

The Impact of Traffic Flow on Fuel Consumption Increase in the Urban Environment

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Over 70% of the European population lives in urban areas. This puts pressure on urban transport systems, leading to increased environmental impacts. Such impacts are particularly large in cases where the traffic caused by vehicles with internal combustion engines is repeatedly braking and accelerating due to poorly planned traffic flow. We have evaluated an increase in fuel consumption in the real case of a road section in Celje caused by the difference in traffic flow between the “green” and “red” wave of traffic lights. Based on the obtained results, we are able to estimate the factor of pollution increasing caused by accelerating. By adding the estimates of pollution caused by braking, we get an overall picture of the importance of ensuring a steady flow of traffic to reduce pollution in urban environments.

Keywords: traffic flow, air pollution, PM_x particles, increased fuel consumption, green wave

1. INTRODUCTION

Air pollution is a serious problem, as it increases not only environmental, but also economic and health risks [1]. Ambient air pollution is not just a global, but also a Pan-European and especially a local issue. Pollutants released in one country can travel in the atmosphere of other countries and thus contribute to poor air quality far and wide [2].

Among the pollutants that affect human health most, the solid particles, known as PM particles, are also present in the atmosphere. Long-term and high exposure to these pollutants can cause problems in the respiratory system and thus premature death. Around 90% of the urban population in Europe is exposed to the pollution with PM particles the concentration of which is higher than the acceptable ambient air quality laid down by the EU [2]. The limit value for PM₁₀ is set by Directive 2008/50/EC. The daily limit value for PM₁₀ is 50 mg/m³, which means that the value of PM₁₀ in ambient air must not exceed the limit value more than 35 times in a calendar year. Cities as unique ecosystems are particularly problematic because the urban population represents more than 70% of the overall population, and the proportion constantly increases [3]. Urban areas produce a disproportionate amount of road traffic emissions compared to their geographic size, and should be a focus for efforts to mitigate such emissions [4, 5]. For this reason, very sharp environmental requirements are directed to the urban transport and transport systems and fuel consumption.

Increased fuel consumption is caused by heating up

the cold engine and by multiple acceleration and stopping of vehicles (especially at traffic lights). The problem of poor traffic management was well described already in the year 1984 in the contribution *Problems in the Urban Environment: Traffic Congestion and its Effects* of Ross Robinson, where the author emphasizes that one option to reduce congestion and consequently pollution are “new operating rules which ensure greater efficiency – coordinated traffic signals” [6]. As evidenced by Fernando et al., [7], nowadays we know that traffic congestion has significant detrimental impacts on the economy, environment and quality of life of the community.

In this paper, we distinguish between two types of transport challenges in the transport area which require different solutions:

- intra-urban transport and
- inter-urban transport.

In this article, we will focus on inter-urban transport, which is one of the key factors of pollution in modern urban areas. In inter-urban transport, we are faced with more pollution of vehicles per ridden distance than in intra-urban transport, mainly due to increased fuel consumption, tires wears and brake wears. The accelerating and stopping increase tire wear and brake wear. Solutions that are effective in the inter-urban environment, such as electric vehicles, do not perform effectively in the intra-urban environment with respect to the currently used technology.

In inter-urban transport, the movement of vehicles has negative impacts on health, and its omnipresence has great impact on a large part of the population. Pollution causes asthma and/or asthma exacerbation, deterioration of respiratory diseases (for example, inflammation of the respiratory tract causing a decline in lung function, lung collapse, etc.) [8]. The Working group of former Institute of Public Health [8] CEHAP conducted the study which shows that in three European

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countries (Austria, Switzerland and France) from 19.000 to 44.000 people die each year due to the effects of polluted ambient air. It is also found that about 6% of all deaths per year are attributable to exposure to ambient air pollution, which is twice as many as the number of traffic accident victims [8]. The main contributor to the release of pollutants in transport sector is road traffic. For the majority of contaminants, its share is greater than 80% [9].

Despite the fact that Slovenia is a specific country since it does not have a lot of urban areas, half of the employees in the country work outside their home municipality and thus they do a lot of traveling – often alone in their own cars, which are relatively easy to afford. This means that, regardless of the ridden distance, we are talking about intra-urban transport, which begins and ends mainly as inter-urban transportation. According to the Statistical Office of the Republic of Slovenia (SURSTAT), in 2014 there were almost 392,000 economically active citizens driving to work to another municipality, which represents almost 51% of the overall economically active population. The proportion of commuters (slightly) increases from year to year. In 2013, the number of economic migrants between municipalities increased by almost 8,700 people, while the number of employed persons whose workplace is in the municipality of residence was falling – at the end of 2014, there were slightly less than 378,000 or a little more than 49% of them. In 2014, the residents of Ljubljana were those who most often (in 84%) worked in the area of their municipality. This means that around 91,800 locals worked in Ljubljana, while the remaining 16% of them (about 17,100 people) was driving to work to another municipality [10,11].

In this article we will also focus on pollution caused by higher fuel consumption when starting at intersections. Statistical data on the increase of PM_x particles do not exist for starting like they do for braking [12,13]. Therefore, we will, based on real data traffic flows in a real road section, assess the increase in fuel consumption caused by each braking due to the effect of "red wave" (as opposed to "green wave") at lighted intersections. We can conclude that the relative increase in pollution by various pollutants, such as PM₁₀ particles, CO₂ and others in the case of "red wave" is even greater than the relative increase in fuel consumption caused by starting, because it is necessary to add the increase in environmental pollution due to braking, and consequently wear of the brakes and tires and the road itself (which is particularly harmful because of the composition of these particles), to the increased combustion due to acceleration [12].

The case research was conducted on the Mariborska road in Celje for which we collected data on road traffic flow. These data were later used in the calculation part of the paper. There are 14 traffic lights in the observation area. We observed the difference between the theoretical "green wave" when cars do not stop, and the "red wave" when cars stop at intersections - which means from 1 to 14 stops. In doing so, we assumed that along the entire length of the observation route the traffic is steady, which of course is not true – sometimes the traffic is heavy, sometimes it is light. We also assumed that the day for which we obtained the data is a typical day, and thus the obtained data apply to all days in the year, although we know that this is not true for Sundays and holidays. Moreover, we discussed only the traffic flow in the north-south direction and vice versa, and we did not take into account traffic on connecting roads. We wanted to show the amount of environmental burden of increasing fuel consumption at an intersection in a given direction on a given day. Although we know that the observed route is busiest in Celje, we also know that it represents only a fraction of the total traffic in the city.

The measurement results in a relatively small area (3,2 km of road) show significant differences in fuel consumption, which may reach more than 1,6 million liters of fuel annually between the "green" and the "red wave". This can be generalized to the wider urban area by appropriate multiplication.

The data used in the calculation are derived from our own measurements and from information obtained from individuals and companies.

2. METHODOLOGY

The area of our study is presented in Figure 1, which shows the 3,2 km long section of the Mariborska road in Celje. In the figure, the traffic lights are marked with numbers from 1 to 14 and the numbering starts at the exit of the highway in the northern part of the road.

The data on road traffic flow along the Mariborska road were obtained on the basis of the official road traffic counting data from the Directorate of RS for Infrastructure. Further, we distinguished between the same types of vehicles as considered by the Directorate in the counting of road traffic. These types are: personal vehicles, light, medium and heavy trucks, trucks with trailers, tractors, buses and motorcycles. In the subsequent calculating, it turned out that there was no significant difference between the trucks, trailers and tractors at starting and, consequently, consumption, so we merged them into one group.

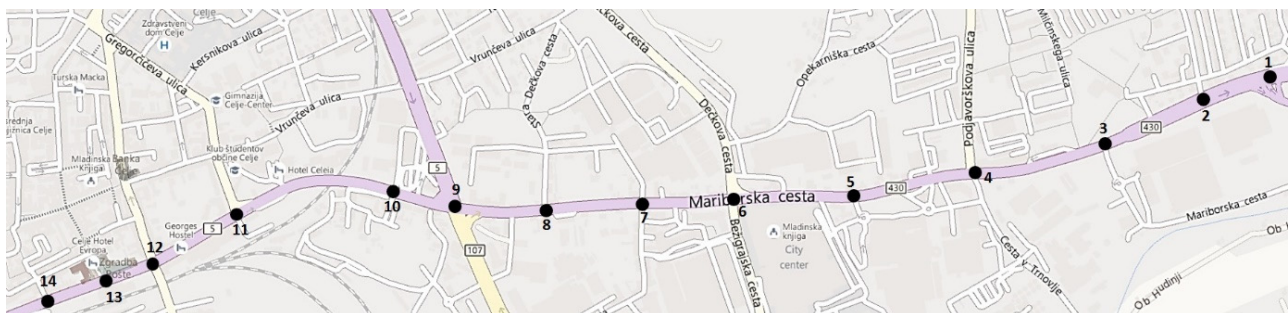


Figure 1. Sketch of the road with marked intersections [14]

Road traffic flow was represented on a typical day through the intersection number 4 in the north-south direction and vice versa, without taking into account the traffic on the roads that intersect the observed route. This flow was later generalized to all intersections throughout the whole year.

In the subsequent calculating we distinguished between petrol-driven and diesel-driven vehicles. Personal vehicles were divided according to the proportion of fuel as calculated by the SURS on the basis of the registration of the vehicles [15]. We assumed that all motorcycles were petrol-driven, while trucks and buses were invariably assumed to be diesel-driven vehicles. Other types of drives represent a negligible portion (e.g. 0,8% of cars).

In calculating fuel consumption, we assumed that the vehicles were driven in accordance with the regulations – their speed not exceeding 50 km/h. For each type of vehicle, average consumption data were measured or acquired. The table below (see Table 1) shows the acceleration time from 0 to 50 km/h measured for each type of vehicle. For personal vehicles, the consumption was taking into account the increased fuel consumption during accelerating from 0 to 50 km/h. Later, when further information was obtained, we found that the factor of this increase in consumption during the acceleration may also be applied to trucks and buses, but the acceleration time (and consequently the distance made by a vehicle) is longer. In the case of trucks, we witnessed the fact that the acceleration time varies greatly depending on the weight of the load.

Table 1. Average acceleration times up to the desired speed of 50 km/h and distances travelled during acceleration [16]

Type of vehicle	Average acceleration time from 0 to 50 km/h (sec)	Distances travelled during acceleration (m)
Cars	10.4	72
Light goods vehicles (< 3.5t)	12	83
Medium goods vehicles (3.5t – 7t)	14	97
Heavy goods vehicles (over 7t)	16	111
Trailer vehicles	18.5	128
Buses	15	104
Motorcycles	8.2	57

In our calculations we did not take into account potential multiple stoppings at the same intersection – we assumed that the vehicle definitely drove through the intersection, although in practice this is not always the case. It often happens that at the same traffic lights people repeatedly accelerate and brake. Our results are thus optimistic as the consumption is in fact higher than shown in this paper.

We presumed that the traffic flow along the entire road was steady, even though we knew that the flow might be heavy or light at intersections. Almost the entire route is a four-lane highway where traffic is steady, except at intersections number 12, 13 and 14

where it is light, and the road is a single-lane for each direction separately. We observed the traffic flow in the direction of marked intersections and the different levels of sub-optimum flow caused by waiting due to a poorly designed or even completely absent "green wave". At this stage of research, we did not evaluate the road traffic flow crossing the observed traffic directions at the observed intersections.

There is no direct link between the increased pollution (for example with PM10 particles) and the increased fuel consumption, but there is an assessment of increased fuel consumption for different numbers of acceleration and braking actions at those intersections. For the observed section, this increase in fuel consumption over a period of one year can be relatively easily expressed in terms of money, but in this moment, we do not know how much more PM10 particles are in the atmosphere due to the combusted fuel.

Also, we cannot tell how much more PM10 particles are in the atmosphere due to the stopping of vehicles, but it can be estimated that the PM10 particles increase by a factor as big as a factor defined by the increased consumption of the fuel. On the other hand, we know that smooth road traffic without braking does not create PM10 particles, which would have resulted from braking. For each action of braking we can assume that at least as many PM10 particles would be generated as due to acceleration. The assumption is based on the above mentioned research [12] and [13] which can be applied to inter-urban transportation.

For the measurements, we used different types of vehicles, the characteristics of which are described in the work report [16], and are briefly summarized below.

2.1 Cars

The data for cars were acquired by measurements of fuel consumptions obtained from observing average drivers from starting to achieve a speed of 50 km/h. They were driving average petrol and diesel-driven vehicles.

2.2 Light Goods Vehicles (< 3.5t)

This category includes light (small) trucks and vans. The time (t) needed by light goods vehicles to accelerate from 0 to 50 km/h was determined after timing and measuring the vehicles from Post of Slovenia d.o.o., which belong in this category. We were driving empty and loaded vehicles. It has to be taken into account that there are many differences between vehicles as regards the types of chassis, tonnage, volume, gearboxes (automatic, manual) and engines, which means that there are many differences between the measured times.

2.3 Medium Goods Vehicles (3.5t – 7t)

Also, in this case, the time needed by medium trucks to achieve the desired speed was measured on the vehicle of the selected company. These measurements were also made for loaded and empty vehicles. It should be noted vehicles with automatic gearbox respond noticeably quicker and reach the desired speed sooner.

2.4 Heavy Goods Vehicles (over 7t)

In this case, we have chosen the same metrics as in the previous two cases. It was possible to detect a marked difference in acceleration between an empty and loaded vehicle; there were also significant differences detected between vehicles with automatic and manual gearboxes.

2.5 Trailer Vehicles

The time needed by trucks with trailers to reach 50 km/h is the same as for tractors, as empty or loaded weigh about the same. Moreover, the employees of various logistics companies have confirmed that there is almost no difference between tractors and trucks with a trailer. As expected, the results are widely dispersed depending on the load to be carried (up to 40 tonnes).

2.6 Buses

The acceleration time was determined on the basis of conversations with bus drivers. It was necessary to take into account the differences between urban driving (inter-urban transport) and intercity buses (intra-urban transport), since city buses have standing places and thus accelerate slightly slower than intercity buses where there are seats only. Table 1 gives an average acceleration time between the mentioned types of buses.

2.7 Motorcycles

The category of motorcycles includes classic motorcycles, scooters, three-wheelers and four-wheelers. Vehicles from this category of engines represent only 0.5% per day on the Mariborska road, so the impact on the final results of this research is very small or insignificant [17]. As the vehicles in this category vary greatly (by acceleration, use, form...), we decided to choose a normal motorcycle with a capacity of 125 ccm as a model in accelerating for this category. Because of the small effect on the final results we did not use other motorcycles.

3. RESULTS

Average acceleration times up to the desired speed of 50 km/h and distances travelled during acceleration are shown in Table 1, while the comments on specificity are described below. All results are summarized in the work report [16].

3.1 Fuel Consumption during Acceleration

Average fuel consumption was calculated on the basis of monitoring the consumption during acceleration via computer in the car, conversations with professional drivers and the assessment of fuel consumption in different enterprises in different driving cycles. It was calculated as a quotient between consumption during acceleration and average fuel consumption.

The quotient is presented by the formula (1):

$$Factor = \frac{consumption_during_acceleration}{average_consumption} \quad (1)$$

It turns out that practically for all vehicles on our roads and in the standard driving mode this factor is 2.65. As we have seen, the difference is mainly in the duration of acceleration, which varies depending on the type of vehicle, and is already presented in Table 1. Thus, a personal car with an average consumption of 8,13 litres/100 km has a consumption of 21.8 litres/100 km during accelerating. Acceleration to 50 km/h takes 10.4 seconds during which the car travels 72 m. The average consumption is 0.0000813 litres/m, while consumption during acceleration is 0.0002158 litres/m. Table 2 shows all collected and calculated data for individual vehicle types, taking into account, of course, the factor of increased consumption, which is equal to 2.65 for all types of vehicles.

Table 2. Fuel consumption by individual types of vehicles [16]

Type of vehicle	Average consumption (l/m)	Consumption during acceleration (l/m)
Cars	0.0000813	0.0002158
Light goods vehicles (< 3.5t)	0.0001120	0.0002968
Medium goods vehicles (3.5t – 7t)	0.0001690	0.0004478
Heavy goods vehicles (over 7t)	0.0002350	0.0006227
Trailer vehicles	0.0003500	0.0009275
Buses	0.0002800	0.0007420
Motorcycles	0.0000400	0.0001060

3.2 Type and Number of Vehicles in an Average Day

Table 3 gives the number of vehicles for each type in an average day, while Figure 2 visualizes these data. The data were obtained from the Directorate for Infrastructure RS [17].

3.3 Calculations of Increased Consumption

The calculated increases in consumption for one vehicle in each category (see Table 1 and Table 2) were multiplied by the number of vehicles of each type on an average day (see Table 3). This value was then multiplied by the number of days in a year (365 days), and we got the final calculation of the annual consumption with different number of stoppings and accelerations (1-14 stops) for each type of vehicle separately. Finally we also separately calculated the consumption for petrol vehicles and diesel vehicles.

We presumed that traffic density was the same every day, although it is a fact that on Saturdays, Sundays and public holidays it is not the same as on weekdays. Thus, the actual annual density of road traffic was probably exceeded by more than 20%. On the other hand, we underestimated the actual number of times the vehicles accelerated or braked at traffic lights by at least the same percentage, assuming that whilst traffic lights are at red, the vehicle braked and accelerated only one time.

The fuel consumption in one year, based on the information obtained separately for petrol vehicles and diesel vehicles presents Figure 3. Figure 4 shows the difference between fuel consumption of vehicles driving with and without stopping.

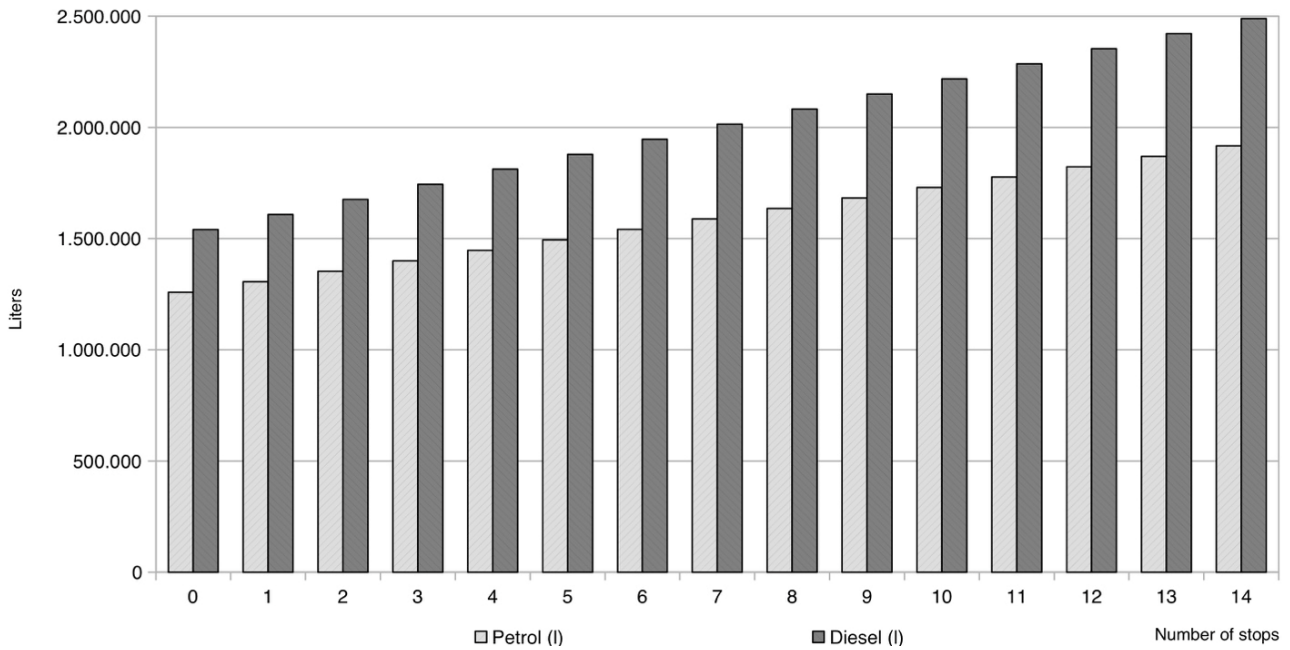


Figure 3. Total fuel consumption of all vehicles in one year [16]

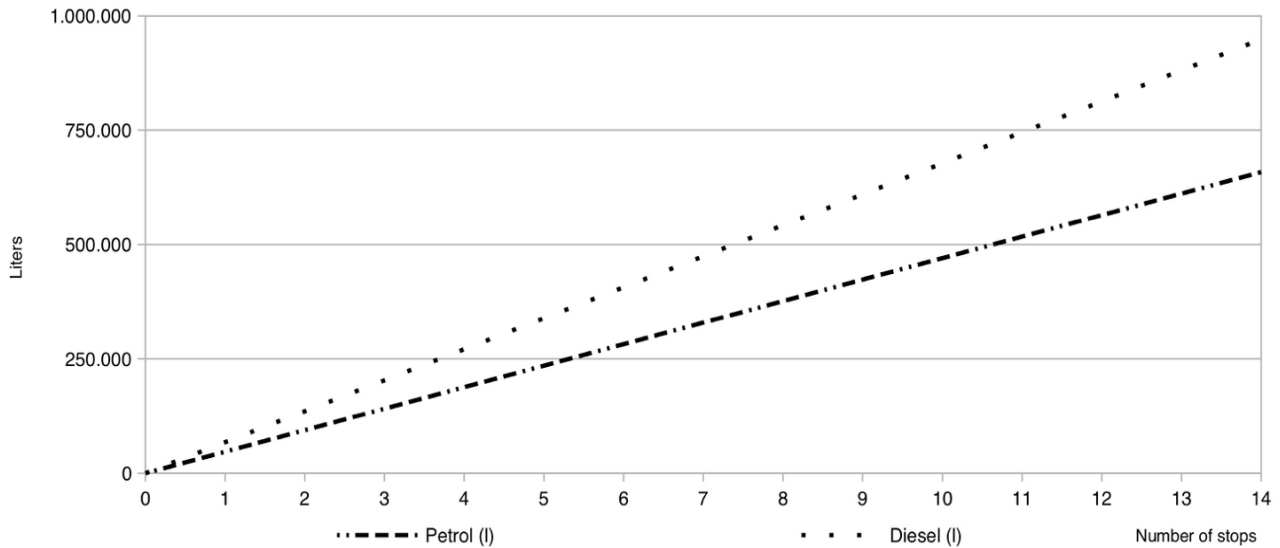


Figure 4. Graphical display of differences in fuel consumption of all vehicles together in one year with 15 stops [16]

The category of petrol-driven vehicles includes cars (57%) and motorcycles, while the category of diesel-driven vehicles may include cars (42,2%), buses and all kinds of trucks [15].

Table 3. The number of vehicles according to the type of vehicle in an average day [16]

Type of vehicle	Number
Cars	23.122
Light goods vehicles (< 3.5t)	1.746
Medium goods vehicles (3.5t – 7t)	397
Heavy goods vehicles (over 7t)	179
Trucks with trailer	134
Tractors	462
Buses	125
Motorcycles	120
All together	26.285

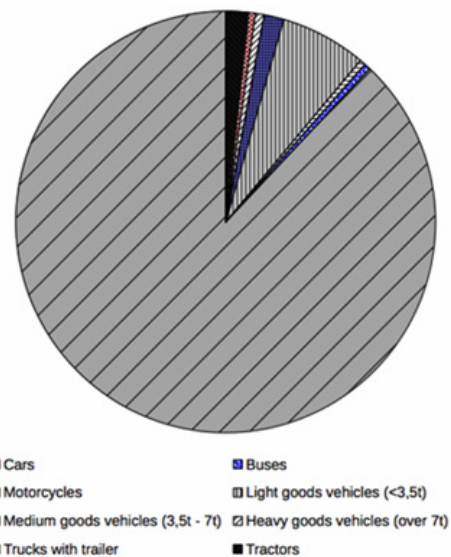


Figure 2. The average number of vehicles per day [16]

4. CONCLUSION

Sustainable urban mobility has been identified as one of the major challenges of the future [18]. Achieving this goal requires a move away from reliance on single-occupancy, fossil-fueled vehicles through a combination of development of new solutions, adoption of these solutions, and changes in people's everyday travel behavior [18] but in hand to hand with this process we need to create solutions for existing traffic.

It can be seen from the research that the flow of road traffic has an unexpectedly big impact on fuel consumption, and consequently also on the amount of PM10 particles. In the case of the Mariborska road in Celje, with 14 traffic lights at a distance of 3.2 km and thus 14 possible arrangements for travel on the route, it can be concluded that, at best, 2.8 million litres of fuel are consumed and, at worst 4.4 million litres. The difference is 1.6 million litres of fuel, which at the price of 1.2 euros/litre represents cca 2 million euros. This is a direct saving of money, although it relates only to fuel consumption. Of course, the cost of increased wear on the tires, brakes and damage caused by general jolts of powertrain of the car as a result of starting and braking should also be considered.

In addition to the direct costs due to increased fuel consumption, we should also take into consideration pollution, which manifests itself in an increase of noise and significant release of CO₂ and PM10 (includes also PM_{2.5} and PM₁) particles. A study on the increase in pollution due to increased CO₂ emissions and PM particles during acceleration will be carried out next year. The study will take into account the data from this study and the latest findings from the relevant literature. In doing so we distinguish between "gray" and "black" PM particles, and those PM particles which arise from braking. It is characteristic of gray particles that they spread in the atmosphere fairly evenly and extend far from their origin. Black particles are primarily derived from combustion of fuels in internal combustion engines and remain close to the place of origin (the road); as regards PM particles generated as a by-product of braking, we know for sure they are particularly dangerous to health due to their composition.

The study on the increase in pollution is the ultimate goal of our research, as on the basis of relatively short sections of the roads for which we have data on the structure and the number of vehicles, we can generalize the results of the increase in pollution to the whole city, under different fluidity policies of traffic flow conditions in the city. With the knowledge of the consequences of poorly planned traffic flow we are able to justify investments in new and better planned and less polluted traffic in our cities.

Nowadays, we know a few solutions which can contribute to better traffic city flow regardless of fact, that green flow in both directions at the same time is impossible. One of them is Adaptive traffic control systems (ATCSs), which aim to minimize stop times and delays in a bid to reduce traffic congestion in major urban areas. A large number and variety of ATCSs have been developed and researched using different control methods and structure to reduce travel times and con-

gestion [7]. The data collected via the induction loops is gathered within the local controller situated at each intersection which is then transmitted to a regional computer. The data is then analyzed and assessed by the regional computer in order to calculate the most appropriate cycle lengths, splits and offsets for the network of local controllers within vicinity of the regional computer.

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УТИЦАЈ ПРОТОКА САОБРАЋАЈА НА ПОВЕЋАЊЕ ПОТРОШЊЕ ГОРИВА У УРБАНИМ СРЕДИНАМА

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Више од 70% европске популације живи у урбаним подручјима. Тиме се врши притисак на урбане транспортне системе, па се повећава и њихов утицај на животну средину. Такви утицаји су посебно велики у случајевима понављања убрзања и кочења возила са СУС моторима, услед лоше испланираног протока саобраћаја. Извршена је процена повећања потрошње горива у реалним условима на деоници друма у Цељу, чији је узрок разлика у протоку саобраћаја између „зеленог“ и „дрвеног“ таласа на semaforu. Коришћењем добијених резултата може да се израчуна фактор повећања загађења изазваног убрзавањем возила. Додавањем процене повећања загађења изазваног кочењем добија се укупна слика значаја организовања равномерног протока саобраћаја у циљу смањења загађења у урбаним срединама.