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A typology of urban driving patterns: a descriptive analysis and estimation of environmental effects

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Abstract

Driving patterns, i.e. speed and acceleration profiles, have a large effect on emissions and fuel consumption. This study aimed at creating a typology of urban driving patterns and applying it on data of speed, acceleration and engine speed profiles etc. collected in real urban traffic. To obtain a typology of driving patterns cluster analysis was initially tested but was, however, found to yield unstable results. Instead a typology was built based on exogenous segmentation of speed, occurrence of speed changes, acceleration and stopping occurrences. Fifteen segments were found to cover more than 98 % of the total length, time of driving and exhaust emitted. The driving pattern types were described in terms of speed, acceleration, deceleration, speed oscillation, percentage of stopping, RPA and engine speed. Their exhaust emission factors and fuel consumption factors were modelled and the contribution to the total amount of emission and fuel consumption within the city was calculated.

1. Introduction

Driving patterns, i.e. the speed and acceleration profiles of vehicles are studied because of their influence on exhaust emissions and fuel consumption. Driving patterns vary to a large extent especially in urban areas, and it is a common research issue to try to aggregate driving patterns to representative driving cycles. The driving cycle should ideally represent a typical speed profile for a certain vehicle type in urban, rural or highway driving. Driving cycles are used for emission modelling and to certify that vehicles meet the emission legislation. Various methodologies to achieve representativity of driving cycles have been tested [1], [2]. However, driving cycles have so far not been aimed at describing the various types of driving patterns that occur within e.g. a local urban area.

This study was aimed at creating a typology of urban driving patterns, to describe the frequency of different driving pattern types and to investigate their respective relative and total effect on exhaust emissions and fuel consumption in urban driving. Initially cluster analysis was tested to obtain a typology which would have been endogenously determined. However, it was not possible to find a stable solution using this methodology. Instead an exogenous segmentation based on speed, occurrence of speed changes, acceleration and occurrence of stop was chosen. When tested on a sample of 14051 driving patterns, 15 types of driving patterns were found to cover more than 98 % of the total length driven, duration and exhaust emissions. The 15 types were described in terms of seven driving pattern parameters, emission factor of Nitrogen Oxides (NO_x) and Hydrocarbons (HC) and fuel consumption factors. Furthermore, the total share of emission and fuel consumption was estimated for each type.

2. Methodology

2.1 Driving pattern data

Driving patterns representing 2550 journeys and 18 945 km of driving had been collected in an earlier study [3]. For the study, five passenger cars of different sizes and performance were equipped with data-logging systems (for speed measurement) and GPS (Global Positioning Systems) receivers (to make it possible to afterwards relate driving patterns to the prevailing street environment). The cars were used for normal daily driving by 29 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. Since driving patterns vary due to the external environment each driving pattern was divided into subsections according to street and traffic characteristics, which resulted in 14051 driving patterns. 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. Further details on the investigations are presented in [3] and [4]. For each driving pattern, 62 parameters were calculated e.g. measures of speed, frequency of speed changes i.e. accelerations and decelerations, acceleration and deceleration levels, power demand and engine speed [3]. A factorial analysis revealed that driving patterns consists of several dimensions/properties. For the present study 7 dimensions were chosen to illustrate the driving pattern namely the speed level, the oscillation of the speed curve i.e. number of speed changes, the occurrence of stops, the acceleration and deceleration level and the occurrence of high engine speeds. The dimensions were chosen for being

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important descriptors of driving patterns and for having considerable effect on the amount of exhaust emission and fuel consumption. Each dimensions was represented by one parameter, see table 1.

2.2 Choice of method for creating a typology of driving patterns

Different methods may be applied to the aim of creating a typology for a set of multi-dimensionally characterised cases. Cluster analysis is a comprehensive label for one group of such techniques, having that in common that they seek to reveal some kind of group structure implied by the data itself. There are two major types of cluster analysis available: Hierarchical methods and Optimisation methods, of which the latter is generally known to be the more efficient for large number of cases, [5]. Optimisation methods tries to find the optimal distribution of cases over clusters, given a pre-set total number of clusters. Different dialects of optimisation methods evolve from choosing different optimisation criteria. A set of such criteria has been suggested in literature, all aiming for the same basic target: the clustering should be made so that cases would be as similar as possible within clusters, and as dissimilar as possible between clusters. Already at limited sample sizes and number of clusters, however, the total number of different possible clusterings becomes very large. Thus, a global optimisation based on testing all the alternatives is not feasible. Instead, iterative re-allocations of single cases would typically be applied, starting from an initial clustering that may be arbitrarily defined by the user, or computed from the data in different ways. Unfortunately, the techniques available (basically hill-climbing) do not ensure that a global optimum for the criterion is found. Thus, it is recommended that several optimisations be made on the same data set, starting from different initial solutions. If there were a strong inherent structure in the data, one would then expect to end up with basically the same optimal solution, despite starting point. If that is not achieved, that would be an indication that either the number of clusters was inappropriate, or that there is a lack of structure in the data, [6].

But a typology does not always have to be determined by the data itself. In many cases, it may be just as useful to delimit segments by exogenously pre-set levels (or combinations of levels) for the classifying variables, reflecting a division that is perceived by the researcher as (potentially) relevant and interpretable based on a priori knowledge. Such, exogenous, segmentation has the disadvantage that neither similarity within segments, nor dissimilarity between segments, can be ensured. In that sense, the resulting "types" and their characteristics (as represented by, e.g. mean values of variables within the segments) represent prototypical, rather than typical, observations.

In this study, the initial aim was to apply an optimisation clustering technique to define a set of typical driving patterns, based on the observed characteristics. To this aim, the optimisation cluster analysis method implemented in SPSS (*K-means*) was applied to the data, described by the standardised transformation of 7 relevant parameters chosen (described above, and in Table 1). It was decided on beforehand that there was an upper limit of around 20 types for the typology to be tractable for description and interpretability. To find the best typology meeting this criterion, the cluster structure was successively optimised for each of the numbers of clusters in the range 5 to 25, rerunning the analysis at each of these levels. In this range, the optimal solution found for 12 clusters turned out superior (as measured by short average distance within clusters, and long average distance between clusters) to the solutions for other numbers of clusters tested. However, when re-optimising the cluster structure, keeping the number of clusters constant (12), but starting from another initial solution, the optimal solution found turned out quite different. Thus, despite that 12 had proven to be the best number of clusters in the range of interest, it was not possible to find a stable optimal solution at that level. As a consequence, it was concluded that the driving pattern data was not structured in distinct concentrations of patterns with similar characteristic combinations, separated from other concentrations by far less common combinations of characteristics. Rather, the results implied that the data was well, and rather independently, dispersed in all the dimensions considered for the analysis.

The alternative segmentation strategy, exogenously defined segment cut-off values, was then applied to the data. Because of multiplication effects, the number of parameters involved had to be reduced from 7, and the number of levels of each parameter kept at a minimum, to form a tractable number of types with this method. The initial typology chosen is described in Table 1. It is based on cut-off values determined from the marginal distribution of each parameter, and under consideration of a priori knowledge, and results reported in [3], about important relations between driving pattern characteristics and environmental effects from the driving patterns.

The initial segmentation, as defined by the cut-off values in Table 1, thus identified 24 (3·2·2·2) driving pattern types. Table 2 reports the distribution of total vehicle mileage in the study, distributed over those 24 types. As can be seen from the table, and was to be expected, several of the defined types are uncommon, and represent very small parts of vehicle mileage.

In the following, only the 15 major driving pattern types highlighted in Table 2 will be further described and analysed. The 15 pattern types thus selected, are those that each represents at least 1% of total vehicle mileage. Further, neither does any other type serve for more than 1% of total driving duration, nor of total estimated emissions of any of the estimated exhaust compounds. In total, 98-99% of total vehicle mileage, driving pattern duration and exhaust emissions for all compounds are produced by patterns that fall into one of the highlighted types.

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Table 1: The parameters upon which the cluster analysis and endogenous segmentation was based, respectively. Cut-off values for the exogenous segmentation

Base for Cluster analysis		**Exogenously defined typology**	
Characteristic Type	**Parameter notation; Parameter**	**Cut-off value(s)**	**Segment notation**
Speed	V; Time mean speed	30[1] km/h 60[2] km/h	v_{low} v_{medium} v_{high}
Speed fluctuations	**MM**; frequency of speed fluctuations *vmax-vmin*> 2km/h	0[3] Hz	*even* *fluct*
Stops	**STOPT**; percentage of total time at stop (v<2 km/h)	0[4]	*no stop* *stop*
Accelerations	A; mean acceleration over time when accelerating	v_{high}: 0.15[5] m/s^2	a_{low} a_{high}
		v_{low} , v_{medium}: 0.6[6] m/s^2	a_{low} a_{high}
Decelerations	R; mean deceleration Over time when decelerating	not applied	not applied
Power demand	**RPA**; relative positive acceleration[6]	not applied	not applied
Engine speed	**RPM35**; percentage of time with engine speed>3500 rpm	not applied	not applied

1) Representing the 25-percentile of the overall marginal distribution over observations
2) Representing the 75-percentile of the overall marginal distribution over observations
3) Representing the 25-percentile of the overall marginal distribution over observations
4) Representing the 75-percentile of the overall marginal distribution over observations
5) Representing the 25-percentile of the overall marginal distribution over observations. Cut-off is speed dependent to reflect levels of power demand: this, lower, cut-off applies to segments with time mean speed> 60 km/h
6) Representing the 75-percentile of the overall marginal distribution over observations Cut-off is speed dependent to reflect levels of power demand: this, higher, cut-off applies to segments with time mean speed< 60 km/h
7) RPA defined as $(\int va^+ dt)/x$, where v is instantaneous speed, a^+ is acceleration when positive, and x is total distance driven

Table 2: Distribution of total vehicle mileage (percentages) produced over the 24 initially defined segments. Highlighted types each serve for at least 1% of total vehicle mileage

			v_{low}	v_{medium}	v_{high}
even	***stop***	a_{low}	0.2	0.1	0.0
		a_{high}	0.1	0.1	0.0
	no stop	a_{low}	0.4	**5.6**	**6.0**
		a_{high}	0.2	**1.3**	**2.7**
fluct	***stop***	a_{low}	**5.2**	**3.2**	0.0
		a_{high}	**2.7**	**2.0**	**1.3**
	no stop	a_{low}	**2.3**	**25.4**	**16.7**
		a_{high}	**1.1**	**6.7**	**16.7**

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2.3 Method to investigate effects on exhaust emission and fuel consumption

Emission factors had been calculated for the VW Golf and the Volvo 940, (both petrol catalyst cars) which together formed 5217 cases. For the VW Golf the emission and fuel consumption factors had been calculated by Rototest AB (A Swedish Consultant Company) using an emission model developed in 1999, [4]. For the Volvo 940 another emission model, VETO, developed by Swedish National Road and Transport Research Institute, [7], was used. VETO has been validated against measured fuel consumption and exhaust emission data for a Volvo 940, [8]. The Rototest model has not yet been validated. Hence, calculations of emissions of hydrocarbons (HC), nitrogen oxides (NO_x) and fuel consumption were performed with two different mechanistic instantaneous emission models, one for each of two cars. Both models use the engine map and other vehicle parameters of the 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. Means for emissions (g/km) and fuel consumption (litres/10 km) was calculated for the different types of driving patterns according to the cluster analysis. Further total amounts of emission and fuel consumption was calculated for suggested typology by multiplication with the individual driving pattern lengths.

3. Results

As described above, the segments were defined by *cut-off values* for each parameter that was (with one exception) independent of other parameters. Nevertheless, because parameters are not independent, the *mean* value of a parameter within a segment will depend not only on the segment's characterisation with respect to that specific parameter, but also, quite strongly, on how the segment is defined in other parameters. Further, one would expect not only segmentation variables, but also many other characteristics, to vary between pattern types. Table 3 reports about the average localisation of each of the 15 major pattern types, in each of the initial 7 dimensions.

The emission factors for each driving pattern type are reported in table 4. Each emission factor was multiplied with the total vehicle mileage for that segment to obtain the contribution of each driving pattern type to the total emission and fuel consumption. This distribution is reported in table 5.

Table 3: Mean values of characterising parameters for the 15 major driving pattern types that were identified. See Table 1 and [3] for parameter definition.

Segment description	**V** km/h	**A** m/s^2	**R** m/s^2	**MM** 0.01Hz	**RPA** m/s^2	**STOPT** % of time	**RPM35** RPM
v_{low}, a_{low}, *fluct, stop*	15.2	0.4	-0.4	7.3	2.2	36.3	0.1
v_{low}, a_{high}, *fluct, stop*	19.6	0.9	-0.7	8.7	4.6	27.8	0.5
v_{low}, a_{low}, *fluct, no stop*	24.0	0.4	-0.5	9.8	1.8	0.0	0.1
v_{low}, a_{high}, *fluct, no stop*	25.1	0.8	-0.8	10.9	4.2	0.0	0.4
v_{medium}, a_{low}, *even, no stop*	46.7	0.2	-0.4	0.0	1.3	0.0	0.2
v_{medium}, a_{high}, *even, no stop*	43.1	0.9	-0.5	0.0	5.7	0.0	1.9
v_{medium}, a_{low}, *fluct, stop*	38.7	0.4	-0.5	6.1	1.4	13.8	0.3
v_{medium}, a_{high}, *fluct, stop*	38.1	0.9	-0.7	7.5	3.4	12.4	1.5
v_{medium}, a_{low}, *fluct, no stop*	45.9	0.3	-0.4	7.4	1.6	0.0	0.2
v_{medium}, a_{high}, *fluct, no stop*	42.3	0.8	-0.7	8.8	3.9	0.0	1.6
v_{high}, a_{low}, *even, no stop*	75.3	0.1	-0.2	0.0	0.4	0.0	0.5
v_{high}, a_{high}, *even, no stop*	71.6	0.4	-0.2	0.0	2.9	0.0	2.4
v_{high}, a_{high}, *fluct, stop*	68.1	0.7	-0.5	6.9	2.4	5.5	1.4
v_{high} a_{low}, *fluct, no stop*	80.5	0.1	-0.2	4.8	0.5	0.0	1.4
v_{high} a_{high}, *fluct, no stop*	70.6	0.4	-0.3	6.5	1.9	0.0	1.6

Table 4: Emission factors (g/km) for the driving pattern types according to two emission models and two cars. Emission factors more than 10% higher than the average is highlighted.

	Volvo 960, VETO emission model			VW Golf, Rototest emission model		
Driving pattern type	FUEL	HC	NO_X	FUEL	HC	NO_X
v_{low}, a_{low}, *fluct, stop*	**1.640**	0.033	0.257	**1.931**	**0.071**	0.079
v_{low}, a_{high}, *fluct, stop*	**1.701**	**0.051**	**0.412**	**1.748**	**0.046**	**0.395**
v_{low}, a_{low}, *fluct, no stop*	1.103	0.014	0.180	1.158	0.026	0.036
v_{low}, a_{high}, *fluct, no stop*	**1.390**	0.039	0.315	**1.437**	**0.042**	0.189
v_{medium}, a_{low}, *even, no stop*	0.783	0.009	0.207	0.769	0.022	0.056
v_{medium}, a_{high}, *even, no stop*	**1.500**	**0.135**	**0.676**	**1.444**	**0.041**	**0.699**
v_{medium}, a_{low}, *fluct, stop*	0.877	0.017	0.236	0.871	0.023	0.062
v_{medium}, a_{high}, *fluct, stop*	**1.225**	**0.096**	**0.516**	0.961	0.014	0.223
v_{medium}, a_{low}, *fluct, no stop*	0.797	0.012	0.202	0.822	0.017	0.086
v_{medium}, a_{high}, *fluct, no stop*	1.143	**0.089**	**0.473**	**1.137**	0.029	**0.519**
v_{high}, a_{low}, *even, no stop*	0.631	0.006	0.213	0.592	0.009	0.005
v_{high}, a_{high}, *even, no stop*	1.005	**0.079**	**0.432**	0.839	0.013	0.212
v_{high}, a_{high}, *fluct, stop*	0.948	**0.054**	0.347	1.056	0.017	**0.952**
v_{high}, a_{low}, *fluct, no stop*	0.704	0.009	0.242	0.649	0.011	0.031
v_{high}, a_{high}, *fluct, no stop*	0.820	0.047	0.338	0.815	0.018	0.290
Average emission factor	1.084	0.046	0.336	1.082	0.027	0.256
Average + 10%	1.194	0.050	0.370	1.190	0.029	0.281

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Table 5: Percent of total emission (Sum of (emission factor · mileage for the driving pattern type) over all driving pattern types). Highest percentages bold.

	Volvo 960 VETO emission model			VW Golf, Rototest emission model		
Driving pattern type	FUEL	HC	NO_X	FUEL	HC	NO_X
v_{low}, a_{low}, *fluct, stop*	9.43	5.61	4.78	**11.11**	**17.65**	2.51
v_{low}, a_{high}, *fluct, stop*	4.99	4.49	3.91	5.14	5.78	6.42
v_{low}, a_{low}, *fluct, no stop*	2.83	1.10	1.49	2.97	2.89	0.51
v_{low}, a_{high}, *fluct, no stop*	1.64	1.36	1.20	1.70	2.16	1.23
v_{medium}, a_{low}, *even, no stop*	4.83	1.66	4.13	4.75	5.86	1.93
v_{medium}, a_{high}, *even, no stop*	2.09	5.65	3.05	2.02	2.46	5.40
v_{medium}, a_{low}, *fluct, stop*	3.09	1.77	2.69	3.08	3.57	1.21
v_{medium}, a_{high}, *fluct, stop*	2.63	6.16	3.58	2.07	1.35	2.66
v_{medium}, a_{low}, *fluct, no stop*	**22.22**	9.72	**18.18**	**22.93**	**20.32**	**13.25**
v_{medium}, a_{high}, *fluct, no stop*	8.41	**19.74**	**11.26**	8.38	9.10	**21.16**
v_{high}, a_{low}, *even, no stop*	4.16	1.28	4.55	3.91	2.68	0.19
v_{high}, a_{high}, *even, no stop*	3.02	7.12	4.20	2.53	1.69	3.53
v_{high}, a_{high}, *fluct, stop*	1.31	2.23	1.55	1.47	1.04	7.31
v_{high}, a_{low}, *fluct, no stop*	**12.94**	4.74	**14.38**	**11.93**	8.41	3.18
v_{high}, a_{high}, *fluct, no stop*	**15.01**	**25.72**	**20.00**	**14.94**	**13.91**	**29.40**
Total percentage	98.60	98.36	98.96	98.90	98.87	99.89

According to table 4 the highest emission and/or fuel consumption factors (g/km and litres/10 km) occurred for driving patterns with low fluctuating speed and high acceleration levels especially if they included stops, and for driving patterns with medium speeds and high acceleration level. However, the largest total amounts of emission and fuel consumption was produced for driving patterns with high fluctuating speed without stops (especially those with high acceleration) and medium fluctuating speeds without stops which is due to the fact that those driving patterns are the most common, see table 2.

4. Discussion and conclusion

In driving cycle research the overall aim is to find a typical driving pattern within a certain sample of driving patterns. In this study cluster analysis was performed on a large set of driving pattern data to study whether driving patterns within an urban area was structured in distinct concentrations of patterns with similar characteristic combinations. The inability to find such distinct driving patterns types according to this study implies that urban driving patterns is a phenomenon with wide variability in many dimensions and that the issue to find one of a couple of 'typical' driving pattern might be hard if the definition of typical is a driving pattern essentially more common than others.

Instead an exogenous segmentation was chosen for creating a typology which can not be automatically assumed to result in 'typical' driving patterns. Table 3 shows that mean values vary considerably between segments, also for those parameters that were not directly involved in the segmentation (R, RPA and RPM35). Thus, we may conclude that the resulting typology reflects not only an arbitrary split of the data according to the cut-off values forced upon it in specific dimensions, but constitutes different 'types' of driving patterns also in a more general meaning. The suggested typology could be viewed upon as a aggregated but however more balanced description of the types of driving patterns occurring in urban driving compared to using one common driving cycle.

Different cars emit different amounts of exhaust per km. In this study two instantaneous emission models were used to model the effect of different driving patterns on emission and fuel consumption. Each model was calibrated for a car like the one respective driving pattern originated from. However, emission factors reported in table 4 differ. It is not clear whether the discrepancies are due to differences in the emission models used 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. Yet, some agreement can be noted emission factors tend to be high and low for approximately the same types of driving patterns. Still the tabulated values should be seen as examples rather than representative emission of a vehicle park.

Naturally, there is reason to assume that the local traffic environment have an impact on driving pattern characteristics, and that such variation in turn affects local emissions and thus local air quality. Some initial results of that kind, focusing average pattern characteristics in different environments, is reported in [3]. The presented typology offers an alternative approach to such research, in that it allows us to describe the distribution of driving patterns (over types) in different environments. Preliminary analyses with this approach show that all street types carries vehicle traffic representing several driving pattern types, but, yet, that the distribution over types varies considerably between street types.

The study emphasises the importance to view specific emission factors together with the vehicle mileage and thus the total share of emission and fuel consumption as was highlighted in [9]. The emission factors are essential to study among other things for pointing out driving styles that increase emissions and fuel consumption while the total amount of emissions is dependent of how common different types of driving pattern are and thus how much they contribute to the total environmental effects. For example the driving pattern types with the highest emission factors only represented a small part of the total vehicle mileage and the total emission. Thus it is not enough to measure individually high but uncommon emission factors (or driving styles). A decrease of environmental effects from traffic would also require a reduction of the total vehicle mileage and a significant lowering of emission factors of the most common types of driving patterns.

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