Potential of energy and environment savings in different infrastructural design

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Abstract

Detrimental air pollution related to traffic flow in the road and street infrastructure has reached the critical level in many cities. Road users and also residents near intersection are dangerously exposed for hazardous components in the exhaust pollutants. At intersections, and other disturbance points in the traffic flow, the deceleration and acceleration of vehicles give substantial additional amounts of emitted exhaust pollution and use of fuel. It is therefore necessary to pay attention to the infrastructural design aspects when looking for ways of reduce them. This paper will deal with the possibilities of quantifying the energy saving aspects of intersection design and advanced traffic signal control systems on the microlevel by recently developed methods and models for comparison of the effects of different intersection performances. The results of this paper show many ways to reduce energy consumption, and specifically save energy by reducing fuel consumption for the vehicles in the road and street infrastructure, especially in congested areas.

Keywords – energy saving, environmental impact, roundabout, traffic calming

1. Introduction

Detrimental air pollution related to the traffic flow in the road and street infrastructure has reached the critical level in many cities. Road users and also residents near intersections are dangerously exposed for hazardous components in the exhaust pollutants. The reduction of such ambient air disturbances is a prime requisite for the future sustainable use for the individual transportation vehicle.

At intersections and other disturbance points in the traffic flow, the transient driving patterns, i.e. the decelerations and accelerations of vehicles, give substantial additional amounts of emitted exhaust pollution. It is therefore necessary to pay attention to the infrastructural design aspects, when looking for ways of reducing the traffic related emissions to the ambient air. The choice of the optimal design solution for given intersection with a given flow intensity and flow distribution could therefore be crucial for the surrounding air quality situation. Methods for quantifying the amount of emitted air pollution use various parameters such as driving patterns and traffic management conditions as well as vehicle category, engine type and specific factors.

There has been very parsimonious R&D-activities within this area. This paper highlights some factors that affect on how traffic signal control functions. It also gives some ways to increase efficiency at the signalised intersections and introduces environmental benefits and disbenefits of roundabouts and traffic calming methods.

2. Project structure and main objectives

The energy saving and environmental aspects of intersection design and advanced traffic signal control systems are highly neglected in the planning and construction process. The planning regulations are not valid in many countries. The fuel consumption as well as the detrimental exhaust emissions at intersection are much higher than at the links between. We also know, that the present vehicle engine, gasoline as well as diesel, will have a reduced fuel consumption and also give a significantly less contribution to the air pollution, working at constant reasonable speed than during acceleration, stopping and at low speeds.

The potential for energy savings and emission reductions vary along the urban roads. One of the reasons is that vehicles spend longer periods of time near junctions queuing, decelerating and accelerating and the other is that the transient operating modes themselves are generally more fuel consuming and more polluting than unobstructed cruising.

These facts indicate that that the traffic intersection and this design should be given a much higher attention in the discussion concerning potential energy saving and environmental remedy. The nodes must be given more than the present parsimonious exposition, and the possibilities of alternative design and traffic control systems with energy saving potentials must be taken in consideration.

Basically, the project dealt with opportunities of quantifying the energy saving aspects on the intersection design and using advanced traffic signal control systems. The overall objective was to reduce energy consumption, especially fuel, in the traffic systems, especially in the congested urban areas.

The new innovative aspects of the project were the microlevel estimation of the fuel consumption and the alternative reduction methods using different kind of infrastructural design or new urban traffic control systems. The cost-benefit-analysis was very remarkable part of the project. By the cost-benefit-analysis it is possible to find an optimal or better solution for intersection design. The large dissemination part was done in helping municipalities, organisations, media and companies to understand results achieved in this project [3].

3. Research methodology

The methodology used is traffic simulation with specially designed additional computer programme for the calculation of the fuel consumption and the exhaust pollution. HUTSIM – the simulation model developed in the Laboratory of Transportation Engineering at Helsinki University of Technology has given the traffic flow parameters, such as average delays, number of stops, average travel speeds, etc..

HUTSIM also generates singular vehicle speed profiles containing information of acceleration, deceleration, idling time and cruising speed. In combination with the computer programme, called HUTEMCA, for emission calculations, based on three dimensional emission matrixes, and the singular vehicle driving characteristics, we will get continuous emission profiles for each vehicle in studied road or intersection section.

Before using simulation as a research method one must make sure that the model is verified, calibrated and validated. HUTSIM – microscopic simulator is especially designed for the analysis of modern traffic actuated signals, complicated intersections and changing traffic conditions [6]. All validation results of HUTSIM have been good, and we can trust the results of this study [8]. The additional methods of this research and this analysis were a normal video recording and video recording from the helicopter.

4. Isolated traffic signal control

4.1 Introduction

The traffic signal design can be viewed as measures of the performance of intersection operation criteria or, in other words, desirable outcomes: hence a decrease in each of delay, number of stops, fuel consumption, pollutant emissions, noise, vehicle operating costs, queue length and personal time as well as an increase in the consideration for pedestrian, bicycle and transit traffic and safety are all desirable. The functioning of the traffic signal control has a significant effect on the environment. The general main goal is that the number of stops has to be minimized at the level of the transportation system, while at the level of one intersection the delays have to be minimized.

The fluency of the traffic flow has a decisive effect on the emissions and fuel consumption of traffic. The functioning of the traffic signal control has a significant effect on the environment. According to aerial video recording 20 % of the vehicles in downtown Helsinki drives normally at the desired or free speed, 30 % is stopped at the signalised intersections and the rest of the vehicles are accelerating, decelerating or turning. Traffic signal control seems to be an important part of our daily life. In the case of one signalised intersection, the modern traffic actuated control operates effectively if the traffic signal control works as it was planned to do.

The problems of signalised intersections are:

- to plan and select a correct control program
- to select a correct rest-phase pattern
- to locate detectors to the correct distances
- to make a right decision, if the control programs or detectors have errors.

4.2 Traffic actuated signals vs. fixed timing

The traffic actuated signal mode (VA) is more adaptive than fixed signal timing (fixed, Webster-timing). The compared results from Oulunkylä, the local sector of Helsinki, are shown in Table 1 [9].

According to these results, the benefits of traffic actuated control are biggest during the great variations of traffic demand (low demand conditions and day traffic), even 6 – 12 l/h. During the peak-hours the variation of cycles and traffic demands is smaller, which means that the benefits are much smaller. In our case, the evening peak-hour was oversaturated, and the estimation of fuel consumption using the simulation was not valid.

Tab. 1 – Comparison of traffic actuated signal mode and fixed timing [9]

Time	delay VA	delay fixed	Δ delay	Δ fuel consumption
Morning peak	36,2 s	36,7 s	0,5 s	0,07 l/100 km
day traffic	34,7 s	47,5 s	12,8 s	1,61 l/100 km
evening peak	86,3 s	Oversaturated	-	-
low demand	29,9 s	36,8 s	6,9 s	0,90 l/100 km

4.3 Signal control policy for low demand conditions

The motivation for the is a statement, which orders that traffic signals should be in operation all the time, including the night time. The fixed timing causes much unnecessary vehicle delay compared with non-signalised control (yielding, stop, signals switch off, or yellow flashes). The best solution for signal control will be that the signals work in the traffic actuated mode. That means that we have to determine the strategy for a traffic situation without detections (rest phase arrangement).

Three most common rest phases are all red, main street and last phase. In the "all-red" rest phase, all signal groups remain red until green is demanded by any of the detectors. In the "main-street" rest state, the main direction remains green when no request exists. In the "last phase" rest phase, the last activated phase remains green until new requests appears. The results of preliminary study showed that "all-red" rest phase proved to be slightly better than the other rest phases in terms of average delays and stop percentages.

The preliminary study was done only at one signalised intersection, but this study was done at the intersections of a different number of phases and in different traffic environments. The two-phase control is, perhaps, the most common control strategy at signalised intersections in the world. The results of this simulation study have also shown that the "all-red" rest phase is the best arrangement for the two-phase control. The results of the average delay are shown in Figure 1.

The results of the three-phase control shown in Figure 2 indicate that the importance of the rest-phase arrangement is greater in it than in the two-phase control. In spite of that, the results are quite the same as in the two-phase control. The best solution is the "all-red" rest phase arrangement without pedestrian secondary requests, and the effects of the pedestrian crossing control strategy are greater than the effects of the rest-phase arrangements.

The conclusion was that the rest-phase has an effect on the traffic fluency when the traffic volume is lower than 500 veh/h. There are practically no rest-phases any more when the traffic volume is more than 500 veh/h. At two- or three-phase controlled intersections without pedestrian crossings the all-red-rest-phase is the best alternative for the traffic fluency and the vehicle fuel consumption. At intersections with pedestrian crossings the best alternative is a control strategy where pedestrian crossings do not have secondary requests and the rest-phase is all red. It becomes a poor alternative for pedestrians when the traffic volume exceeds 200 veh/h. It seems that the best alternative for pedestrians is a rest-phase where all crossings have green signal.

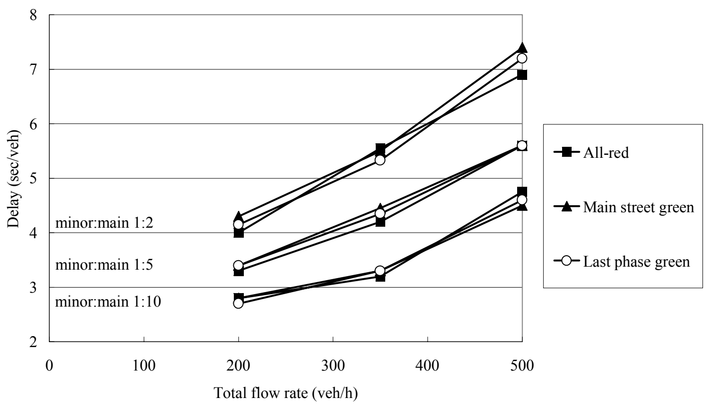


Fig. 1 – Average delay of two-phase control

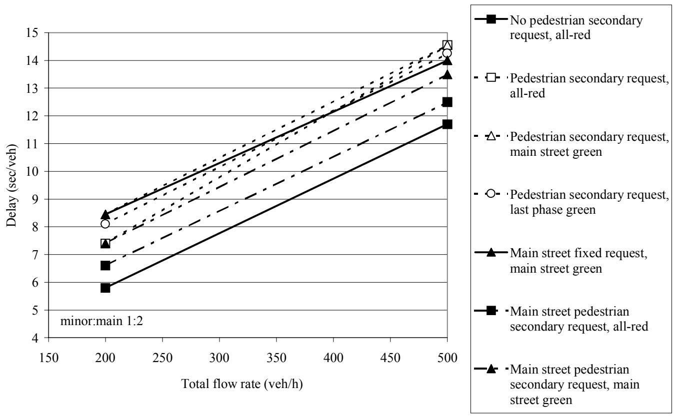


Fig. 2 – Results of three-phase control with pedestrian crossing

The all-red-rest-phase is always the best one for minor roads. At two-phase intersections without pedestrian crossings the fluency of the main road is greatest if the rest-phase is main road green or last phase green.

When the number of phases increases or there are pedestrian crossings, the all-red-rest-phase is also the best alternative for main road traffic in almost all traffic situations. When the traffic volume is 500 veh/h, the delays of main road traffic are at a minimum in those rest-phase alternatives where the main road signal groups have green signal.

4.4 Effective detector functions

The detection of each vehicle is the basis of traffic-actuated signal control. The detector mode, size and location are the most important variables in vehicle detecting. The results of our study show that the right rest phase arrangement is more significant than the detector location in low traffic demand situations, but also that, if the detectors of each approach are located sufficient distance, there will be no differences between the rest phase arrangements. Normally, the first detector of main approach is located 80 - 120 meters from the stop line. The corresponding distance for roads with a 70 km/h speed limit is 100 - 160 meters. The longer detection location inside these limits gives a smaller number of stops, and the shorter detection location gives less delays. The differences are quite small.

In the case of one signalised intersection, the modern traffic actuated control operates effectively, if the traffic signal control works as it was planned to. An incorrect traffic signal program does not necessarily repeal this advantage. The influence of detector errors is bigger. One detector error at a low traffic demand repeal the advantage of traffic actuated control. If there is more than one detector error, the situation is worse than it would be by the fixed timing plan. For traffic safety reasons the upstream detectors on the main road have to be located at least at the distance where the dilemma zone ends. With a 50 km/h speed limit, the detectors have to be at least 80 meters before the stop line. The average delay of all vehicles and the fuel consumption are at a minimum when the detectors are located 100 meters before the stop line. In order to minimize the percentage of stops the detectors have to be located at least 120 meters before the stop line.

Tab. 2 – Effects of detector errors

Time	**error**	**Δ delay**	**Δ fuel consumption**
Day traffic	1 detector	-4,0 s	-0,6 l/100 km
Day traffic	3 detectors	-11.4 s	-1,6 l/100 km
Evening peak	3 detectors	Oversaturated	-

Detector errors are a very difficult problem for a traffic signal planner. We tested in Oulunkylä, Helsinki, what is the effect of a detector error in isolated traffic signals (Table 2.). In the first measurement, the detector error was located in the low demand approach. In the second and third measurements, the detector errors were located in three different approaches.

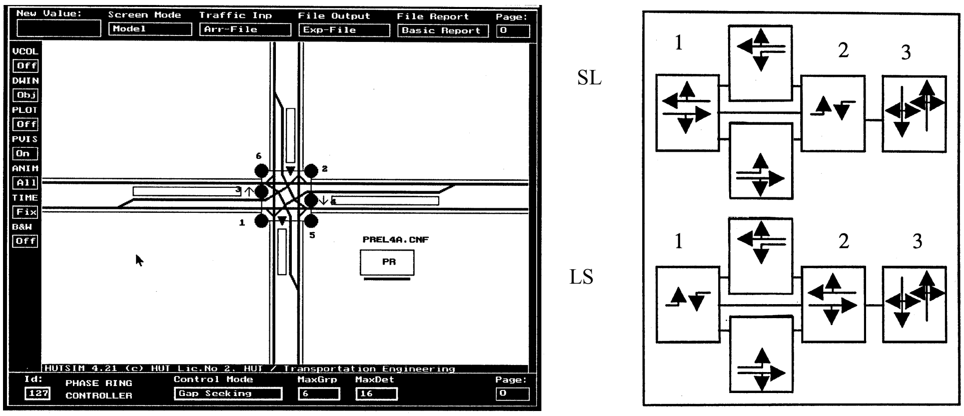
According to our results, the effect of the first detector can be the same as the positive effect of the traffic actuated control mode. If there is more than one detector error at the signalised intersection, the recommendation is to change the control program to fixed timing. The total disadvantages of the first detector can be approximately to 3.5 l – 7.0 l /hour. The effect is not strong during rush-hours, and it can even be positive if traffic is congested or oversaturated.

5. Some ways to increase energy efficiency at the signalised intersections

5.1 Phase order

The knowledge that most vehicles are at the impact area of traffic signals in suburban area is a great challenge for traffic engineers. Some proposals for improvement have been discussed in this chapter.

Signal group control has been developed in the Nordic countries since the late sixties. Signal group control is more flexible than stage control and is therefore able to adapt to better traffic conditions. The intersection adapts to the traffic situation during each cycle. Extra time can be given to the one of the left turners that has the most green demand.



SL left turning phase is after main phase; LS left turning phase is before main phase

Fig. 3 – Simulation model and compared phase orders

Tab. 3 – Summary of phase-order results [12]

SL = left turning phase is after main phase
LS = left turning phase is before main phase

delay (s)

	SL		LS	
	minor/main		minor/main	
volume (veh/h)	1\2	1\5	1\2	1\5
200	13.6	10.2	14.6	9.6
400	24.4	19.3	26.1	19
600	32.7	24.9	34.7	23.9
800	43.3	31.4	42.5	29

percentage of stops (%)

	SL		LS	
	minor/main		minor/main	
volume (veh/h)	1\2	1\5	1\2	1\5
200	42	28.9	43.1	29.7
400	59.2	46.3	57.4	43.7
600	66.4	56.4	65.2	51.3
800	71.6	61.7	70.3	56.8

queue length (veh)

	SL		LS	
	minor/main		minor/main	
volume (veh/h)	1\2	1\5	1\2	1\5
200	3.8	1.5	3.8	1.3
400	21.7	14.9	24.8	14.8
600	46.3	30.1	44.9	27.6
800	65.8	42.5	66.6	40.4

fuel consumption (l)

	SL		LS	
	minor/main		minor/main	
volume (veh/h)	1\2	1\5	1\2	1\5
200	21.7	16.8	21.9	16.5
400	55.4	40	57.2	39.8
600	93.8	67.3	96.3	65.6
800	122.6	99	124.3	94.6

NOx (g)

	SL		LS	
	minor/main		minor/main	
volume (veh/h)	1\2	1\5	1\2	1\5
200	436.3	341	437.7	341.9
400	983.8	734.2	981.3	722.5
600	1551.1	1174.7	1532.4	1145.4
800	1880.1	1666.6	1803.2	1593.4

CO (g)

	SL		LS	
	minor/main		minor/main	
volume (veh/h)	1\2	1\5	1\2	1\5
200	3296.3	2516.9	3309.9	2490.7
400	8262.3	5925.5	8467	5864
600	13760	9852.2	14042	9598.4
800	17601	14365	17774	13757

HC (g)

	SL		LS	
	minor/main		minor/main	
volume (veh/h)	1\2	1\5	1\2	1\5
200	596.9	444	596.7	446.9
400	1456.7	1046.4	1449.4	1023.3
600	2330.3	1724.3	2323.3	1675
800	2776	2466.3	2833.6	2375.6

By selecting the *right phase order* or *minimizing the intergreen* times, a better capacity as well as a lower fuel consumption can be achieved, because the idling times are some seconds shorter. Our example was the ordering of a left turning phase. The simulated intersection and compared phase orders are shown in Figure 3.

According to our simulation results phase order 2 is better if the minor/major road flow ratio is 1/5. The average delays are 0.3 – 2.4 s shorter than in phase order 1. The fuel consumption savings are 0.2 – 4.4 l/h, and the total emissions are 20 – 770 g/h lower.

If the minor/major road flow ratio is 1/2, then phase order 1 is slightly better. The estimated fuel consumption savings are 0.2 – 2.5 l/h. In some cases phase order 2 can be better, depending the balance of the measures of effectiveness. The simulated results of phase orders 1 and 2 with two minor/major road flow ratio are shown in Table 3.

5.2 Free right turn (or European right-turn-on-red)

"*Right turn on red*" (RTOR) was introduced over 60 years ago, but the use of RTOR has not been popular in Europe. The reason is that the accident potential is higher than in traditional control. One solution for the accidents could be the "Right turn on red after stop"-solution, which is used in some states in USA. The RTOR has become more popular in Finland, because the new planning methods with the separate turn lane have shown these kinds of new types of RTOR-solutions are not so accident risky. According to McGee (1976) the total delay savings for average right turner are

- 9 % in CBD-area
- 31 % in Urban area
- 39 % in Rural area.

The measured energy and emission results of the free right turn are shown in Table 4. The approach delays of these examples were 25 – 35 % smaller than the delays in intersections without free right turn. The percentage of stops was 15 – 25 % smaller.

The traffic volumes were measured, but the fuel consumption and emissions were simulated using HUTSIM.

According to the simulations, the daily savings are 8– 10 liters in Pasila and even 30 – 40 liters in Pitäjänmäki. The total amount of emissions is 1.5 – 2.0 kg smaller in Pasila and 7 – 8 kg smaller in Pitäjänmäki.

5.3 Additional turning traffic signals

One- or two-opening signals or additional turning traffic signals are used in urban areas as a RTOR-solution, but the permission for a green signal is given when there is no conflicting traffic. The savings and the effects are not so large as in the RTOR-solution, because the green signal (green arrow) is only additional green time for that signal group. The summary of the results is that the reduction of fuel consumption is 3 – 20 liters/day and the reduction of the total amount of emissions is 0.9 – 3.3 kg/day, if one- or two opening signals can be used.

6. Roundabout and environmental benefits

In order to study the possible positive effects of roundabouts, the case study was simulated in the semi-central urban area in Malmö, Sweden. Three different alternative intersection designs were tested by simulation [5]: A – Existing traffic signal intersection, B – Improved traffic signal intersection, C – Two-lane roundabout.

Tab. 4 – Results of free right turn in two intersections

	fuel consumption (l)	emissions (g)			
		CO	HC	NO_x	Total
Pasila klo 12.30pm-13.30pm	0,47	93,9	6,3	-10,4	89,8
Pasila klo 14.30pm-15.30pm	0,80	152,7	5,0	-20,2	137,5
Pitäjänmäki klo 7.30am-8.30am	3,0	653,0	72,6	-61,9	663,7

Tab. 5 – Comparison of three different intersection alternatives

		Delay	STOP %	Fuel	CO	NO	HC
	PEAK HOUR TRAFFIC	s	%	L/100 km	g/ veh.km	g/ veh.km	g/ veh.km
A	Signalized	30,7	77,4	12	17,7	1,9	3,3
B	Signalized (improved)	17,6	53,3	8,8	14,8	1,7	2,7
C	Roundabout	20,3	63,5	9,9	14,4	1,6	2,8
	DAY TRAFFIC						
A	Signalized	19,3	64	10,8	15,9	1,8	2,8
B	Signalized (improved)	13	46,7	9,7	13,9	1,7	2,4
C	Roundabout	11,3	29,6	8,3	11,3	1,3	2,1
	LOW-DEMAND TRAFFIC						
A	Signalized	18,3	54,5	10,8	15,8	1,8	2,7
B	Signalized (improved)	14,1	50,2	10,1	14,6	1,7	2,6
C	Roundabout	7,5	10,9	8,4	11,8	1,4	1,9

If only maximum capacity is interesting, the different alternatives could be studied only during the maximum hour flow. Emission calculations are more complex, and the emitted amount of exhaust pollution is dependent on both the total flow intensity as well as the vehicles' driving patterns. The driving patterns are flow intensity dependent and different for different times of the day. All three intersections are therefore also studied during the day-time and during the low-demand conditions. Results are presented in Table 5.

The table is showing, for a given vehicle flow, comparable figures for three different intersection alternatives. For the studied maximum flow hour, the best alternative is the improved traffic signal intersection, if both capacity and emission values are compared. For the traffic flow situation during the day traffic, the best alternative is the roundabout. Also for low traffic flow the roundabout is the best alternative.

These results show that the choice of best alternative of intersection design is a very difficult question. The driving behaviour and the vehicles' driving patterns change according to the different traffic situations. The drivers interact differently depending on the flow density and the vehicle composition in the flow, and it is therefore very difficult to predict the results. This is particularly valid for emissions, but in some extent also for the traffic flow parameters, if used models are sensitive to different driving patterns. As a summary of this test, we can say that the best capacity and efficiency solutions are not always best if air pollution aspects are also concerned. This fact is underlining the necessity of a total solution, where all aspects of traffic safety, capacity and environment are considered [11].

7. Traffic calming and environmental disbenefits

The application of humps for speed reduction is often used for safety reasons without considering the negative effects on the increased amounts of detrimental exhaust pollution. In our case study we had four different alternatives [4]:

1) No hump on the studied road length of 1500 m, i.e. constant vehicle speed.

2) One hump on the studied road length of 1500 m, i.e. a speed change approx. 50-30-50 km/h.
3) 10 humps on the studied road length of 1500 m, i.e. 10 speed decreases-increases 50-30-50 km/h.
4) 10 humps on the studied road length of 1500 m, but only one decrease 50-30 km/h in the beginning and one increase 30-50 km/h at the end and between those constant vehicle speed along the road length.

Tables 6 and 7 show the results of case study. In Table 6 the amounts of emissions for singular vehicles (vehicles without and with catalyst) passing the studied road length of 1500 m are given in g for the substances CO, NO and in ml for the fuel consumption. Table 7 shows a comparison between the different amount in Table 6 by mean of indices. Index 100 is given the emitted amount for a vehicle driving through the road length with constant speed.

The case study results show that the ambient air quality is getting worse if traffic calming devices, such as humps, are used. The calculations give only the emitted detrimental exhaust pollution from passing vehicles. We are not describing the immissions, i.e. the quantity of pollutant substances in the air after the dispersion process has taken place. But for infrastructural comparisons the emitted amounts give us the needed information.

8. Conclusions

The potential for energy savings and emission reductions vary along the urban roads. As well known, the energy (fuel) consumption as well as the detrimental exhaust emissions at intersections are much higher than at the links between. One of the reasons is that vehicles spend longer periods of time near intersections queuing, decelerating and accelerating and the other is that the transient operating modes themselves are generally more fuel consuming and more polluting than unobstructed cruising. Traffic intersections forces the traffic flow to slow down and stop in varying patterns of interruptions of the ideal constant traffic flow at an ideal traffic speed. The larger amount of stop is, and the longer time the stops last, the more fuel will be consumed and the worse the exhaust will be. The results of this study have shown fuel consumption reductions of 30 % in an intersection designed as a roundabout instead of using traffic signals. Environmentally optimised traffic control systems have proved an energy saving potential of 10 – 20 % in different cases. The results of paper indicate that the traffic intersection with its conventional design should be given a much higher attention in the discussion concerning potential energy saving and environmental remedy. The nodes must be given more than the present parsimonious exposition, and the possibilities of alternative intersection design and traffic control systems with energy saving potential must be taken in consideration. It is important to pay a lot more attention to the energy saving and environmental aspects at an early stage in traffic planning process.

Tab. 6 – The emission results of our case study

	A10 FUEL ml	A12 FUEL ml	A10 CO g	A12 CO g	A10 NO g	A12 NO g
ALT 1	161	177,7	15,1	0,4	1,2	0,2
ALT 2	169,2	184,2	16,9	0,5	1,4	0,2
ALT 3	242,9	243	32,4	1,1	3,8	0,5
ALT 4	223,7	221,4	23,1	0,4	1,1	0,2
	wthout catalyst	wth catalysta	wthout catalyst	wth catalysta	wthout catalyst	wth catalysta

Tab. 7 – The emission results of our case study by mean of indexes

	A10 FUEL ml	A12 FUEL ml	A10 CO g	A12 CO g	A10 NO g	A12 NO g
ALT 1	100	100	100	100	100	100
ALT 2	105	104	111	120	122	118
ALT 3	151	137	214	297	320	283
ALT 4	139	125	153	115	96	129

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