1-p) \ C_p}{p \ C_p}$

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

- **Right lane on major entry**
  - 4 flow percentages
    - 100% “car”;
    - 10% “truck”+90% “car”;
    - 20% “truck”+80% “car”;
    - 100% truck
  - 10 capacity values for a given combinations of flow percentages

- **Left lane on major entry**
  - 4 flow percentages
    - 100% “car”;
    - 10% “truck”+90% “car”;
    - 20% “truck”+80% “car”;
    - 100% truck
  - 10 capacity values for a given combinations of flow percentages

- **Right lane on minor entry**
  - 4 flow percentages
    - 100% “car”;
    - 10% “truck”+90% “car”;
    - 20% “truck”+80% “car”;
    - 100% truck
  - 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

- **4 flow percentages**
  - 100% “car”;
  - 10% “truck”+90% “car”;
  - 20% “truck”+80% “car”;
  - 100% truck

120+280 = 400 simulated values of capacity $\rightarrow$ 4000 simulations
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.
### 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.

<table>
<thead>
<tr>
<th>vehicular percentages</th>
<th>$R^2$</th>
<th>parameter</th>
<th>parameter estimation</th>
<th>standard error</th>
<th>t-statistic</th>
<th>p-value</th>
<th>confidence interval *</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% truck</td>
<td>0.999523</td>
<td>$T_c$</td>
<td>5.32656</td>
<td>0.0964877</td>
<td>55.2045</td>
<td>$1.28624 \times 10^{-11}$</td>
<td>5.10406, 5.54906</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_f$</td>
<td>2.69525</td>
<td>0.0270715</td>
<td>99.5604</td>
<td>$1.15681 \times 10^{-13}$</td>
<td>2.63282, 2.75768</td>
</tr>
<tr>
<td>20% truck 80% car</td>
<td>0.999755</td>
<td>$T_c$</td>
<td>4.08475</td>
<td>0.0630056</td>
<td>64.8316</td>
<td>$3.56411 \times 10^{-12}$</td>
<td>3.93946, 4.23004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_f$</td>
<td>2.35396</td>
<td>0.017734</td>
<td>132.738</td>
<td>$1.16025 \times 10^{-14}$</td>
<td>2.31307, 2.39486</td>
</tr>
<tr>
<td>10% truck 90% car</td>
<td>0.999706</td>
<td>$T_c$</td>
<td>3.90996</td>
<td>0.0674909</td>
<td>57.9332</td>
<td>$8.75134 \times 10^{-12}$</td>
<td>3.75433, 4.0656</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_f$</td>
<td>2.30904</td>
<td>0.0191305</td>
<td>120.7</td>
<td>$2.48147 \times 10^{-14}$</td>
<td>2.26493, 2.35316</td>
</tr>
<tr>
<td>100% car</td>
<td>0.999428</td>
<td>$T_c$</td>
<td>3.73143</td>
<td>0.092694</td>
<td>40.2553</td>
<td>$1.59563 \times 10^{-10}$</td>
<td>3.51767, 3.94518</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_f$</td>
<td>2.26604</td>
<td>0.0264516</td>
<td>85.6673</td>
<td>$3.84587 \times 10^{-13}$</td>
<td>2.20504, 2.32704</td>
</tr>
</tbody>
</table>

* $\alpha$ significance level
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.

<table>
<thead>
<tr>
<th>vehicular percentages</th>
<th>$R^2$</th>
<th>parameter</th>
<th>parameter estimation</th>
<th>standard error</th>
<th>t-statistic</th>
<th>p-value</th>
<th>confidence interval *</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% truck</td>
<td>0.999633</td>
<td>$T_e$</td>
<td>5.21216</td>
<td>0.0831251</td>
<td>62.7026</td>
<td>4.65326x10^{-12}</td>
<td>5.02047 5.40385</td>
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<tr>
<td></td>
<td></td>
<td>$T_f$</td>
<td>2.74204</td>
<td>0.024255</td>
<td>113.051</td>
<td>4.18844x10^{-14}</td>
<td>2.68611 2.79797</td>
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<tr>
<td>20% truck 80% car</td>
<td>0.99962</td>
<td>$T_e$</td>
<td>3.99916</td>
<td>0.0245052</td>
<td>163.197</td>
<td>2.22362x10^{-15}</td>
<td>3.94265 4.05567</td>
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<tr>
<td></td>
<td></td>
<td>$T_f$</td>
<td>2.36964</td>
<td>0.00704609</td>
<td>336.306</td>
<td>6.8427x10^{-18}</td>
<td>2.3534 2.38589</td>
</tr>
<tr>
<td>10% truck 90% car</td>
<td>0.99822</td>
<td>$T_e$</td>
<td>3.77777</td>
<td>0.0516165</td>
<td>73.1892</td>
<td>1.35303x10^{-12}</td>
<td>3.65874 3.89679</td>
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<tr>
<td></td>
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<td>$T_f$</td>
<td>2.33173</td>
<td>0.0151171</td>
<td>154.244</td>
<td>3.49154x10^{-15}</td>
<td>2.29687 2.36659</td>
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<tr>
<td>100% car</td>
<td>0.99787</td>
<td>$T_e$</td>
<td>3.62675</td>
<td>0.0558058</td>
<td>64.9888</td>
<td>3.49585x10^{-12}</td>
<td>3.49806 3.75544</td>
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<td></td>
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<td>$T_f$</td>
<td>2.28131</td>
<td>0.0163185</td>
<td>139.799</td>
<td>7.66559x10^{-15}</td>
<td>2.24368 2.31894</td>
</tr>
</tbody>
</table>

* $\alpha$ significance level

73
### Results of regressions for the right lane on minor entry

<table>
<thead>
<tr>
<th>Vehicular percentages</th>
<th>$R^2$</th>
<th>Parameter</th>
<th>Parameter estimation</th>
<th>Standard error</th>
<th>t-statistic</th>
<th>p-value</th>
<th>Confidence interval *</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% truck</td>
<td>0.996428</td>
<td>$T_c$</td>
<td>6.83515</td>
<td>0.313297</td>
<td>21.8168</td>
<td>2.05503×10^-8</td>
<td>6.11269 7.55761</td>
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<td></td>
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<td>$T_f$</td>
<td>2.7624</td>
<td>0.0720031</td>
<td>38.365</td>
<td>2.34022×10^-10</td>
<td>2.59636 2.92844</td>
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<tr>
<td>20% truck 80% car</td>
<td>0.999934</td>
<td>$T_c$</td>
<td>4.91513</td>
<td>0.0344126</td>
<td>142.829</td>
<td>6.45751×10^-15</td>
<td>4.83578 4.99449</td>
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<tr>
<td></td>
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<td>$T_f$</td>
<td>2.20238</td>
<td>0.00808662</td>
<td>272.349</td>
<td>3.69864×10^-17</td>
<td>2.18374 2.22103</td>
</tr>
<tr>
<td>10% truck 90% car</td>
<td>0.999743</td>
<td>$T_c$</td>
<td>4.54072</td>
<td>0.0651728</td>
<td>69.6721</td>
<td>2.00528×10^-12</td>
<td>4.39044 4.69101</td>
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<tr>
<td></td>
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<td>$T_f$</td>
<td>2.14082</td>
<td>0.01572</td>
<td>136.185</td>
<td>9.45183×10^-15</td>
<td>2.10457 2.17707</td>
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<tr>
<td>100% car</td>
<td>0.999305</td>
<td>$T_c$</td>
<td>4.02581</td>
<td>0.100879</td>
<td>39.9072</td>
<td>1.7099×10^-10</td>
<td>3.79318 4.25844</td>
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<td>$T_f$</td>
<td>2.08169</td>
<td>0.0255953</td>
<td>81.3312</td>
<td>5.82469×10^-13</td>
<td>2.02267 2.14071</td>
</tr>
</tbody>
</table>

* $\alpha$ significance level
<table>
<thead>
<tr>
<th>vehicular percentages</th>
<th>$R^2$</th>
<th>parameter</th>
<th>parameter estimation</th>
<th>standard error</th>
<th>$t$-statistic</th>
<th>$p$-value</th>
<th>confidence interval*</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% truck</td>
<td>0.98733</td>
<td>$T_{ci}$</td>
<td>5.26815</td>
<td>0.195772</td>
<td>26.9096</td>
<td>$1.32323 \times 10^{-36}$</td>
<td>4.87705 5.65925</td>
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<td></td>
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<td>$T_{ce}$</td>
<td>5.63692</td>
<td>0.204802</td>
<td>27.537</td>
<td>$3.3981 \times 10^{-37}$</td>
<td>5.23048 6.04876</td>
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<td>$T_{f}$</td>
<td>3.22537</td>
<td>0.0777851</td>
<td>41.4652</td>
<td>$5.7937 \times 10^{-48}$</td>
<td>3.06998 3.38076</td>
</tr>
<tr>
<td>20% truck 80% car</td>
<td>0.996322</td>
<td>$T_{ci}$</td>
<td>4.19798</td>
<td>0.0978292</td>
<td>42.9113</td>
<td>$2.06056 \times 10^{-49}$</td>
<td>4.0026 4.39336</td>
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<tr>
<td></td>
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<td>$T_{ce}$</td>
<td>4.49392</td>
<td>0.101208</td>
<td>44.4029</td>
<td>$2.40324 \times 10^{-50}$</td>
<td>4.2918 4.69605</td>
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<tr>
<td></td>
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<td>$T_{f}$</td>
<td>2.39767</td>
<td>0.0310105</td>
<td>77.3181</td>
<td>$1.05895 \times 10^{-65}$</td>
<td>2.33574 2.4596</td>
</tr>
<tr>
<td>10% truck 90% car</td>
<td>0.998326</td>
<td>$T_{ci}$</td>
<td>3.97144</td>
<td>0.0647749</td>
<td>61.3115</td>
<td>$3.05426 \times 10^{-59}$</td>
<td>3.84208 4.10081</td>
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<tr>
<td></td>
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<td>$T_{ce}$</td>
<td>4.23483</td>
<td>0.0666998</td>
<td>63.4908</td>
<td>$3.27244 \times 10^{-60}$</td>
<td>4.10162 4.36803</td>
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<td>$T_{f}$</td>
<td>2.30234</td>
<td>0.0201487</td>
<td>114.268</td>
<td>$1.20079 \times 10^{-76}$</td>
<td>2.2621 2.34258</td>
</tr>
<tr>
<td>100% car</td>
<td>0.999064</td>
<td>$T_{ci}$</td>
<td>3.6684</td>
<td>0.0465887</td>
<td>78.7402</td>
<td>$5.45744 \times 10^{-67}$</td>
<td>3.57538 3.76142</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_{ce}$</td>
<td>3.94255</td>
<td>0.0481695</td>
<td>81.8474</td>
<td>$4.35206 \times 10^{-68}$</td>
<td>3.84637 4.03872</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_{f}$</td>
<td>2.19418</td>
<td>0.0143212</td>
<td>153.212</td>
<td>$5.84016 \times 10^{-86}$</td>
<td>2.16559 2.22278</td>
</tr>
</tbody>
</table>

Results of regressions for the left lane on minor entry

* $\alpha$ significance level 75
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.
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 Qce and Qci
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: 90% cars + 10% truck

entry demand: 100% truck

entry demand: 80% cars + 20% truck
✓ Calculation of the equivalent factors for a given percentage of trucks (Et) was made by using:

\[ E_t = \frac{[C_{\text{car}} - (1-p) C_p]}{p C_p} \]

Where:
- \( C_{\text{car}} \): capacity with a traffic demand of cars only;
- \( p \): share of trucks
- \( C_p \): capacity with a mixed traffic demand characterized by \( p \) trucks.
✓ $C_{\text{car}}$ and $C_p$ depend on $Qc$;

✓ As a consequence $Et$ depends on $Qc$;

✓ So $Et$ is depending on one antagonist traffic flow ($Qce$) for left- and right-lane at major entries and right-lane at minor entries;

✓ $Et$ is depending on two antagonist traffic flows ($Qce$ and $Qci$) for left-lane at minor entries.
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 $E_t = 2$ 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.
✓ $Et = 2$ 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

Eₜ as a function of Qₘₑ and Qₘᵢ 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
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;
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.

References: see eg....


- 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)