Influence of roundabout capacity enhancement on emission production

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Abstract. Secondary effects of intersections insufficient capacity in urban areas are negative impacts on environment out of acceleration and deceleration of vehicles moving in long queues. The positive influence of increased intersection performance to reduce delays and queues, as well as negative impacts on the atmosphere is presented in this paper. The case study includes two single-lane roundabouts located close to each other in Žilina. Both roundabouts do not comply with the current traffic loads. This results in long queues and delays lasting not just during the peak hours. The solution to this problem is a new type of roundabout – turbo-roundabout. Capacity characteristics of both the current and new state are determined by microsimulation using PTV Vissim software. Obtained main characteristics of traffic flows are used as inputs to establish emission productions of NOx, CO and HC at the roundabout entries. The paper shows that proposed basic turbo-roundabout provides significant higher capacity performance compared with current state. Waiting times and queue lengths decrease about ten times. Due to this reduction, emission productions decrease about 50-60%.

1. Introduction
Lack of intersection capacity performance causes the overflow waiting times and long queues. This traffic state results in increase of emission production. One of the fundamental solutions is new design of intersections with highest capacity performance. The increase of speed and decrease of density at intersection entries reduced the acceleration and deceleration effects which cause production of emission.

The microsimulation allows evaluate the traffic flow characteristics second by second on base of new design elements. Software PTV Vissim could log several indicators (e.g. speed, density and volumes) from lane segments. Mentioned traffic flow characteristics and known emission factors are used in emission calculation procedure. The data reflect the changes of traffic flow characteristics depending on new design. The comparison of output data shows the positive or negative impacts to emission productions.

The presented case study compares the changes resulting from new layout design of roundabout in Žilina town. The positive influence of increased intersection performance to reduce delays and queues, as well as negative impacts on the atmosphere is presented in this paper.

2. The current and new state
The case study includes two single-lane roundabouts RA 1 and RA 2 located in mutual distance about 160 m (Fig. 1). Traffic problems with queues, long travel times and low speeds daily occur due to the
high traffic volumes and un-sufficient capacity of these roundabouts. Additional problem is with two lanes of four-lane road which are merging into the single-lane entry of roundabout RA 1 (entry A). It results in the long delays and queues with length 600 m lasting not just during rush hour (Figure 1).

**Figure 1.** Existing roundabouts RA 1 and RA 2 and queues during rush hour at the entry A of RA 1.

Actual directional distribution of traffic flows at all roundabout entries were ascertained by traffic survey during common working day and it is shown in Figure 2a for the peak hour.

There are plans to cancel the first roundabout RA 1 and then rebuild the existing road to four-lane road along the whole length. There will be designed an uncontrolled intersection instead of RA 1 with main four-lane road, where all left turns will be canceled. The left turn traffic flow from the main entry A will be carried by U-turn around the second roundabout RA 2. The left turn traffic flow from the minor entry C will be carried out of this intersection and solved area. All these factors and also an increase of traffic flow due to unmet transport need at the entry A of RA 1 were considered to set a new traffic flow distribution – see Figure 2b.

There were investigated three scenarios of the case study (see Figure 2):

- Scenario 1 – current state of two existing single-lane roundabouts,
- Scenario 2 – cancelation of the first roundabout and new traffic flow redistribution at second roundabout while the geometry layout of RA 2 maintain,
- Scenario 3 - cancelation of the first roundabout and new traffic flow redistribution at second roundabout that is reconstructed into the basic turbo-roundabout TRA 2.

**Figure 2.** Three investigated scenarios and traffic flow redistributions during the peak hour.
3. Capacity characteristics of investigated scenarios

There were modeled all three scenarios of the case study mentioned above using PTV Vissim software. To set and calibrate simulation current state Scenario 1 to correspond to the real condition of roundabout, complex field data from survey such as speeds, entry capacities, delays and queue lengths were used.

Values of waiting times (w) and queue lengths (N95) calculated according to the Slovak technical regulation TP16/2015 [2] and obtained from microsimulation are listed for Scenario 1 in Table 1. The calibrated current state settings of Scenario 1 were applied at Scenario 2 and Scenario 3 that differ with traffic flow distribution and geometry layout. Capacity characteristic results of Scenario 2 and Scenario 3 calculated according to the Slovak technical regulations TP16/2015 [2] and TP14/2015 [1] and also determined by microsimulations are presented in Tab. 2. Microsimulation time period for evaluation of three scenarios was 3600 seconds; however simulation period was set 4200 seconds with warm up period 600 seconds. The values of microsimulation results are average values of 100 simulation runs with Random seed increment 1 [3].

Table 1. Capacity characteristics of existing roundabouts – Scenario 1.

| Entry | TP 16/2015 | Vissim | TP 16/2015 | Vissim |
|-------|------------|--------|------------|--------|
|       | v/c (-)    | w (s)  | w (s)      | N95 (m)| N95 (m)| w (s)  | N95 (m)|     |
| A     | 1.15       | 286.5  | 273.6      | 468.7  | 0.94   | 43.9   | 153.4  | 44.6  | 166.2 |
| B     | 0.90       | 27.5   | 13.0       | 59.7   | 1.03   | 134.0  | 214.7  | 138.3 | 186.8 |
| C     | 0.39       | 14.6   | 8.3        | 21.4   | 0.93   | 66.0   | 114.3  | 81.5  | 126.2 |
| D     | -          | -      | -          | -      | 0.85   | 42.7   | 76.4   | 54.7  | 83.7  |

Table 2. Capacity characteristics of existing roundabout RA 2 (Scenario 2) and designed TRA 2 (Scenario 3) with new traffic flow distributions.

| Entry | TP 16/2015 | Vissim | Lane | TP 14/2015 | Vissim |
|-------|------------|--------|------|------------|--------|
|       | v/c (-)    | w (s)  |      | v/c (-)    | w (s)  |
|       | N95 (m)    | N95 (m)|      | N95 (m)    | N95 (m)|
| A     | 1.03       | 114.2  | Left | 0.47       | 6.1    |
|       | 285.1      | 133.7  | Right| 0.49       | 6.6    |
|       | 303.9      | 250.9  |      | 4.9        | 26.8   |
| B     | 1.12       | 267.4  | Left | 0.45       | 9.1    |
|       | 319.2      | 273.4  | Right| 0.48       | 10.2   |
|       | 253.4      | 253.4  |      | 3.5        | 27.2   |
| C     | 1.04       | 169.4  | Left | 0.65       | 16.5   |
|       | 193.8      | 151.5  | Right| 0.10       | 4.4    |
|       | 208.0      | 208.0  |      | 0.3        | 0.6    |
| D     | 0.92       | 71.1   | Left | 0.36       | 9.5    |
|       | 107.8      | 62.0   | Right| 0.30       | 7.0    |
|       | 92.2       |        |      | 1.6        | 7.0    |

Comparison of the roundabout RA 2 performance in three scenarios is presented due to its entries degree of saturation (v/c) in Table 1 and Table 2. Scenario 1 entries degree of saturation approach or even rich value 1.0 which determine Level of Service (LOS) evaluated as F – un-sufficient entry capacity to corresponding volume. Waiting times and queue lengths as capacity characteristics are related to the capacity performance of roundabout and the comparison of their values obtained from microsimulation for three scenarios is shown in Figure 3. It is obvious that new traffic flow redistribution at RA 2 of Scenario 2 affects degree of saturation and therefore both capacity characteristics. The degree of saturation at entries A, B and C overlap value 1.0 resulting in LOS F. Due to that the waiting times arise two even three times and the queue lengths arise about 100 m at all entries except of the entry D. Solution of Scenario 2 capacity problem is Scenario 3 with a new geometry layout of basic turbo-roundabout that provide significant higher capacity performance. In
this scenario degree of saturation is lower than 1 with high capacity reserve and waiting times and queue lengths decrease about ten times at all entries.

\[ \text{Figure 3. Microsimulation results of three scenarios capacity characteristics.} \]

Since this paper is focus on environmental impact of un-sufficient roundabout capacity, microsimulation models of three scenarios were used to determine not only capacity characteristics but also traffic volumes, speeds and densities, necessary to calculate emission productions.

Density is defined as the number of vehicles per unit length of the roadway and it is related to speed and flow. It reflects traffic conditions on a road network. Occurred queues and long delays cause reduction of speed and increase of density at roundabout entries. Differences between each scenario densities are shown in Figure 4.

\[ \text{Figure 4. Results of three scenarios densities.} \]
4. Emissions

While capacity and congestion have historically been the major motivating factors of transportation management, new performance metrics have recently garnered attention. In addition to standard traffic metrics, now there is a strong interest in traffic-related emissions in terms of pollutants (e.g. carbon monoxide (CO), hydrocarbons (HC), nitrides of oxygen (NOx), and particulate matter) [4].

It is generally difficult to measure emission from specific mobile sources under real-world conditions due to the mixing and dispersion of emissions as well as contributions from additional sources such as other vehicles, nearby factories and secondary pollutants. These issues are further influenced by environmental factors such as meteorological conditions and topographic features. Some methods of emission measurements, such as tunnel studies, remote sensing, and portable emission monitoring systems, address these problems to some extent. However, these methods, either do not isolate emissions from specific vehicles, or are very limited in testing locations and cannot be practically applied to large sets of vehicles.

One of the ways to quantify traffic-related emissions is the use of emission models. These emissions models are implemented in several softwares which are intended to model in different area scale [5]:

- Macro – e.g. VISUM, CUBE (base on average speed)
- Macro – mesco – e.g. SATURN (base on running speed – three-mode elemental)
- Micro – mesco – e.g. SIDRA INTERSECTION (base on four-mode elemental)
- Micro – e.g. VISSIM, AIMSUN, SIDRA TRIP (base on second-by-second characteristics)

The general formula for emissions calculating is the following:

\[
Emission = Traffic\ Activeity\ (vkm) \times Emission\ Factor\ (g/vkm)
\] (1)

Emission factors are commonly associated with average speed, and researchers often use average speed as a traffic performance measure. It is possible to create these speed-based emission factors (in terms of grams per kilometer) by simply taking the accumulated vehicle activity database and running each individual trip through the emission models. What results is a single emissions value associated with the average speed of the trip.

The used traffic activity characteristics in the case study were evaluated from microscopic model in the PTV Vissim. We can split the trip into smaller segments representing the time spent on freeways, major surface streets, and residential streets. We can then associate an emissions value with the average speed of that particular lane segments on entry lanes of roundabout [3]. Example of speed curve at the entry A is shown in Fig. 5. Low speed in Scenario 2 is due to a long queue at the entry A and a sharp decline in the speed is caused by merging of two lanes into one entry lane 80 m before the single-lane roundabout. A relatively high vehicle speed in Scenario 3 starts to decrease about 130 m before the turbo-roundabout.

In investigated scenarios was used Polutation-emission procedure of PTV Vision software which calculates pollutants CO, HC and NOx, without particulate matter (PM10, PM2.5). This procedure is based on emission factors \( EF \) issued by the Swiss Federal Office for the Environment. For each pollutant, a regression curve with polynomials to the 5\textsuperscript{th} degree is used of the form [3]:

\[
EF = a + b.x + c.x^2 + d.x^3 + e.x^4 + f.x^5
\] (2)

Where \( a, b, c, d, e \) and \( f \) are parameters of the polynome determined separately for different pollutant and \( x \) is speed in km/h.

The basic speed-emission factors used in the case study are included in emission module of PTV Vision and listed in Table 3. Example of emission factor of CO related to the speed is shown in Fig. 6.

The results of HC, NOx and CO emissions calculated for all scenarios by emission factor and traffic activity are shown in Fig. 7. The mutual comparison is in Table 4.
Table 3. Basic speed-emission factor coefficients of PKW for HC, NOx and CO emissions.

| PKW | a     | b       | c       | d       | e       | f       |
|-----|-------|---------|---------|---------|---------|---------|
| HC  | 0.4361| -1.34E-02| 1.86E-04| -1.22E-06| 3.97E-09| -5.66E-12|
| NOx | 0.1897| 5.58E-03 | -1.93E-04| 2.57E-06 | -6.56E-09| -2.07E-11|
| CO  | 3.2587| -8.05E-02| 6.73E-04| -1.21E-06| -6.39E-09| 3.77E-11|

Figure 5. Speed curve of scenario 2 and 3 at entry A.

Figure 6. Dependence of emission factor of CO on speed.

Figure 7. The HC, NOx and CO calculated emissions of three scenarios.

Table 4. Variation of emissions by investigated scenario.

| Entry | Scenario comparison | HC | NOx | CO |
|-------|---------------------|----|-----|----|
|       | S1 (kg.km⁻¹)        | 0.16 | 0.12 | 1.28 |
| A     | S2 – S1 (%)         | + 17.8 | + 18.4 | + 15.0 |
|       | S3 – S2 (%)         | - 65.5 | - 51.9 | - 65.7 |
| B     | S1 (kg.km⁻¹)        | 0.09 | 0.07 | 0.70 |
|       | S2 – S1 (%)         | + 17.5 | + 10.1 | + 16.6 |
|       | S3 – S2 (%)         | - 61.3 | - 44.1 | - 62.1 |
| C     | S1 (kg.km⁻¹)        | 0.11 | 0.10 | 0.89 |
|       | S2 – S1 (%)         | + 23.2 | + 12.2 | + 21.8 |
|       | S3 – S2 (%)         | - 78.5 | - 47.0 | - 79.0 |
| D     | S1 (kg.km⁻¹)        | 0.07 | 0.10 | 0.53 |
|       | S2 – S1 (%)         | + 20.3 | + 7.7 | + 21.7 |
|       | S3 – S2 (%)         | - 73.1 | - 50.0 | - 74.6 |
The single-lane roundabout with the new traffic flow redistribution (Scenario 2) causes about 20% increase of emissions compared to Scenario 1. The highest difference was monitored at the entry C with 23.2% increase of HC emissions; contrariwise the smallest difference was monitored at the entry D with 7.7% increase of NOx emissions.

The comparison of Scenario 2 and Scenario3 determine the 60% - 70% decrease of HC and CO emissions. The NOx emissions decrease with 40% -50% at roundabout entries. The highest difference was monitored at the entry C with - 78.5% decrease of HC emissions; contrariwise the smallest difference was monitored at the entry D with - 44.1% decreases of NOx emissions.

5. Conclusions
Estimation of emissions for evaluating traffic conditions is useful for sustainable environmental assessment in traffic design, operations and planning. The modern trends of road design content as capacity issues as well as environmental impacts.

Turbo-roundabouts improve the road network performance. The reductions of waiting times and queues at entries cause the increase of speed and decrease of density. Mentioned positive impact reflects the decrease of emissions.

The presented case study point out the new design of turbo-roundabouts providing higher capacity performance that results in reduction of emissions. The current single-lane roundabout considering the new traffic flow redistribution that is planned in future has the degree of saturation that overlap value 1 resulting in LOS F at entries A, B and C. Due to that waiting times and queue lengths increase at all entries. The change of layout geometry causes the decrease of queues and waiting times about ten times with the same traffic conditions. Also the single-lane roundabout causes the 20% increase of emissions in comparison with the turbo-roundabout with the same traffic flow redistribution that reduces HC and CO by 60% - 70% and NOx values are reduce by 40-50%.

While capacity and congestion are still strong motivating factors of transportation management, emissions have recently garnered attention because they are related to capacity performance of road network as it is shown in this case study. In future Department of Highway Engineering will monitor not only gas particles but also the solid particles [6]. It is necessary to take in consideration also this factor in planning and operating changes in road network.

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