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Independent driving pattern factors and their influence on fuel-use and exhaust emission factors

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Abstract

This study is aimed at finding independent measures to describe the dimensions of urban driving patterns and to investigate which properties have main effect on emissions and fuel-use. 62 driving pattern parameters were calculated for each of 19 230 driving patterns collected in real traffic. These included traditional driving pattern parameters of speed and acceleration and new parameters of engine speed and gear-changing behaviour. By using factorial analysis the initial 62 parameters were reduced to 16 independent driving pattern factors. Fuel-use and emission factors were estimated for a subset of 5217 cases using two different mechanistic instantaneous emission models. Regression analysis on the relation between driving pattern factors and fuel-use and emission factors showed that nine of the driving pattern factors had considerable environmental effects. Four of these are associated with different aspects of power demand and acceleration, three describe aspects of gear-changing behaviour and two factors describe the effect of certain speed intervals.

Keywords: Driving pattern factors; Emission factors; Fuel consumption; Gear changing; Power demand

1. Introduction

Driving pattern affects the emission and fuel-use of vehicles together with other variables such as vehicle, engine and fuel types. Driving pattern is generally defined as the speed profile of the vehicle, but can be expanded to include other parts of driving behaviour, such as gear changing. The concept of driving pattern does not normally include trip generation, choice of travelling mode or route choice. The latter factors are of great importance for the emission and fuel-use and they should generally be included in any holistic analysis of the environmental impact. A model for vehicular emissions and fuel consumption is presented in Fig. 1.

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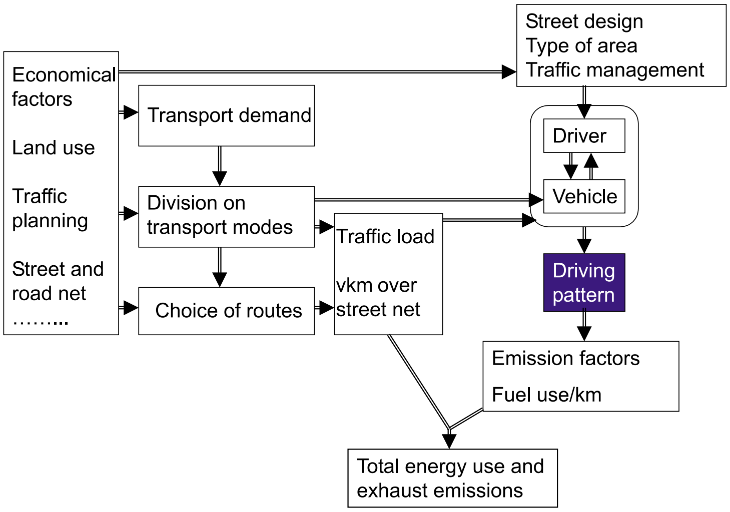

Fig. 1. Model describing factors that affect the amount of vehicular energy use and exhaust emission.

Newman and Kenworthy (1984) drew attention to the "abuse of driving pattern research" when researchers, planners and decision makers draw conclusions on an overall planning level from results gained on a detailed micro-level. Thus, comparing the emission factors of vehicles in traffic jams to that in smoothly flowing traffic has motivated the expansion of roads in urban areas. This expansion is closely related to the general trend of increasing urban sprawl, which leads to more car trips and higher traffic loads and, finally, higher emission and fuel-use. Yet, the criticism of driving pattern research is concerned more with how the results are interpreted and applied than questioning the need for more knowledge. According to Cost 319 (1999) action driving pattern research in general and especially studies in various countries are of high priority to gain a better geographical representation of driving behaviour.

Driving patterns can been described by many parameters; average speed being the most common. Kuhler and Karstens (1978) introduced a set of 10 driving pattern parameters: average speed, average driving speed (excluding stops), average acceleration (for all acceleration phases when $a > 0.1$), average deceleration (for all deceleration phases when $r < -0.1$), mean length of a driving period (from start to standstill), average number of acceleration–deceleration changes (and vice versa) within one driving period, proportion of standstill time ($v < 3$ km/h, $|a| < 0.1$ m/s^2), proportion of acceleration time ($a > 0.1$ m/s^2), proportion of time at constant speed ($|a| < 0.1$ m/s^2), and proportion of deceleration time ($a < -0.1$ m/s^2). These criteria were used to compare driving cycles, i.e., standardised driving patterns used to test vehicle emission and fuel consumption in laboratories. André (1996) reviewed the parameters used to characterise driving patterns and driving cycles. He found that the most common parameters were duration, average speed, acceleration standard deviation, positive kinetic energy, idle period, number of stops per kilometre, running speed (excluding stops), average values of speed, acceleration and deceleration, average duration of running periods, the number of acceleration and deceleration shifts and relative and joint distribution of speed, acceleration and deceleration. Fomunung et al. (1999) used variables representing surrogates for inertial power (acceleration × speed) and drag power (acceleration × speed^2) in a model for NO_x emission. Ericsson (2000a) used a set of 26 driving pattern parameters divided into level measures, oscillation measures and distribution measures to characterise different properties of driving patterns.

Many of the parameters that have been used to model emissions and fuel consumption are probably correlated in real traffic. The inclusion of many correlated driving pattern parameters in such a model will induce several problems: the effects will be difficult to present in a condensed way, will be difficult to estimate, and if effects can be estimated, they will be difficult to interpret correctly. The effect of one parameter may in reality be cancelled out by that of another parameter correlated to the first having the opposite effect.

The aim of this study was to find independent measures describing the properties of driving patterns and to investigate which of them has main effect on emission and fuel consumption per kilometre. A set of 19 230 driving patterns from real-traffic urban driving was examined in three steps. In step 1, the driving patterns were described using 62 parameters. 44 parameters were used to describe the occurrence, frequency and levels of speed and acceleration/deceleration of the driving patterns, and 18 parameters were used to describe the engine speed and choice of gears. In step 2, factorial analysis was performed on all 62 parameters to explore the underlying properties or *factors* that summarise driving patterns. Here, the 62 initially calculated parameters were reduced to 16 independent factors, each describing one dimension of the driving pattern. In step 3 the emission and fuel-use factors were calculated for the driving patterns of the Volvo and of the VW Golf, consisting of a subset of 5217 cases. The driving patterns of these cars were chosen because calibrated emission models were available for these two car models. Both emission models use a mechanistic approach and are designed to simulate the forces that influence the car and the resulting effect on the emission and fuel consumption. The detailed speed profiles of the models in addition to the engine speed and gear level are used as vehicle input variables. Using regression analysis, the relation between the 16 factors describing the driving patterns, on the one hand, and the emission and fuel-use factors, on the other, was examined. Nine of the 16 factors were found to have considerable effect on emission and/or fuel consumption per kilometre.

2. Driving patterns of ordinary drivers in real traffic

2.1. Collection of data

Driving patterns were studied in an average-sized Swedish city. Data representing 2550 journeys and 18 945 km of driving were collected using five passenger cars of different sizes and performances specially equipped with data-logging systems. The car models were Volvo 940, Ford Mondeo, WV Golf, Toyota Corolla and VW Polo. The cars were used for normal daily driving by 30 [1] randomly chosen families in the city of Västerås, Sweden, for two weeks each. Each family borrowed a measuring car of the same size and performance as their ordinary car. An enquiry among the participating families revealed that about 45 different subjects had driven the cars. The study was carried out in co-operation between the Swedish National Road Administration and the Department of Technology and Society, Lund Institute of Technology.

[1] The measuring equipment failed during one of the measuring periods which left out data from 29 families.

Table 1
Parameters recorded in the data-logging system of the cars

Parameter	Unit	Measuring frequency (Hz)
Wheel rotation[a,b]	RPM[c]	10
Engine speed[b]	RPM	10
Ambient temperature[b]	°C	1
Position[b]	Position co-ordinates	2
Use of brakes[b]	Brake lights on/off	10
Fuel-use[d]	ml/s	10
Engine inlet air temperature[d]	°C	1
Engine water temperature[d]	°C	1
Exhaust temperature before catalyst[d]	°C	1
Exhaust temperature after catalyst[d]	°C	1
Oxygen content in exhaust[d]	Volt (lambda sensor)	10
Throttle angle[d]	Volt	10
Mass air flow sensor[d]	Volt	10

[a] Parameters that were registered in all five cars.
[b] Wheel rotation was the basis for vehicle speed via wheel circumference.
[c] Revolutions per minute.
[d] Parameters that were registered in two of the cars: the VW Golf and the Ford Mondeo.

Vehicle speed, engine speed and ambient temperature were logged in all cars. For two of the cars, the VW Golf and the Ford Mondeo, a set of engine parameters was also registered (see Table 1). All cars were equipped with global positioning system (GPS) devices that logged the position of the car during each trip. Rototest AB, a Swedish consultant company, developed the equipment and installed the devices in the cars. Further details on the investigations are presented in Johansson et al. (1999a), and Ericsson (2000b).

Engine data from the VW Golf and the Ford Mondeo were collected for the development of instantaneous emission models.

2.2. Localising driving patterns to the correct street

GPS data were entered into the GIS tool Arcview where each driving pattern was attributed to street type, street function, street width, traffic flow and codes for location in the city (central, semi-central and peripheral) (see Table 2). Driving patterns were divided into subsections by cutting the driving pattern when any of the attributed values describing external conditions changed. Thus, the driving patterns could be divided and grouped into different categories depending on the external conditions. The division of the driving patterns resulted in 19 230 cases with corresponding external conditions. The driving patterns were given codes for driver characteristics and type of car. The categories used for coding and dividing the driving patterns are listed in Table 2.

A map-matching procedure was developed to locate logged driving patterns to the right street and to provide them with the attributes of street type, etc. [2] The issue was problematic as no

[2] The map-matching programme was developed by visiting Professor Henrik Edwards and experts from GIS Centre at Lund University, especially Dr. Petter Pilesjö.

Table 2
Codes attributed to each driving pattern[a]

Grouping variable	Groups
Street function	(1) Thoroughfare (2) Radial arterial road (3) Collector street (4) Local street
Street type	(1) Motorway (4 lanes, flyover intersections) (2) Road with > 3 lanes and a central reserve (3) Street > 10 m no central reserve (4) Street < 10 m, two lanes
Type of environment	(1) Residential (2) Industrial (3) Other
Location in city	(1) Central (2) Semi-central (3) Peripheral
Street width	3–25 m
Speed limit (km/h)	(1) 30 (2) 50 (3) 70 (4) 90
Traffic flow	ADT
Vehicle size	(1) Large > 1340 kg (2) Medium between 1050 and 1340 kg (3) Small < 1050 kg
Vehicle mass/effect (performance)	(1) High > 0.07 (2) Medium between 0.06 and 0.066 (3) Low < 0.049
Driver's age	(1) 18–25 (2) 25–35 (3) 36–59 (4) 59
Driver's gender	(1) Female driver[b] (2) Male driver[b] (3) Mixed[b]

[a] Driving patterns were divided based on the 11 grouping variables.
[b] If the car was driven 75% or more by a woman the driver was defined female, 75% or more by a man the driver was defined as male, otherwise the driver category for gender was defined as "mixed".

standard method was available and the development of a map-matching method took several man-months. The principles used will be reported in a forthcoming paper.

In this study, only driving patterns that originated from the developed area of Västerås, see Fig. 2, were included since the aim was to study urban driving patterns.

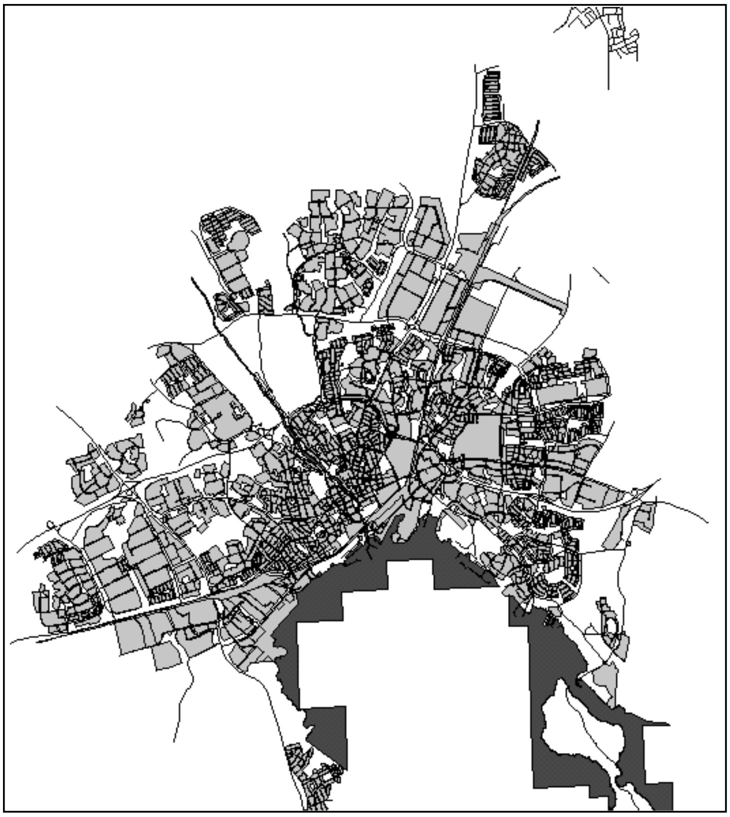

Fig. 2. Map showing the street net of Västerås, where the driving patterns of this study were collected.

2.3. Driving pattern parameters

The speed and acceleration profiles were estimated from measured data according to a methodology presented by Bratt and Ericsson (1999). This method estimates the acceleration profile from measured speed data while minimising the variance and bias of the estimation. For each driving pattern, 62 parameters were calculated. The parameters measure different aspects of driving patterns such as levels and distributions of speed, acceleration and deceleration, occurrence of stops, the amount of oscillation of the speed curve and parameters acting as surrogate variables for vehicle power as in Fomunung et al. (1999), Grant (1998) and Weijer van de (1997), e.g., RPA and speed $\times$ acceleration. Furthermore, 18 parameters were added describing the engine speed and distribution of different engine speeds when driving in different gears. The parameters are listed in Table 3.

2.4. Extraction of independent driving pattern factors – factorial analysis

Generally, factorial analysis is used (1) to *reduce* the number of variables and (2) to *detect structure* in the relationships between variables, that is, to *classify variables* (Statsoft, 2000). The

Table 3
The driving pattern parameters that were calculated for each driving pattern

Driving pattern parameter	Denotation
Average speed	V_AVG
S.D. of speed	V_STD
Average acceleration	A_AVG
S.D. of acceleration	A_STD
Average deceleration	R_AVG
Deceleration S.D.	R_STD
Number of acceleration/deceleration shifts per 100 m where the difference between adjacent local max-speed and min-speed was > 2 km/h	MM_100M
Number of acceleration/deceleration shifts per 100 m where the difference between adjacent local max-speed and min-speed was > 10 km/h	LMM_100M
Number of acceleration/deceleration shifts per 100 s where the difference between adjacent local max-speed and min-speed was > 2 km/h	MM_100s
Number of acceleration/deceleration shifts per 100 s where the difference between adjacent local max-speed and min-speed was > 10 km/h	LMM_100s
Relative positive acceleration: $1/x \int va^{+}\,dt$, $x =$ total distance	RPA
Integral of the square of the acceleration :$1/n \int a^2\,dt$, $n =$ no time steps	Int_a2
% of time when speed < 2 km/h	PC_STOPT
Average stop duration	STOPDURA
Number of stops per kilometre	STOP_PKM
% of time in speed interval 0–15 km/h	v0_15
% of time in speed interval 15–30 km/h	v15_30
% of time in speed interval 30–50 km/h	v30_50
% of time in speed interval 50–70 km/h	v50_70
% of time in speed interval 70–90 km/h	v70_90
% of time in speed interval 90–110 km/h	v90_110
% of time in speed > 110 km/h	v110_200
% of time in deceleration interval (−10)–(−2.5) m/s^2	r100_25
% of time in deceleration interval (−2.5)–(−1.5) m/s^2	r25_15
% of time in deceleration interval (−1.5)–(−1.0) m/s^2	r15_10
% of time in deceleration interval (−1.0)–(−0.5) m/s^2	r10_05
% of time in deceleration interval (−0.5)–(0) m/s^2	r05_0
% of time in acceleration interval 0–0.5 m/s^2	a0_05
% of time in acceleration interval 0.5–1.0 m/s^2	a05_1
% of time in acceleration interval 1.0–1.5 m/s^2	a1_15
% of time in acceleration interval 1.5–2.5 m/s^2	a15_25
%− of time in acceleration interval 2.5–10 m/s^2	a25_100
Average engine speed	RPM_AVG
Engine speed S.D.	RPM_STD
% of time with engine speed 0–1500 rpm	RPM0_15
% of time with engine speed 1500–2500 rpm	RPM15_25
% of time with engine speed 2500–3500 rpm	RPM25_35
% of time with engine speed > 3500 rpm	RPM35_99
% of time in gear 2 with engine speed 0–1500 rpm	G2_R0_15
% of time in gear 2 with engine speed 1500–2500 rpm	G2_R15_25
% of time in gear 2 with engine speed 2500–3500 rpm	G2_R25_35
% of time in gear 2 with engine speed > 3500 rpm	G2_R35_99

Table 3 (*continued*)

Driving pattern parameter	Denotation
% of time in gear 3 with engine speed 0–1500 rpm	G3_R0_15
% of time in gear 3 with engine speed 1500–2500 rpm	G3_R15_25
% of time in gear 3 with engine speed 2500–3500 rpm	G3_R25_35
% of time in gear 3 with engine speed > 3500 rpm	G3_R35_99
% of time in gear 4 with engine speed 0–1500 rpm	G4_R0_15
% of time in gear 4 with engine speed 1500–2500 rpm	G4_R15_25
% of time in gear 4 with engine speed 2500–3500 rpm	G4_R25_35
% of time in gear 4 with engine speed > 3500 rpm	G4_R35_99
% of time in gear 5 with engine speed 0–1500 rpm	G5_R0_15
% of time in gear 5 with engine speed 1500–2500 rpm	G5_R15_25
% of time in gear 5 with engine speed 2500–3500 rpm	G5_R25_35
% of time in gear 5 with engine speed > 3500 rpm	G5_R35_99
Positive kinetic energy, PKE: $(\sum(v_f^2 - v_s^2))/x$, when $\mathrm{d}v/\mathrm{d}t > 0$	PKE
v_f = final speed, v_s = start speed, x = distance	
% of time when $(va) < 0$	va_0
% of time when (va) is 0–3	va0_3
% of time when (va) is 3–6	va3_6
% of time when (va) is 6–10	va6_10
% of time when (va) is 10–15	va10_15
% of time when (va) is > 15	va15_99
Average (va)	va_avg

basic idea is to combine two or more correlated variables into one factor. These "principal components" are extracted so as to minimise the variance around the new variables/factors and create factors that are not correlated. Thus, the new factors describe the independent dimensions that vary over the investigated phenomenon, in this case the driving pattern. The connection between variables and factors is described by *factor loadings*. These loadings have a value between 0 and 1, 0 indicating a low degree of connection between the variable and the factor, and 1 that the variable and the factor are totally connected.

A large number of driving pattern parameters are used to guarantee that the different characteristics of the driving pattern are covered. However, when using many parameters it is likely that some of them will be correlated. In this study, one of the aims was to obtain a detailed description of driving patterns using a set of independent measures, i.e., to take into account the correlation between parameters that occur in real traffic. The sample size of 19 230 urban driving patterns, which originated from the whole street network and included about 45 drivers, was assumed to cover a variety of driving conditions and driving styles.

The factorial analysis was performed using the software SPSS for Windows version 10.0. The general settings were extracted by the factors using "Principal component method", extracting eigenvalues over 1, and rotating the axis in the original variable space according to the *Varimax method* (this method maximises the variability of the new variable/factor while minimising the variance around the new variable (Statsoft, 2000)). Factor scores, i.e., the estimated value of the factors for each driving pattern, were calculated and saved as a new variable. Driving pattern parameters according to Table 3 were used as input data/variables in the analysis. To avoid too high a degree of linear dependence within the matrix, four parameters were excluded from the analysis:

(1) percentage of time between 30 and 50 km/h,
(2) percentage of time with acceleration between 0 and 0.5 m/s^2,
(3) percentage of time with engine speed 2500–3500 rpm,
(4) percentage of time when *va* was 0.3 m^2/s^3.

Each of these four parameters represents one interval in the speed, acceleration, deceleration and engine speed distributions used. The excluded interval overlapped the sample mean for that parameter, thus making the remaining variable indicators of deviations from average driving conditions. After the first run of factorial analysis it was found that the parameter average *va* (va_avg) loaded higher than 0.5 on more than one factor. The interpretation of this is that (average *va*) has a diffuse influence factor, which is why it was removed from the analysis. Besides this, the overall strategy was to include as many of the original parameters as possible in the analysis and study if they contributed to the estimation of any of the factors. Parameters that only had small loading on several factors, as for example average speed, were retained in the analysis since the principal aim with the factorial analysis was not data reduction but to obtain a set of independent factors that could describe the properties of the driving patterns with high explanatory power.

Factor analysis has been accused of being a rather unstable method. Factorial analysis was performed in an earlier study, Ericsson (1999), but the method was abandoned because the results were found to be very sensitive to small changes in the input variables. However, Barcikowski and Stevens (1975) and Huberty (1975) found that the calculated coefficients are rather unstable unless the number of cases is fairly large, at least 20 times more cases than variables. In this study, with 19 230 cases and 62 variables, it was found that the sample size was sufficiently large to give rather stable results. Tests were performed when excluding different sets of variables, but approximately the same factors resulted. The analysis resulted in 16 independent factors that could replace the original 62 parameters.

2.5. Calculation of emission and fuel consumption factors

The second aim of this study was to investigate which independent driving pattern factors had significant effects on the emission and fuel consumption in urban driving. Only cars equipped with catalysts were used in this study as more than 73% of Swedish light-vehicle mileage is driven with petrol catalyst cars (Swedish National Road Administration, 1999). Emission factors were calculated for the VW Golf and the Volvo 940, which together formed 5217 cases. For the VW Golf the emission and fuel consumption factors had been calculated by Rototest AB using an emission model developed in 1999 (Johansson et al., 1999a). Rototest AB is a Swedish consultant company that was funded by the Swedish National Road Administration to develop an instantaneous emission model including transient effects based on the engine parameters of the VW Golf in this project. The model has not yet been validated. The other emission model, VETO, developed by the Swedish National Road and Transport Research Institute (originally Hammarström and Karlsson, 1987) was used for the Volvo 940.

VETO has been extensively used in Swedish investigations and has been validated against measured fuel consumption and exhaust emission data for another Volvo 940 [3] (Hammarström,

[3] The car in the validation study was a Volvo 940 GL while the car in the Västerås study was a Volvo 940 Turbo.

1999). The validation showed no significant biases for transient situations at ordinary driving cycles. The validation showed especially good agreement for fuel consumption and thus CO_2 emission. In the present study, VETO was extended to include measured engine speed and actual measured gear choice as input data in addition to the speed profile. The performance of the VETO model concerning measured and simulated speed profiles, engine speed and gear choice is demonstrated in Fig. 3.

The engine variables used in the two models varied somewhat. For example, lambda (air to fuel ratio in the exhaust) was included in the Rototest model while it was not in the VETO model. The effect of lambda on exhaust emissions and fuel consumption is different when the car is in the cold start mode compared with the case when the engine and catalyst have reached their normal operating temperature. Since the Rototest emission model includes lambda as an input variable but is not able to model the effect of cold starts, the driving patterns of the VW Golf for which the registered engine water temperature was < 70°C were excluded from the calculation of emissions and fuel consumption.

Hence, calculations were performed with two different mechanistic instantaneous emission models, one for each car. These models use the engine map and other vehicle parameters of a specified vehicle and model the performance of the engine and the emission control system while the vehicle is being driven according to a certain speed profile. Both the models also used the actual measured engine speed and gear-changing behaviour as input data. (Other models of this type normally use a standardised scheme for the gear-changing behaviour.) In Ericsson (2000b) it was found that different types of cars (e.g., cars with different performances) were driven differently by their owners. In the present study it was an advantage to be able to use an emission model that was developed for the same car model as the driving pattern originated from.

In this study, fuel-use factors (l/10 km) and three emission factors (g/km) were analysed. The emissions were hydrocarbons (HC), nitrogen oxides (NO_x) and carbon dioxide (CO_2). These three emissions represent pollutants which have serious effects on a local, regional and a global level. Traffic is one of the main sources of these kinds of pollutants. One vehicular emission compound

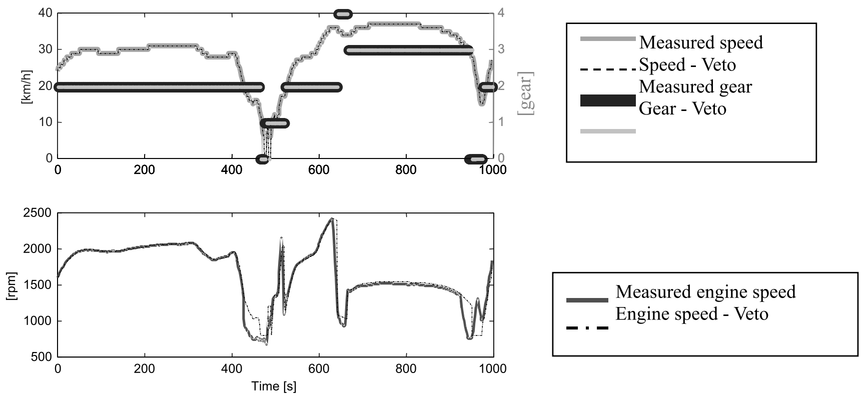

Fig. 3. Example of measured and simulated speeds, gear choice and engine speed for the instantaneous emission model, VETO.

not discussed in this paper is carbon monoxide (CO). The reason for this is that the VETO model is not properly validated for this compound and it was therefore decided not to include it in analysis. The CO_2 emission is linearly related to the fuel consumption.

2.6. Method for investigating the relation between driving pattern factors and emissions

To investigate which driving pattern factors had important influences on emission and fuel-use, a regression analysis was performed with emission and fuel-use factors as dependent variables and the 16 driving pattern factors as independent variables. The analysis was a straightforward linear analysis including all independent variables simultaneously.

Separate regression analyses were performed for the emission and fuel-use factors modelled by the VETO model and the Rototest model. The models gave similar but not completely congruous results. The regression models that used VETO emissions as dependent variable had generally higher explanatory power than the ones that used Rototest emissions. It is not clear whether the discrepancies are due to differences in the emission models or to the fact that driving patterns affect the emissions from different cars differently. Both factors probably contribute to the discrepancy since different cars react differently to the same driving conditions, and different emission models have different weaknesses. However, since the VETO model was validated against measured data, this model was used as the norm.

3. Reduction from 62 parameters to 16 independent factors

The factorial analysis extracted 16 factors from the original 62 driving pattern parameters. All factor loadings greater than 0.4 in the rotated component matrix are given in Table 4. The table shows which main parameters are combined in each factor and how much each parameter contributes to the factor.

The factors are combinations of 1–9 original parameters. Most factors include at least one loading greater than 0.7 but one factor, no. 14, has four parameters which are equally loaded (0.40–0.45). If the aim had been to reduce the number of factors as much as possible, factor 14 would probably have been left out. However, since the aim in this case was to identify as many variations using a set of independent factors as possible, it was retained in the analysis. For factors 15 and 16, there was only one parameter that loaded on each factor, which means that these parameters are essentially independent and represent separate, specific properties of the driving pattern.

Factorial analysis extracts a set of factors that can be used to describe the underlying properties of the phenomenon that is being investigated. For the results to be useful, however, one more condition should be fulfilled, i.e., the factors must be interpretable. If they cannot be interpreted, then the whole procedure is of limited use. In Table 5, an interpretation of each factor is presented. Each factor is described by a "typical parameter", usually the parameter that has highest loading on the factor.

The fact that the factors are independent, means that a driving pattern can have high or low values of any of the factors in combination. Consequently, a driving pattern may have high values of the factor for accelerations with strong power demand as well as of the factor for acceleration

Table 4
Rotated component matrix[a]

Original parameter	Factor															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
R_AVG	−0.93															
R_STD	0.84															
r25_15	0.81															
inta2	0.75					0.48										
r15_10	0.67															
V_STD	0.57													0.40		
R100_25	0.57															
RPM_STD	0.54															
r10_05	0.42															
RPA		0.81														
va10_15		0.80														
a10_15		0.79														
A_AVG		0.66				0.42										
a05_10		0.66			0.43											
va15_99		0.65														
PC_STOPT			0.93													
V0_15			0.88													
STOPDURA			0.74													
STOP_PKM			0.70											–		
V_AVG			–					0.43	0.46							
MM_100S				0.85												
LMM_100S				0.81												
LMM_100M			0.41	0.73												
PKE				0.68												
MM_100M			0.48	0.65												
va3_6					0.81											
va_0					–											
r05_0		–			–											
va6_10		0.49			0.52											
a25_100						0.73										
A_STD						0.55										
a15_25		0.48				0.51										
V15_30							0.69									
G2R0_15							0.59									
G3R0_15							0.52									
RPM0_15			0.46				0.48									
G5R25_35								0.84								
V90_110								0.77								
RPM_AVG																
V70_90									0.81							
G4R25_35									0.65							
G5R15_25									0.55							
G4R15_25										0.78						
V50_70										0.70						
G3R25_35											0.70					
G2R25_35											0.55					
rpm15_25											–					

Table 4 (*continued*)

Original parameter	Factor															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
RPM35_99												0.81				
G4R35_99												0.67				
G3R35_99												0.62				
G2R35_99											0.44	0.45				
G5R35_99													0.83			
v110_200													0.74			
G2R15_25														0.45		
g3r15_25														0.40		
G4R0_15															0.80	
G5R0_15																0.90

[a] Parameters with loading 0.4 on each factor.

with moderate power demand. This means that in this particular driving pattern there can be sequences of accelerations with very high power demand together with sequences with moderate power demand. Consequently, there may for example be combinations of moderate accelerations and heavy accelerations, of moderate engine speed at gear 2 and late gear changing from gear 2, etc.

4. Which driving pattern factors cause main effect on fuel-use and emissions?

A model for the prediction of fuel consumption and exhaust emissions for HC and NO_x was derived from the regression analysis. The explanatory variables are given in Table 5. The model is based on the emissions and fuel consumption of the Volvo 940. As described in Section 2.4 the most common interval in each distribution of speed, acceleration, deceleration and engine speed was removed before the factorial analysis. Consequently, acceleration with strong respective moderate power demand should be interpreted as measures that describe the way in which power demand differs from the most common state, i.e., acceleration with low power demand. At ‘‘normal’’ amount of high power demand the factor has a value around 0, when the high power demand is greater or lesser than the average factor has a value > 0 or < 0, respectively.

The values of the parameter B and the standardised B are given in Table 6. Standardised B gives the size of the effect (in S.D.s), if the driving pattern *factor* changes by one S.D.

The estimated model in Table 6 represents one car and one emission model. Since different cars emit differently and consume different amounts of fuel, and since emission models have uncertainties, the reported values of B in Table 6 should be used with caution.

To test the validity of the regression model in Table 6, a similar calculation was performed for the emission factors modelled with the Rototest model for the VW Golf. The two regression models did not give the same parameter values, which was not to be expected, but approximately the same driving pattern factors were found to have significant effects. Table 7 gives driving pattern factors with significant effects according to the VETO model, i.e., when the estimated parameter was significant and had an absolute value of standardised B of at least 0.1. Effects supported by only the VETO model are shown in parentheses. Thus, the regression based on the

Table 5
Interpretation of driving pattern factors extracted by the factorial analysis v = speed, a = acceleration (+)

Factor	Variables with high factor loading	Interpretation	Designation (new name)	Typical parameter
1	Average and S.D. of deceleration % of time in heavy deceration levels Integrated a^2 (increase if the speed profile curves)	The factor describes the amount of deceleration in the driving pattern and becomes high with much heavy deceleration and small with few, light deceleration	Decelaration factor	Average deceleration
2	Relative positive acceleration, RPA % of time when $va > 10$ % of time when a is between 0.5 and 1.5 m/s^2 Average acceleration (small loading) % of time when a 1.5–2.5 m/s^2 % of time when va 6–10 (small loading)	This factor collects measures that are connected to the existence of very high power demand which is also connected to acceleration. Thus the factor is high when the driving pattern includes a great amount of high power demand accelerations and low when sequences of high power demand are few	Factor for acceleration with strong power demand	RPA
3	% of time the vehicle has stopped ($v < 2$ km/h) % of time when speed is 0–15 km/h Average duration of stops Number of stops per kilometre A small negative loading on average speed	In this factor parameters that describe the occurrence and duration of stops in the driving pattern are collected	Stop factor	Percentage of time $v < 2$ km/h
4	Frequency of oscillation of the speed curve >2 km/h respective >10 km/h per 100 s and per 100 m PKE, positive kinetic energy	This factor describes the oscillation of the speed curve. The factor increases with many local max and min of the speed curve and decreases if the speed curve only has few or no values	Speed oscillation factor	Frequency of oscillations of the speed curve per 100 s
5	% of time va is between 3 and 10 % of time when $va < 0$, negative loading % of time when r is −0.5 to 0 m/s^2, negative loading	Acceleration with moderate power demand. The factor become low if acceleration is undertaken with either higher or lower product of va than the interval 3–10	Factor for acceleration with moderate power demand	% of time when va is 3–6 m^2/s^3
6	% of time at the highest acceleration level $a > 2.5$ % of time when a is 1.5–2.5 m/s^2 S.D. of the acceleration Integrated a^2, small loading Average acceleration, small loading	This is a factor that measures if very high acceleration occurs in the driving pattern. These extreme accelerations can be, but are not necessarily connected to high power demand. Whether they are, depends on the speed at which the acceleration is undertaken	Extreme acceleration factor	% of time when acceleration exceeds 2.5 m/s^2
7	% of time speed is 15–30 km/h % of time at very low engine speed (< 1500) when driving in gear 2 or gear 3 % of time at engine speed below 1500 rpm	Increases with high % of time in speed interval 15–30 km/h when driving at fairly even speed, since higher acceleration is not possible at engine speed below 1500 rpm	Factor for speed 15–30 km/h	% of time when speed is 15–30 km/h

8	% of time at speed in 90–110 km/h % of time at engine speed 2500–3500 when in gear 5	Driving at speed 90–110 km/h	Factor for speed 90–110 km/h	% of time in speed interval 90–110 km/h
9	% of time in speed interval 70–90 km/h % of time when engine speed is 2500–3500 when in gear 4 % of time engine speed is 1500–2500 when in gear 5	Driving in speed interval 70–90 at moderate engine speed in gear 5 or high engine speed in gear 4. The factor increases when these parameters increase and decreases when the speed is either higher or lower than 70–90 km/h	Factor for speed 70–90 km/h	% of time at speed 70–90 km/h
10	% of time at speed 50–70 % of time engine speed is 1500–2500, when in gear 4	Driving at speed 50–70 km/h	Factor for speed 50–70 km/h	% of time at speed 50–70 km/h
11	% of time engine speed is 2500–3500, when driving in gear 3 or 2 % of time engine speed is 1500–2500, negative % of time engine speed is > 3500 when in gear 2	Late gear changing from gears 2 and 3 when accelerating	Factor for late gear changing from gears 2 and 3	% of time engine speed is 2500–3500 when in gear 3
12	% of time at engine speed > 3500 % of time when engine speeds is > 3500 when at gear 4, 3 and 2	High % of time at very high engine speed	Factor for engine speed > 3500	% of time when engine speed is > 3500
13	% of time speed > 110 km/h % of time engine speed is > 3500, when in gear 5.	Speed > 110 km/h, which is also connected to high engine speed, > 3500, when at gear 5	Factor for speed > 110	% of time > 110 km/h
14	% of time engine speed is 1500–2500 when in gears 2 and 3 Number of stops per km, negative S.D. of speed	The factor describes a changing speed curve with few stops, where speed changes are achieved without speeding the engine in gear 2 or 3. High % of time with moderate engine speed in gear 2 and 3 imply that acceleration is moderate and/or late gear changes occur when decreasing the speed	Factor for moderate engine speeds in gear 2 and 3	% of time when engine speed is 1500–2500 in gear 2
15	Engine speed < 1500 when in gear 4	Gear changing strategy, to drive in gear 4 at lowest possible speed	Factor for low engine speed in gear 4	% of time engine speed < 1500 when at gear 4
16	Engine speed < 1500 when in gear 5	Gear changing strategy, to drive in gear 5 at lowest possible speed	Factor for low engine speed in gear 5	% of time engine speed < 1500 when at gear 5

Table 6
Models for emission and fuel-use factors as a function of driving pattern factors based on emissions calculated by the mechanistic emission model VETO on a Volvo 940[a]

Driving pattern factor	Fuel ($R^2 = 0.76$)		HC ($R^2 = 0.49$)		NO_x ($R^2 = 0.66$)	
	B	B_{std}	B	B_{std}	B	B_{std}
Constant	**1.042**		**0.036**		**0.308**	
Deceleration factor	**−0.062**	−0.107	**0.006**	0.07	**−0.019**	−0.062
Factor for acceleration with strong power demand	**0.261**	0.432	**0.029**	0.31	**0.137**	0.431
Stop factor	**0.298**	0.524	**0.008**	0.08	**0.017**	0.055
Speed oscillation factor	**0.105**	0.185	−0.001	−0.01	**−0.007**	−0.022
Factor for acceleration with moderate power demand	**0.116**	0.210	**−0.008**	−0.09	**0.023**	0.077
Extreme acceleration factor	**0.112**	0.177	**0.047**	0.46	**0.149**	0.448
Factor for even speed < 30	**0.028**	0.059	0.001	0.01	**−0.031**	−0.123
Factor for speed 90–110 km/h	0.009	0.011	0.001	0.01	**0.031**	0.069
Factor for speed 70–90 km/h	**−0.073**	−0.120	**0.007**	0.07	**0.023**	0.073
Factor for speed 50–70 km/h	**−0.117**	−0.196	−0.002	−0.02	**−0.009**	−0.028
Factor for late gear changing from gears 2 and 3	**0.058**	0.092	**0.022**	0.22	**0.098**	0.298
Factor for engine speed > 3500	**0.046**	0.051	**0.031**	0.22	**0.091**	0.192
Factor for speed > 110 km/h	0.007	0.008	**0.008**	0.06	**0.021**	0.046
Factor for moderate engine speeds in gears 2 and 3	**−0.114**	−0.206	**−0.011**	−0.12	**−0.031**	−0.105
Factor for low engine speed in gear 4	**−0.068**	−0.132	**−0.002**	−0.03	**−0.032**	−0.117
Factor for low engine speed in gear 5	**−0.051**	−0.140	**−0.002**	−0.03	**−0.021**	−0.109

[a] Sig. values of B are in bold. B_{std} = standardised B.

VETO emissions serves as the norm and the regression based on the Rototest emissions serves as a validity check of the results. The assumption was that if a certain driving pattern factor was found to have a certain effect according to two different cars and two independent emission models, an effect of this estimated sign was likely to exist.

It was found that the Rototest-modelled emissions supported the results (in terms of showing a significant effect with the same sign) according to the VETO-modelled emissions for 30 out of 34 effects, see Table 7. The largest effects were found for the factor for acceleration with strong power demand and for the extreme acceleration factor. Altogether, nine factors had a standardised B value of 0.2 or more (i.e., at least ++ or −−) for any effect. Fuel consumption was affected by the factors for acceleration with high and moderate power demand, stop, speed oscillation, extreme acceleration, speed 50–70 km/h (negative effect) and moderate engine speed at gears 2 and 3 (negative effect). Emissions of HC were primarily affected by factors for acceleration with high power demand and extreme acceleration. NO_x emissions were mainly affected by the factors for acceleration with high power demand, extreme acceleration, engine speeds > 3500 rpm and late gear changing from gears 2 and 3. These result are supported by findings in a study on eco-driving performed by the Swedish National Road Administration (Johansson et al., 1999b). It was found that high engine speed and accelerations had high explanatory power for NO_x emission, HC emissions increased due to powerful accelerations and high engine speed, but were also found to be highly affected by the throttle angle. De Vlieger (1997) employed cars measuring emissions and

Table 7
Driving pattern factors with significant effect on emissions and fuel-use[a]

Driving pattern factor	Fuel	CO_2	HC	NO_x
Deceleration factor	–	–		
Factor for acceleration with strong power demand	++++	++++	+++	++++
Stop factor	+++++	+++++		
Speed oscillation factor	++	++		
Factor for acceleration with moderate power demand	++	++		
Extreme acceleration factor	++	++	+++++	++++
Factor for speed 15–30				–
Factor for speed 90–110				
Factor for speed 70–90	–	–		
Factor for speed 50–70	––	––		
Factor for late gear changing from gear 2 and 3	+	+	(++)	+++
Factor for engine speed > 3500			(++)	++
Factor for speed > 110				
Factor for moderate engine speeds at gears 2 and 3	––	––		–
Factor for low engine speed at gear 4	–	–		(–)
Factor for low engine speed at gear 5	–	–		(–)

[a] Effects supported by only one model are shown in parentheses. The number of + or – signs represents the size of the effect (+ indicates std *B* is approximately 0.1, ++ indicates std *B* is approximately 0.2, etc.).

fuel consumption simultaneously with logging the driving pattern. Driving patterns registered during aggressive driving (defined as sudden and high acceleration and heavy braking) were found to cause several times more exhaust and 30–40% higher fuel consumption than calm driving. The considerable effects due to high and sudden acceleration on emissions and fuel consumption were confirmed by results of the present study.

Different car models are sensitive to different characteristics in driving behaviour. Johansson et al. (1999b) found that the VW Golf (which was also used in that study) was fairly insensitive to high engine speeds, while a Volvo S80 showed increased emission at high engine speeds. These results agree with those presented in Table 7, where engine speeds > 3500 rpm had less effect on emission from the VW Golf than from the Volvo in this study.

Overall, average and S.D.s of emissions and fuel-use factors for the Volvo 940 and the VW Golf, according to the emission models used here are given in Table 8.

In an earlier study (Ericsson, 1999), 26 driving pattern parameters were investigated in connection with fuel-use and emissions of HC and NO_x. Five driving pattern parameters were found

Table 8
Average values and the S.D. of the emissions and fuel-use factors for urban driving according to the two cars and the two emission models used in the study

Effect	Volvo 940		VW Golf	
	Average	S.D.	Average	S.D.
Fuel-use, l/10 km	1.03	0.55	1.08	0.68
CO_2 emissions, g/km	244	131	242	151
HC emissions, g/km	0.031	0.089	0.027	0.071
NO_x emissions, g/km	0.278	0.292	0.185	0.395

to have significant positive effects on all investigated dependent variables. The most important parameters were:

(1) RPA (see Table 3),
(2) number of oscillations/100 m,
(3) percentage of time when acceleration exceeds 1.5 m/s^2,
(4) percentage of time when deceleration was between −1.5 to −2.5 m/s^2,
(5) percentage of time at speed below 15 km/h.

These parameters are all representative of different driving pattern factors according to the present study, namely the factors for: (1) acceleration with high power demand, (2) speed oscillation, (3) extreme acceleration (4) deceleration and (5) stop. The resulting effects on emissions and fuel consumption of the two studies are quite similar, with only one exception. In Ericsson (1999) decelerations in the interval −1.5 to −2.5 m/s^2 had increasing effect on fuel-use and emissions. This is in agreement with the assumption used in the concept of eco-driving (Smith, 1999; Ahlvik et al., 1999), in which heavy deceleration should be avoided as this causes energy loss. In the present study, the deceleration interval −1.5 to −2.5 m/s^2 in real traffic was found to be strongly correlated to several other driving pattern parameters, e.g., average deceleration, S.D. of deceleration and integrated a^2, which formed a deceleration factor. This deceleration factor was found to have a small but significant decreasing effect on fuel-use. The other four parameters that had considerable effects on emission and fuel consumption factors according to Ericsson (1999) were also found to represent driving pattern factors that had considerable effects according to the present study.

5. Discussion

5.1. Independent driving pattern factors

Driving pattern is a complex phenomenon and different methods have been used to represent or describe their variation. In the present study, the aim was to find independent measures/dimensions to describe driving patterns in urban driving and to investigate which dimensions of real traffic driving patterns are important for the amount of exhaust emissions and fuel consumption. The relatively large sample of driving patterns representing driving in different types of streets under different traffic conditions, using different types of cars driven by about 45 randomly chosen drivers, was assumed to be acceptable bases for identifying different dimensions characterising urban driving patterns. However, if the external conditions are radically different in terms of traffic planning and control, distribution over vehicle types and models or if driver behaviour is radically altered, there may be new or other dimensions in the driving pattern that were not observed in the present study. Furthermore, if new types of driving pattern variables were logged they could prove to form new dimensions (but they could also prove to be part of the present driving pattern *factors*).

5.2. Emission modelling methodologies

In this study instantaneous emission models were used to calculate emission as a function of speed profile, engine speed and actual gear level. Jourmard et al. (1999) compared instantaneous emission models with an average speed model (i.e., a model using only average speed as explanatory variable). They addressed the weaknesses of instantaneous emission models and argued in favour of average speed models since they are easy to use and do not give a false impression of accuracy as instantaneous emission models may do. Guensler (1994) made a thorough examination of average speed models. He found that the width of the estimated confidence intervals implies large uncertainties in any application of average speed models. Concerning prediction intervals, Guensler concluded that the large prediction interval of average speed models implies that current models are not very good predictors of emissions and that new model formulations including both new explanatory variables and transformations of existing ones need to be examined.

Certainly, the perfect emission model has not yet been presented. According to Jourmard et al. (1999) instantaneous emission models have uncertainties, as do average speed models according to Guensler (1994). Furthermore, different cars have different responses to the same driving pattern and to the driver's way of handling the accelerator, the brake pedal and the gear stick, Guensler (1994). LeBlanc et al. (1995) stressed the importance of gaining better knowledge of real driver behaviour since new emission modelling will need more information about the characteristics of drivers.

The most proper method of evaluating the emission and fuel-use as a function of driving pattern would have been to measure the emission and fuel consumption for all 19 230 driving patterns in laboratory tests. However, resources were not available to conduct such extensive tests. A common methodologyis to create typical driving cycles to represent the measured driving patterns, as described by André(1996) and André et al. (1995), and to conduct laboratory tests on the driving cycles. One disadvantage of using driving cycles is that this method removes some of the variability from the data. Small but important variations in the driving pattern may be lost, which could cause erratic results and conclusions. Although most driving cycles are created to fulfil a set of assessment criteria to represent the measured driving patterns, the driving cycle runs the risk of being smoothed in some respects in comparison with the real traffic data. Using a mechanistic instant-emission model has the advantage of averaging after, not before, the emission estimation.

However, to obtain representative emission factors from mechanistic emission models requires the models to be further refined and validated, especially for transient situations. In addition, a large set of engine maps and vehicle parameters must be made available to ensure that different vehicle types, engines, and emission control systems can be modelled.

The present study aimed at identifying the dimensions of real traffic driving patterns that had considerable effects on emission and fuel consumption and resulted in Table 7. However, the model derived from linear regression can also be used as an emission model, which is somewhere between an instantaneous emission model and an average speed model.

6. Conclusions

The large amount of data made it possible to use factorial analysis on the 62 primary calculated driving pattern parameters. This analysis resulted in 16 independent driving pattern factors, each describing a certain dimension of the driving pattern.

When investigating the effect of the independent driving pattern factors on emissions of HC, NO_x and CO_2 and on fuel consumption it was found that nine driving pattern factors had an important effect on fuel consumption and emissions. These were the factor for acceleration with strong power demand (+), the stop factor (+), the speed oscillation factor (+), the factor for acceleration with moderate power demand (+), the extreme acceleration factor (+), the factor for speed 50–70 km/h (−), the factor for late gear changing from 2nd and 3rd gear (+), the factor for engine speed > 3500 rpm (+) and the factor for moderate engine speeds in 2nd and 3rd gear (−).

Four of the factors describe different aspects of acceleration and power demand, three factors describe aspects of gear-changing behaviour and two factors are related to speed level. Many emission models focus on the speed variables alone (as described in Meet, 1999). This study shows that independent factors describing acceleration and power demand, as well as gear changing behaviour, are important explanatory variables for emission and fuel consumption, in addition to speed.

These results have some direct implications for future environmental policy. Since the different factors are independent it can be concluded that speed in itself does not cause large environmental problems in this kind of urban traffic. Thus, the issue of lowering speed limits for traffic safety reasons is not a main problem from an environmentally point of view. Instead we need to focus on changing environments, drivers and vehicles in a way that does not promote heavy acceleration, power demand and high engine speeds. The question of how this can be achieved will be a challenge for further research and development of traffic planning and management, vehicle technology and driver education.

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