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Environmental effects of driving behaviour and congestion related to passenger cars

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Abstract

Using Vito's on-board measuring system the influence of track, driving behaviour and traffic conditions on fuel consumption and emissions were studied for a small test fleet of passenger cars. City traffic resulted in the highest fuel consumption and emissions. Fuel consumption was about two times higher than for ring roads, which generally gave the lowest values. This was even more pronounced for emissions. Depending on road type and technology, fuel consumption increased with up to 40% for aggressive driving compared to normal driving. Again, this was more pronounced for emissions, with increases up to a factor 8. Driving behaviour had a greater influence on petrol-fuelled than on diesel-fuelled cars.Traffic condition also has a major effect on fuel consumption and emissions. For city driving intense traffic increased fuel consumption by 20–45%. The increase in fuel consumption and emissions during rush hours were the highest on ring roads, with increases between 10 and 200%. In absolute terms, a surplus of up to 5 l fuel per 100 km was measured. More environment-friendly route option requires the use of ring roads and motorways during rush hours instead of short cuts.

Keywords: On-board measurements; Emissions; Fuel consumption; Driving behaviour; Traffic conditions

1. Introduction

The EU15 energy demand for transport increased from 150 Megaton oil-equivalent (Mtoe) in 1975 to 270 Mtoe in 1995. Transport accounts for 30% of the final energy demand. When no measures are taken this will increase to 33% by 2020. From 1995 to 2020 transport will account for 45% of the incremental energy demand (Leydon, 1996). The EU15 road transport emissions increased by 10–30% from 1980 to 1990 (Stanners and Bourdeau, 1995; Leydon, 1996). Belgium and Flanders are not doing better than the EU15, as their car fleets seem to be the most important fuel consumers and air polluters (Van den Hende, 1998).

The results are even more distressing when taking into account aggressive driving and congested traffic. Under real driving conditions Katayama and Ayusawa (1993) determined an improvement in fuel efficiency of about 25–60% when vehicle speed increases from 10 to 20 km h^{-1}. Measurements in a traffic tunnel by Sjödin et al. (1998) showed that congestion leads occasionally to an increase in emissions by a factor 10 for the average fleet compared to smooth-flowing traffic at moderate speeds. All these studies show the importance of traffic and driving conditions for fuel consumption and emissions. As a result, Vito decided to carry out on-the-road measuring campaigns. In 1995, a first measuring campaign was performed to study the effect of driving behaviour on fuel consumption and emissions. Seven petrol-driven passenger cars were involved (De Vlieger, 1997a). Two more measuring campaigns (respectively 6 and 3 vehicles) were set up, taking driving behaviour and traffic conditions into account as influencing parameters. The findings of these two latest studies are discussed in what follows.

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Fig. 1. The VOEM on-board measurement system in a small passenger car.

2. Experimental aspects

2.1. On-board measurement system

A dedicated system for on-board monitoring has been developed at Vito. It is called Vito's on-the-road emission and energy measurement (VOEM) system. Fig. 1 shows VOEM in a small passenger car. This measurement system consists of a sampling system for the exhaust gases, the gas monitors, the fuel consumption, vehicle speed and lambda value monitors, the power supply, the data acquisition and processing system. The system is based on a new methodology (Lenaers, 1993, 1996) comparing it to its predecessors (Potter and Savage, 1982; Staab and Schürmann, 1987; Nelson and Groblicki, 1993; Grauer and Baumbach, 1993). Basically, the emission concentration measurements are combined with the total exhaust gas mass flow which is calculated from the fuel consumption and lambda value determination.

The measurement principles of the gas analysers are the same as those normally used in vehicle emission laboratories. Carbon dioxide (CO_2) and carbon monoxide (CO) are measured by non-dispersive infrared (NDIR) equipment, total hydrocarbons (HC) by a flame ionization detector (FID), and nitrogen oxides (NO_x) by a chemiluminescence analyser (CLA).

A dedicated piece of apparatus, the PLU 401-108, is used to measure the fuel consumption. It consists of a volumetric sensor and a supporting system. The sensor is accurate to within 1% in the range of $0.5\,l\,h^{-1}$ to $60\,l\,h^{-1}$. The measured volume flow together with the fuel density yields the mass flow. Accurate determination of speed and distance travelled is realised with an optical device.

The data acquisition and processing system handles on-line collection and real-time processing of the measured data. Emission values are determined in $g\,s^{-1}$ and $g\,km^{-1}$. Accuracies were estimated by comparative emission measurements on a chassis dynamometer (Lenaers, 1993, 1994). All errors were found to be below 10%, except in case of a diesel engine where errors were 20% for CO and 25% for HC.

The effective surplus weight of a car equipped with VOEM is roughly equal to that of two persons. This on-board measurement system can be fitted into any vehicle.

2.2. Test programme

Nine popular passenger cars, small as well as large-sized, were tested as received. Selection of these cars was based on information supplied by the Belgian Institute of Statistics and the car importers. Car details are given in Table 1. Most of the vehicles had a relatively low mileage. Except for the Ford Mondeo, the Volvo 850 and the Ford Galaxy, all engines were working under atmospheric pressure.

Mainly three road types were considered: urban driving, rural driving, ring road driving. The measurements for urban driving were performed in the centre of Brussels and Antwerpen. The total distance of the cross-town journey in Brussels was 6.2 km. The track consisted mostly of main roads and contained 23 crossroads all equipped with traffic lights. The cross-town track in Antwerpen consisted of main roads and smaller streets, all together 5.8 km of length. The total distance of the rural track located near Antwerpen and the ring road journey (3–4 lanes in each direction) around Antwerpen were each about 6 km.

The effects on the exhaust emissions were investigated for two types of driving behaviour: calm to normal driving and aggressive driving. Calm driving means anticipating other road users' movements, traffic lights, speed limits, and avoiding hard accelerations. Normal driving implies moderate acceleration and braking. By aggressive driving is meant sudden acceleration and heavy braking. Note that during all tests the national or local city (50 or $30\,km\,h^{-1}$), rural ($90\,km\,h^{-1}$) and ring road Antwerpen ($100\,km\,h^{-1}$) speed limits were respected.

The urban track in Brussels was driven during various traffic conditions: morning peak (7.30–8.30 AM), evening peak (4.00–6.00 PM), normal traffic situation and smooth-flowing traffic situation. The latter was driven on Sundays.

In Antwerpen, the journeys were driven during the morning peak (7.30–9.30 AM) and during normal traffic (10.00–12.00 AM).

The vehicles numbered 1–6 in Table 1 were measured in Brussels. For all these cars fuel consumption and CO_2 emission values were determined, and for cars 3 and 4 CO, HC and NO_x emissions were measured too. For each combination of vehicle/traffic conditions, four to eight tests were performed. All vehicles were driven by

Table 1
Overview of the tested passenger cars

No.	Model	Fuel	cc capacity (l)	Max. power (kW)	Cat[a]	Mileage (km)	Year of manufacture
1	VW Golf	Diesel	1.9	47	No	116,350	1993
2	Ford Mondeo TD	Diesel	1.8	65	No	4544	1995
3	Volvo 850 Tdi	Diesel	2.5	103	Oxycat	17,758	1995
4	Ford Fiesta	Petrol	1.3	44	TWC	8250	1995
5	Toyota Previa	Petrol	2.4	99	TWC	22,023	1995
6	Renault Laguna	Petrol	1.8	68	TWC	7876	1995
7	Renault Mégane	Petrol	1.4	55	TWC	15,470	1996
8	VW Golf	Diesel	1.9	47	No	64,840	1995
9	Ford Galaxy Tdi	Diesel	1.8	66	Oxycat	48,150	1996

[a]TWC = closed-loop controlled three-way catalyst; oxycat = oxidation catalyst.

Table 2
Average measured values in Antwerpen for normal driving behaviour under normal traffic conditions

Car no.	Road type	Speed ($km\,h^{-1}$)	FC[a] ($l\ 100\,km^{-1}$)	CO ($g\,km^{-1}$)	HC ($g\,km^{-1}$)	NO_x ($g\,km^{-1}$)
7	City	22.6 ± 1.6	12.1 ± 0.6	3.19 ± 1.1	0.24 ± 0.11	0.18 ± 0.02
	Rural	41.5 ± 1.7	8.9 ± 0.2	2.56 ± 1.1	0.22 ± 0.08	0.32 ± 0.10
	Ring road	78.2 ± 6.3	5.8 ± 0.4	1.38 ± 0.44	0.09 ± 0.02	0.04 ± 0.02
8	City	22.4 ± 0.6	9.3 ± 0.2	0.82 ± 0.04	0.13 ± 0.01	1.18 ± 0.08
	Rural	41.9 ± 2.8	7.2 ± 0.3	0.61 ± 0.05	0.12 ± 0.01	0.86 ± 0.09
	Ring road	81.8 ± 6.7	4.3 ± 0.2	0.32 ± 0.03	0.04 ± 0.01	0.56 ± 0.04
9	City	24.4 ± 1.7	10.3 ± 0.4	0.92 ± 0.38	0.12 ± 0.01	1.91 ± 0.30
	Rural	43.6 ± 3.0	8.3 ± 0.5	0.42 ± 0.14	0.08 ± 0.01	1.45 ± 0.25
	Ring road	87.1 ± 9.8	5.2 ± 0.2	0.20 ± 0.08	0.03 ± 0.01	0.54 ± 0.08

[a]FC = Fuel consumption.

the same motorist, who had a calm to normal driving behaviour.

The vehicles numbered 7–9 in Table 1 were measured in Antwerpen and its surroundings. CO, HC, NO_x and CO_2 emission values and fuel consumption rates were measured for these three cars. For each combination of car/road type/driving behaviour/traffic condition, four to six tests were performed. All test cars were driven by a calm to normal driver and an aggressive driver.

Both for Brussels as Antwerpen, emissions and fuel consumption values were determined starting with a warm engine.

3. Results and discussion

3.1. Influence of road type on fuel consumption and emissions

Table 2 gives an overview of the average measured speed, fuel consumption and emissions, together with the standard deviation, of the three cars measured in Antwerpen under normal driving behaviour and normal traffic conditions.

Table 2 shows that generally, city journeys resulted in the highest fuel consumption rates and emissions, ring road and motorway traffic gave the lowest fuel consumption rates and emission values. In city traffic fuel consumption was two times higher. Under similar city traffic conditions, the diesel-fuelled cars 8 and 9 resulted in lower fuel consumption, 23 and 15% less, respectively, compared to the petrol-fuelled car. The diesel cars also resulted in lower CO and HC emissions compared to the petrol car, but NO_x was higher. The effect of road type and driving behaviour on emissions are further illustrated for CO in Fig. 2.

The results of the petrol-fuelled car with TWC show some agreement with the results of a measuring campaign on seven petrol-fuelled cars in 1995 near VITO (De Vlieger, 1997a). For TWC cars the CO, HC and NO_x emissions decreased according to road type in the following order: city cold start, city hot start, rural road and motorway.

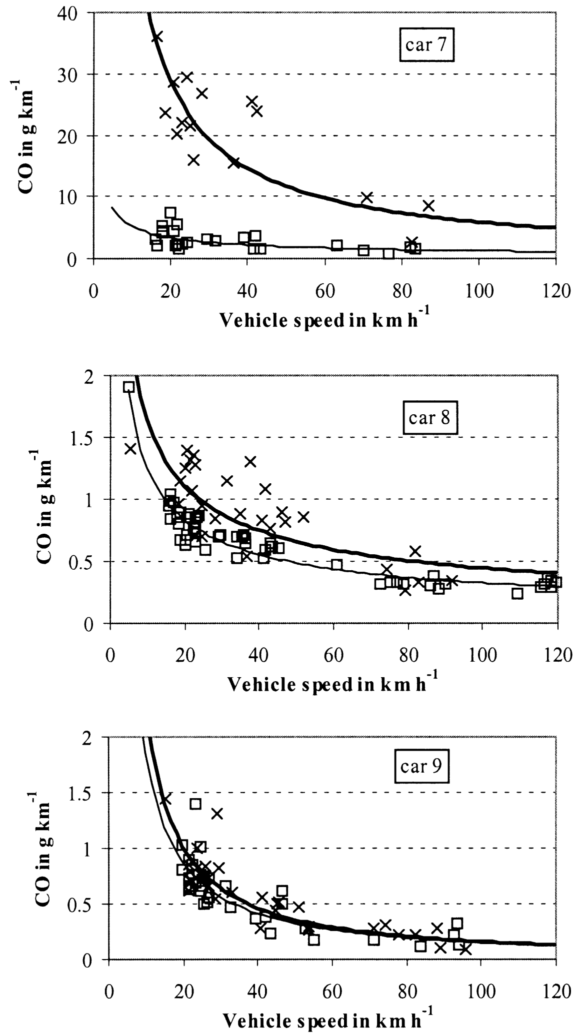

Fig. 2. Effect of driving behaviour on the CO emissions of each car measured in Antwerpen in 1997 (measured data: (□) normal driving, (×) aggressive driving; regression: (thin line) normal driving, (thick line) aggressive driving).

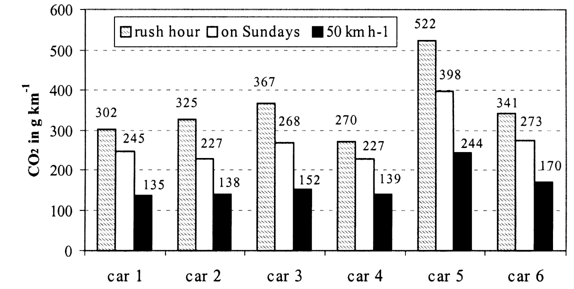

Fig. 3. Average measured CO_2 values for calm to normal driving behaviour under various traffic conditions in Brussels and at $50\,km\,h^{-1}$.

The steadier the traffic flow was, the lower the emissions and fuel consumption. For TWC cars the dynamic behaviour of the closed-loop emission control system resulted in high emissions under transient conditions.

For diesel cars and petrol-driven cars without catalyst, high NO_x emissions are due to a high flame temperature in the engine, arising during fast driving on ring roads and highways.

3.2. *Influence of driving behaviour on fuel consumption and emissions*

Ranges for average positive accelerations on city journeys, as normally defined in our measurement campaigns, are: $0.45–0.65\,m\,s^{-2}$ for calm driving, $0.65–0.80\,m\,s^{-2}$ for normal driving and $0.85–1.10\,m\,s^{-2}$ for aggressive driving.

Table 3 gives an overview of the average measured speed, fuel consumption and emissions of the three cars measured in Antwerpen under aggressive driving behaviour and normal traffic conditions.

Comparing Tables 2 and 3, one can see that the influence of aggressive driving behaviour was highest under city and rural driving. On the ring roads the effect was smaller due to the smoother traffic flow. However, in reality, the effect could be somewhat more pronounced for the ring roads, as within the measurement campaign drivers were asked to stay below the speed limits. In reality, an aggressive driver will go above these limits resulting in higher fuel consumption and emissions.

Aggressive driving resulted in a sharp increase of fuel consumption and emissions compared to normal driving. For the three measured cars, fuel consumption rose by 12–40% for an aggressive driver depending on road type and vehicle technology. CO emissions increased by a factor of 1–8 for the aggressive driver compared to the normal driver. For HC the increase in emissions due to aggressive driving ranged from 15 to 400%. Generally, for NO_x the emissions increased by 20–150%. These increases were due to the higher accelerations and speeds that occurred under aggressive driving conditions. The above results show that fuel consumption and emission rates are influenced by how dynamically the car is driven.

The effect of driving behaviour on emissions was highest for the technology that exhibited the highest baseline emissions. The increase in CO and HC emissions was below 50% for the diesel vehicles, whereas for the petrol car with TWC the increase was up to 700% for CO and 400% for HC. For NO_x the results were not so straightforward, but tended to imply a higher increase for the diesel cars than for the petrol cars. Fig. 2 illustrates the above findings for CO. Measured data as well as regression curves are plotted. These curves clearly show the difference between the emissions due to normal and aggressive driving behaviour. One has to notice that the

Table 3
Average measured values in Antwerpen for aggressive driving behaviour under normal traffic conditions

Car no.	Road type	Speed ($km\,h^{-1}$)	FC ($l\,100\,km^{-1}$)	CO ($g\,km^{-1}$)	HC ($g\,km^{-1}$)	NO_x ($g\,km^{-1}$)
7	City	23.7 ± 2.6	16.4 ± 1.5	24.7 ± 7.7	1.15 ± 0.31	0.28 ± 0.05
	Rural	40.2 ± 3.2	12.3 ± 0.4	21.6 ± 5.4	1.05 ± 0.10	0.24 ± 0.01
	Ring road	84.7 ± 3.1	7.3 ± 0.8	5.56 ± 4.13	0.20 ± 0.12	0.09 ± 0.01
8	City	23.1 ± 2.0	13.2 ± 0.5	1.01 ± 0.09	0.17 ± 0.03	1.86 ± 0.19
	Rural	45.8 ± 4.3	10.0 ± 0.7	0.83 ± 0.05	0.15 ± 0.02	1.37 ± 0.13
	Ring road	82.0 ± 6.3	5.1 ± 0.3	0.39 ± 0.12	0.05 ± 0.02	0.67 ± 0.06
9	City	26.3 ± 1.7	14.4 ± 0.5	0.86 ± 0.26	0.14 ± 0.01	4.51 ± 0.52
	Rural	43.5 ± 2.3	10.6 ± 0.5	0.46 ± 0.11	0.11 ± 0.02	3.05 ± 0.24
	Ring road	82.7 ± 8.8	5.9 ± 0.5	0.22 ± 0.09	0.04 ± 0.01	0.91 ± 0.19

uncertainty of emissions at average speeds lower than $20\,km\,h^{-1}$ is very high as only few tests were executed at these low speeds. For car 9 there is no significant difference in CO emissions for both driving behaviours. This is due to the low CO emissions of diesel cars and the presence of an oxycat.

Emissions of the petrol-fuelled car were relatively more affected by the driving behaviour than those of the diesel cars. This can be explained by the higher level of sophistication for the petrol car due to the dynamic closed-loop control of the lambda value.

The above results for the petrol-fuelled car show good agreement with the results of the measuring campaign in 1995 on seven petrol-driven cars (De Vlieger, 1997a). Whereas in city and rural traffic fuel consumption increased by 20–40% due to aggressive driving, on motorways the increase was only 7%. Compared to normal driving calm driving resulted in a small decrease (5%) in fuel consumption.

For TWC cars aggressive driving resulted in average CO emissions up to three times higher than those for normal driving. In the case of HC and NO_x, emissions were up to two times higher. For motorway driving the differences between normal and aggressive driving were much smaller (5–20%). Emissions for calm driving were always lower than for aggressive driving – in some cases up to a factor of 10. As for to CO and HC, the emissions for calm driving were also significantly lower than those for normal driving. NO_x emissions were comparable or higher depending on the vehicle tested.

3.3. *Influence of traffic conditions on fuel consumption and emissions*

In Brussels, average speed on the urban track in 1996 was about $13.5\,km\,h^{-1}$ during the evening rush hour, $16.5\,km\,h^{-1}$ during the morning rush hour and $23.5\,km\,h^{-1}$ on Sundays. Compared to the traffic on Sundays, the fuel consumption was 20–45% higher during rush hours. The same conclusions were obtained for CO_2 emissions, which are closely linked to the fuel consumption and the amount of carbon in the fuel. Fig. 3 gives the absolute CO_2 values of cars 1–6 under various traffic conditions and at constant speed of $50\,km\,h^{-1}$. During rush hours (at $13.5\,km\,h^{-1}$) CO_2 emissions doubled compared to driving at $50\,km\,h^{-1}$.

As expected, the exhaust emissions were higher during intense traffic. By way of illustration, the average measured emissions for car 3 during the evening rush hour were: 1.65 g CO km^{-1}, 0.52 g HC km^{-1} and 2.31 g NO_x km^{-1}. This is 80% higher than in smooth-flowing traffic (on Sundays) for CO and HC, and 50% for NO_x. The emissions during rush hours were even 10 times higher than when driving at a constant speed of $50\,km\,h^{-1}$ (De Vlieger, 1997b).

Table 4 gives an overview of the average measured speed, fuel consumption and emissions of the three cars measured in Antwerpen under normal driving behaviour and congested traffic conditions.

Tables 2 and 4 show that due to congestion, fuel consumption and emissions increased. In city driving, the emissions of NO_x for the petrol car and of HC for the diesel car could decrease during the rush hour. One has to note that the average speed for the Antwerpen city track differed little for normal and congested traffic. The increase in fuel consumption and emissions during the morning rush was highest on the ring road with a rise by 10–200%. In absolute terms, a surplus up to 5 l fuel per $100\,km^{-1}$ was measured. The impact of rush hours on the traffic conditions was the highest on the ring roads as average speed decreased from 80 to $25\,km\,h^{-1}$ and average accelerations increased from 0.19 to $0.33\,m\,s^{-2}$. City and rural driving were less affected by traffic conditions.

Low average speeds ($10–30\,km\,h^{-1}$) on ring roads resulted in lower fuel consumption and emission rates compared to the rate for city traffic moving with the same

Table 4
Average measured values in Antwerpen for normal driving behaviour under congested traffic conditions

Car no.	Road type	Speed ($km\,h^{-1}$)	FC ($l\,100\,km^{-1}$)	CO ($g\,km^{-1}$)	HC ($g\,km^{-1}$)	NO_x ($g\,km^{-1}$)
7	City	19.6 ± 2.2	13.1 ± 1.3	4.48 ± 1.44	0.28 ± 0.07	0.14 ± 0.01
	Rural	24.8 ± 6.9	10.8 ± 1.0	4.50 ± 2.05	0.32 ± 0.12	0.37 ± 0.05
	Ring road	19.0 ± 3.2	10.2 ± 1.0	2.23 ± 0.71	0.10 ± 0.02	0.04 ± 0.01
8	City	17.1 ± 1.0	10.4 ± 0.5	0.89 ± 0.09	0.11 ± 0.01	1.37 ± 0.17
	Rural	33.5 ± 3.0	7.6 ± 0.3	0.67 ± 0.07	0.09 ± 0.01	0.92 ± 0.06
	Ring road	23.2 ± 0.6	6.7 ± 0.3	0.75 ± 0.10	0.09 ± 0.02	0.75 ± 0.09
9	City	20.9 ± 1.3	10.7 ± 0.1	0.85 ± 0.13	0.14 ± 0.01	2.09 ± 0.24
	Rural	24.7 ± 2.3	9.6 ± 0.7	0.65 ± 0.11	0.10 ± 0.01	1.55 ± 0.15
	Ring road	25.7 ± 0.5	6.7 ± 0.6	0.64 ± 0.12	0.10 ± 0.01	0.66 ± 0.15

Table 5
Total fuel consumption and emissions of the Renault Mégane for two route options

Route (length)	Traffic condition	Travelling time (min)	FC (l)	CO (g)	HC (g)	NO_x (g)
1 (35 km)	Normal	43	2.7	69	5.3	4.8
	Congested	103	3.8	112	6.6	5.2
2 (30 km)	Normal	49	2.8	80	6.7	8.9
	Congested	76	3.4	135	9.4	10

average speed. For the car 8 two traffic jams occurred with an average speed of about 5 $km\,h^{-1}$, this resulted in extremely high fuel consumption (17 and 18 $l\,100\,km^{-1}$) and emissions.

The above observations in Antwerpen were used to calculate the total fuel consumption and emissions of a car following two different routes. One (route 1) goes mainly over ring roads (20 km ring road, 10 km rural and 5 km city), the other (route 2) goes mainly over rural roads as short cuts (0 km ring roads, 25 km rural and 5 km city). Both routes start at the same place (house) outside the city and end at the workplace in the city for a typical commuter. Table 5 gives an overview of the results of both routes for car 7 under normal driving behaviour.

Table 5 shows that route 1 resulted in lower emissions than route 2 for both traffic conditions. When average speed is higher than 10 $km\,h^{-1}$ at rush hours, commuters must be stimulated to take ring roads, because travelling time and fuel consumption may increase, but emissions are lower. Under normal traffic conditions the travelling time is lower on the ring roads, so the commuter will take this trajectory of his own. Similar findings were found for the diesel and turbo diesel car. These findings have to be taken with some caution, as only three cars were measured and calculations were done for only two specific route options.

4. Conclusions

Car mobility increases annually, resulting in more congested traffic. Furthermore, aggressive driving is becoming a more common way of driving in today's traffic. So far, a well-defined correlation between driving behaviour and traffic jams on one hand and fuel consumption and emissions on the other hand has not been established. However, our measurements in Brussels and Antwerpen on a range of passenger cars show the major impact of driving behaviour and traffic conditions.

Compared to normal driving aggressive driving can increase fuel consumption by 40% and emissions by a factor 8. Driving behaviour had a greater influence on petrol-fuelled cars with TWC than on diesel-fuelled cars.

Traffic conditions also have a major effect on fuel consumption and emissions. The increases in fuel consumption and emissions during rush hours were highest on ring roads, with an increase by 10 to 200%. Furthermore, more environment-friendly route option could require the use of ring roads and motorways also during rush hours instead of short cuts, even with a sometimes longer travelling time and sometimes higher fuel consumption.

One has to notice that the conclusions are based on a small test fleet of relatively low-mileage cars. Although popular cars were tested more verification for the overall Belgian passenger car fleet is needed.

Generally, fuel consumption and emissions are the highest during city traffic irrespective of driving behaviour and traffic conditions.

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