Measurements and analysis of real-world driving behavior of urban buses

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Abstract

The present paper contains an analysis of driving behavior measurements of urban buses. The following parameters were measured and logged on a second-by-second basis: engine torque and speed, bus velocity, road gradient, number of passengers in the bus, coolant and oil temperatures and on/off switching of the air conditioning system. For part of the experiments, exhaust gas temperature and braking system activation were also recorded at the same frequency.

Average driving behavior parameters, such as maximal and average bus velocities, accelerations, decelerations, relative time of stops, etc., were derived for various bus routes, as well as for available driving cycles, and an appropriate comparative analysis was performed. Based on the gained data, the effects of road gradient and air conditioning operation on engine power demand were evaluated.
Keys-words*: urban bus, driving behavior, power demand, road gradient, air conditioning.*

Introduction

Vehicle driving patterns have been studied worldwide for decades and serve for the development of various driving cycles, which are used for a great variety of purposes: from quantifying vehicle emissions and energy consumption at different levels to assessment of new vehicle technologies, Andre (1996). Driving patterns can be described by many parameters. Andre (1996) performed a comprehensive analysis and suggested parameters most extensively used for characterization of vehicle driving cycles. These are: duration; average duration of running periods; idle period; number of stops per kilometer; average speed; running speed; positive kinetic energy; average values of accelerations and decelerations; standard deviation of acceleration; number of acceleration-deceleration shifts; relative distributions of speeds, accelerations; joint distributions of speeds and accelerations.

Most driving patterns studies that have been performed are focused on the research of real world driving behavior of cars, Andre (1996), Esteves-Booth et al. (2001), Ericsson (2001). Compared to passenger cars, relatively few studies of driving behavior of heavy-duty vehicles, and in particular urban buses, have been carried out, Andre (1996). The most comprehensive European works, which dealt with a development of driving cycles for urban buses in various traffic situations, were carried out by Steven (1995) and van de Weijer et al. (1993 and 1997).

Following the recommendations of the COST 319 Action (1999), further research on driving behavior of heavy-duty vehicles "with extensive measurement campaigns of all vehicle types and usages" is needed, in order to close existing gaps in knowledge. It is noted in the COST 319 Action that measurement of driving behavior in different countries is of high priority, in order to have a good geographical representation of driving behavior data. Part of the objectives of the on-going ARTEMIS project and COST 346 Action are to address the above-mentioned challenges.

1 - Objectives

A main objective of this work, which was carried out in the framework of the ARTEMIS project and the COST 346 Action, under the financial support of European Commission, was to check the possibility of using available driving cycles for the calculation of bus emissions in countries of the Mediterranean region. For this reason, measurements of real-world driving behavior of urban buses in Israel were performed and compared with gained data from Western Europe. Taking into account this region's typical climatic and topographical conditions, as well as the strong effect of air conditioning (AC) and road gradients on emissions, effects of these factors on power demand and average fuel consumption were also assessed.

2 - Methodology

Measurements of real-world driving behavior of urban buses were carried out in two Israeli cities: Haifa (over 270 thousands inhabitants) and Netania (about 165 thousands inhabitants). These cities were selected as typical average Mediterranean cities, differing mainly by their topography: hilly in Haifa with road gradients up to 16% compared to flat in Netania. Measurements were performed over about 30 various bus routes, which were classified using a method developed by INRETS, Andre & Villanova (2002). Table 1 presents some results of this characterization, with the routes that were selected together with the bus operator (Egged) as representing a wide variety of urban driving patterns. It is noted that the classification, which was performed, is rather approximate, because the required data on population and employment distributions over the routes tested were not completely available.

Route #	Length	Speed (average over a week)	Number of departures at rush hours	Average number of departures	Number of bus stops	**Geograph. Area***	**Class**	Notes
	km	km/h	/hour	/hour	/km			
1a	14.4	16.3	4	3	2.6	**9 ~ 20% 10 ~ 40% 11 ~ 30% other ~ 10%**	**5**	ring
1b	18.0	18.9	4	3	2.3			
2a	33.4	19.1	6	4	2.5	**9 ~ 30% 11 ~ 60% other ~ 10%**	**1**	long segments with road gradients
2b	27.7	15.6	7	4	3.0			
3	5.0	11.1	3	2	3.4	**11**	**5**	ring
4a	15.1	23.9	15	7	1.9	**8 ~ 45% 9 ~ 45% other ~ 10%**	**4**	connects main bus terminals
4b	15.6	21.3	12	7	1.8			
5	12.0	20.0	13	7	1.4	**1 ~ 30% 4 ~ 50% 11 ~ 20%**	**3**	Netania, ring

* The percentages mean a relative part of the total route distance that was traveled by the bus in the specific geographical area, as classified by Andre & Villanova (2002): 1 - low population; 4 - isolated mixed housing; 8 - main roads, high traffic; 9 primary roads, high traffic and population; 10 - concentrated mixed housing; 11 - concentrated collective housing, high population and employment.

Table 1: Characteristics of representative Israeli urban bus routes (based on data of the bus operator).

As may be seen from Table 1, bus routes that were studied are run at rather different conditions, both geographical and operational, e.g. route 3 is run only in city center through areas with concentrated group housing compared to routes 4, which connect between main bus terminals in Haifa and are operated mainly on main and primary roads, with much higher average speeds.

The Israeli bus fleet is mainly composed of popular European makes (Mercedes, MAN and Volvo). A Mercedes O-405 model was selected as a typical urban bus and instrumented for the experiments. The bus was driven by different drivers chosen by the bus operator according to its standard routine. No driving instructions were used. The following parameters were measured, logged and processed on a second-by-second basis: engine torque and speed, bus velocity, road gradient, number of passengers, coolant and oil temperatures, and on/off switching of the AC system. For part of the experiments, exhaust gas temperature and braking system activation were also recorded at the same frequency. Measurements of engine and bus speeds, coolant temperature and activation of bus AC & braking systems were performed by connection to appropriate on-board signals. The exhaust gas temperature was measured at about 0.5 m downstream of the turbocharger outlet. Counting of the passengers number was allowed by access to the database of a special counting system, installed by the bus operator. For measurements of road gradient a special device was developed.

Measurements of engine torque were based on recording of instantaneous position of the fuel injection pump lever, using an on-board available position sensor. The input data required for engine torque calculation are: full load torque curve as function of the engine speed; test bench results of torque and corresponding fuel injection pump lever position for a number of different operation modes. Alternatively, test results over ECE R49 or ESC cycles (torque and corresponding fuel consumption) may be used, if bench-testing the engine that will be instrumented is not available. However, this method will result in a less accurate engine torque signal. Also required are the on-board logged data of engine speed, injection pump lever position and on/off switching of the AC system, which are measured with a frequency of at least 1Hz during real-world bus driving. Two different calculation methods were developed. One for idle and traction operation modes (zero and positive torque values) and another for non-traction modes (negative torque values, also referred to as 'motoring'). Detailed description of this methodology will be presented in a separate publication. Our calculations were based on ECE R49 official approval test results of the OM-447hA diesel engine, because testing the engine, which was instrumented for driving behavior measurements, was impossible. For each operation mode the relative fuel consumption was assumed equal to the relative position of the injection pump lever, and this assumption was validated experimentally by bench tests.

For estimation of the AC system power demand, the mechanical power consumed by the engine-driven compressor and the electric power consumed by fans were taken into account. Power consumed by engine-driven compressor, as function of the engine speed, was estimated based on the appropriate manufacturer's performance for the condenser and evaporator temperatures of 55 ^{o}C and 5 ^{o}C, respectively. These assumptions are justified because day-to-day variations of ambient temperatures during Israeli summer are usually low. Power consumed from the engine for operation of fans was evaluated by measurements of current and voltage supplied to the fans and based on the hot alternator efficiency performance (as function of the engine speed), as was supplied by the alternator manufacturer. Three basic modes of power consumption were defined for the case when the AC system is switched-on: power consumed from the engine is zero if the engine runs in the motoring mode; power consumed from the engine is equal to the measured engine's power if the latter is less than or equal to the AC power demand; power consumed from the engine is equal to the AC power demand if the latter is less than the measured engine's power.

3 – Results and analysis

Results with main parameters of bus driving patterns, as were measured in Israel, and data recorded by VITO in Belgium with its on-board system VOEM(Low), Pelkmans et al. (2001), Van Poppel (2003), ARTEMIS project, are presented in Table 2. These data are compared with the parameters of some available European bus driving cycles developed by Steven (1995) and van de Weijer et al (1993), which were kindly supplied by the ARTEMIS partners from TNO, TUG and RWTUEV. The TNO approach suggested by van de Weijer (1997) was used for the calculation of driving pattern/cycle parameters. For the Israeli driving patterns, parameters of each measured run were calculated and their averages for various bus routes are presented in Table 2.

Cycle parameters	Perc. Stop Time [%]	Avg. Speed [km/hr]	Avg. Running Speed [km/hr]	Avg. acceleration [m/s2] Acc > 0.06	Max. acceleration [m/s2]	Perc. accelerating [%] Acc > 0.06	Avg. deceleration [m/s2] Acc < - 0.06	Max. deceleration [m/s2]	Perc. decelerating [%] Acc < -0.06	Perc. cruising [%]	Estimated perc. no brake [%]	RPA [m/s2] Relative Positive Acceleration	PKE [m/s2] Positive Kinetic Energy
DUBC	22.56	20.96	28.29	0.57	1.69	40.00	-0.69	-2.28	33.10	4.33	74.89	0.26	0.53
Braunschweig	22.01	22.50	30.13	0.55	2.13	37.99	-0.74	-3.11	28.62	11.38	79.54	0.21	0.44
Munich L661	25.49	17.54	24.70	0.6	1.65	33.29	-0.60	-2.16	33.43	7.80	77.86	0.24	0.49
9040	19.63	15.62	20.13	0.47	1.37	37.26	-0.48	-1.57	36.51	6.60	72.85	0.21	0.42
10040	18.75	21.46	27.29	0.45	1.34	38.72	-0.51	-1.65	34.61	7.93	77.39	0.19	0.38
11240up	4.57	27.66	29.67	0.37	1.32	46.14	-0.55	-2.32	31.50	17.80	80.16	0.14	0.28
11440down	9.54	30.97	35.65	0.63	1.85	43.34	-0.70	-2.15	38.77	8.35	72.56	0.24	0.48
Stuttgart	32.79	15.88	25.08	0.71	2.36	30.10	-0.66	-1.67	32.24	4.87	72.47	0.27	0.55
Munich L66	23.85	18.83	25.90	0.57	1.66	35.38	-0.63	-2.45	32.31	8.46	78.33	0.23	0.47
VITO 1A	4.39	18.64	20.01	0.43	1.54	45.70	-0.53	-2.07	36.40	13.52	76.78	0.19	0.39
VITO 1B	2.56	21.19	22.31	0.48	1.35	48.40	-0.59	-2.34	39.57	9.47	72.46	0.23	0.47
VITO 2	5.12	24.25	26.44	0.57	1.62	50.41	-0.76	-2.51	38.37	6.10	68.31	0.29	0.58
Pelkmans (2001)	21	17.9	22.8	0.62	1.32	39	-0.72	-1.88	33	7	N/A	0.28	N/A
Route 1a-1b	31.08	17.18	25.15	0.65	2.02	39.15	-0.75	-2.94	35.18	5.42	85.24	0.29	0.61
Route2a down	27.47	19.57	28.50	0.71	2.5	37.10	-0.83	-3.01	31.75	3.68	74.37	0.34	0.72
Route 2b-up	19.49	24.75	32.06	0.63	2.45	40.05	-0.72	-2.52	35.32	5.14	73.64	0.26	0.53
Route 3	36.10	9.58	15.90	0.56	1.97	30.65	-0.61	-2.16	28.51	4.74	78.61	0.25	0.54
Route 4a-4b	29.62	21.60	31.21	0.54	1.67	35.01	-0.63	-2.43	30.09	5.27	78.32	0.24	0.51
Route 5	24.79	21.97	30.59	0.67	1.98	37.87	-0.78	-2.61	32.56	4.77	74.52	0.28	0.58

Table 2: Main parameters of tested bus driving patterns compared to available driving cycles.

In this table: DUBC – Dutch Urban Bus Cycle; 9040 – Handbook urban cycle, short stop distance; 10040 - Handbook urban cycle, long stop distance; N/A – not available.

$$RPA = \frac{\frac{1}{T}\int_0^T \left(V_i \cdot a_i^{+}\right) dt}{\bar{V}} = \frac{\int_0^T \left(V_i \cdot a_i^{+}\right) dt}{distance} \qquad PKE = \frac{\Sigma(V_{next}^2 - V^2)}{distance} \text{ for } (V_{next} - V) > 0$$

Comparison of driving patterns

Comparison of measured driving patterns with available driving cycles (see Table 2) shows that these cycles cover almost the whole range of traffic situations and measured driving patterns. Driving cycles that show better resemblance to the measured driving behavior of buses in Israel are: Dutch Urban Bus Cycle, ~~Braunschweig Cycle, and~~ both Munich and Stuttgart driving cycles – see Table 2 and example in Figure 1. It is noted that there is no available driving cycle, which could describe suitably a congested city center bus driving pattern, as was measured on route 3 – see Tables 1, 2. Driving patterns, as measured by VITO in Turnhout (city with about 40 thousands inhabitants), are described better by the Swiss-German Handbook driving cycles 9040 and 10040 – see example in Figure 1.

From a comparison of the Belgian (Turnhout) and Israeli bus driving patterns, the following observations can be made: much higher percentage of stop time 19.5 – 36.1% in Israel compared to only 2.6 – 5.1% in Belgium was measured, together with lower levels of average (0.43-0.57 compared to 0.54-0.71) and maximal (1.35-1.62 compared to 1.67-2.50) accelerations, and higher percentage of cruising (6.1-13.5% compared to 3.7-5.4%) in Belgian driving patterns. The driving pattern measured by Pelkmans et al. (2001) in Brussels – city with 950000 inhabitants (see Table 2), is closer to the Israeli measurements, but also here lower maximal acceleration/deceleration values and higher percentage of cruising were observed. The above-mentioned numbers illustrate the more aggressive driving style of Israeli bus drivers.

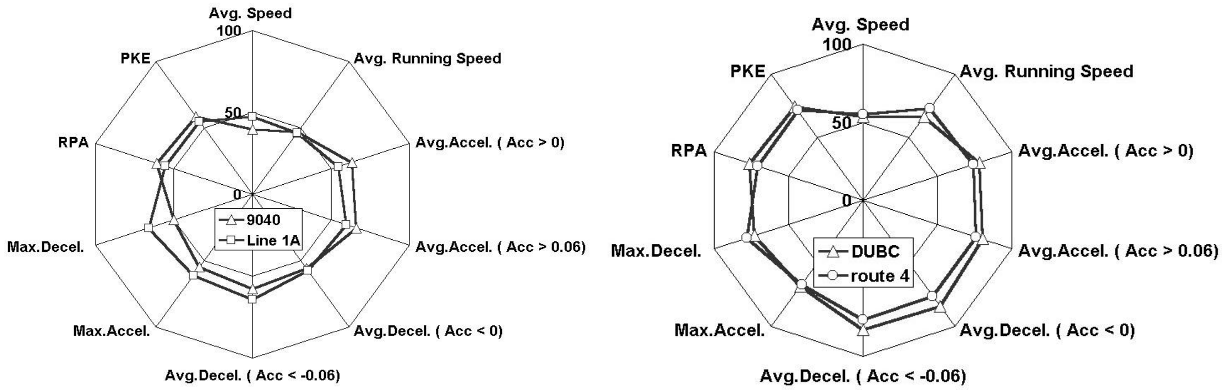

Figure 1: Comparison of measured driving patterns with available driving cycles – examples.

~~The above-mentioned numbers illustrate the more aggressive driving style of Israeli bus drivers.~~ A 'driving dynamics factor' (DDF) is suggested, in order to describe driving dynamics effects on engine power demand. The DDF value was calculated according to the formula:

$$DDF = (TRT/PRT)*V_{PT} \text{ [km/h], where:}$$

TRT – total running time, sec;
PRT – running time with positive engine torque, sec;
V_{PT} – average bus speed of running with positive engine torque, km/h.

Figure 2 shows the dependence of average power demand on DDF values, for a variety of measured bus driving patterns. It can be seen that the average power demand varies remarkably within a given bus route, depending on the driving dynamics (governed by the driving style and road conditions). For example, for route 5 the power demand varies from 56 to 106 kW in accordance with DDF change from 41 to 77 km/h (about 88%); the corresponding change of average running speed for this route is only 48% (from 25.6 to 38 km/h). It was found that the DDF value gives a better measure of how much power is used compared to RPA or speed*accelerations values, Ericsson (2002). For example, the coefficients of correlation between average power demand and DDF, RPA and average running speed*RPA for routes 1a-1b were found to be 0.996, 0.647 and 0.818.

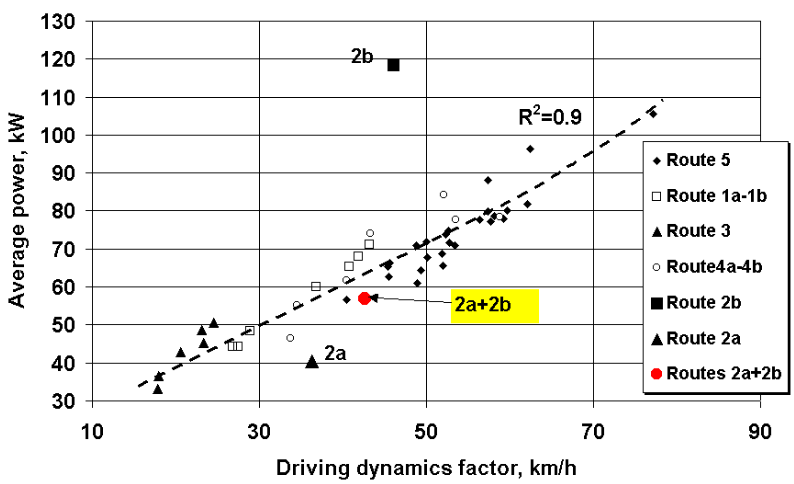

Figure 2: Dependence of the average power demand on the driving dynamics factor.

Figure 2 illustrates also that the dependence of the average power demand on the DDF changes dramatically with the road gradient (see points of routes 2b and 2a on the graph corresponding to uphill and downhill driving, accordingly).

Comparison of the average urban bus speeds in Israel (9.6-24.8 km/h) with those measured in Belgium (18.6-24.2 km/h), shows much lower speed values in city center driving. This results from highly congested traffic and high stop frequency in Israeli city centers. For reasons of comparison: data published by Andre & Hammarstrom (2000) show ranges of average bus speeds for Switzerland - from 6 (when traffic is congested) to 18 km/h and for Germany - from 16 to 21 km/h.

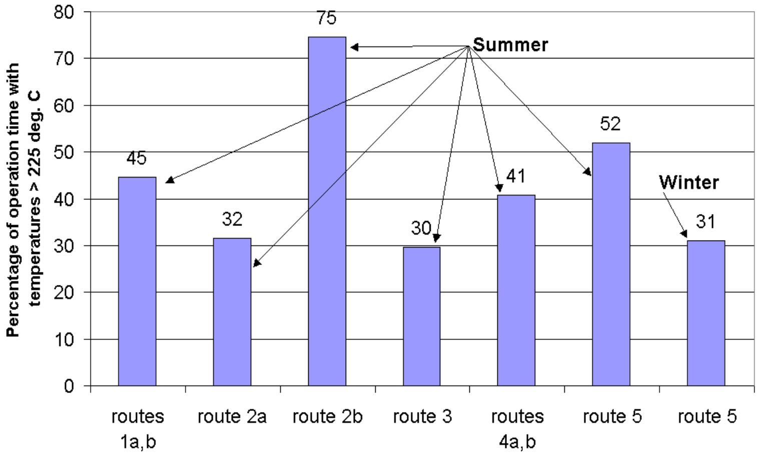

Figure 3: Influence of bus driving pattern on exhaust gas temperature.

Figure 3 shows the influence of the bus driving pattern on the exhaust gas temperature (EGT), as was measured in the experiments carried out in Israel. These data may be useful for the purpose of decision-making concerning installation of exhaust aftertreatment devices in urban buses. As can be seen from Figure 3, for bus driving patterns in congested city centers, the problem of too low temperatures may arise. For example, in route 3 only at 30% of the total driving time the EGT is more than 225 ^{o}C, which may result in problems of light-off or insufficient regeneration of aftertreatment devices. It is noted that the measurements on routes 1-4 were performed during the summer season, when the AC system was operated during almost all of the operation time. On route 5, the appropriate tests were carried out at both summer and winter months. The results show significant differences between measured EGTs (see Figure 3) that resulted mainly from the influence of AC operation on engine power demand. As may be seen from Figure 3, in the winter season the percentage of driving time with EGTs > 225 ^{o}C is about 1.7 times lower compared to summer driving. This may cause severe problems when using exhaust aftertreatment devices. Analysis of measured engine oil and coolant temperatures has shown that only one really cold start per day occurs for all the studied urban bus patterns.

Effects of road gradients

As already noted, the topography of Haifa allowed the measurements of driving behavior on roads with steep gradients. For example, routes 2a & 2b were run on roads with gradients up to 12%. Gradients of more than 3% were measured at about 70% of the total route distance. Figure 4 illustrates the influence of the road gradient on the engine torque, as measured on routes 2a & 2b. It follows from this Figure that the share of maximal torque utilization rises from about 15 to about 55% with the increase of road gradient from the range –3…3% to values of more than 9%. It is interesting to note that even at downhill driving on roads with steep gradients of more than 9%, the share of maximal torque utilization is not zero, but around 3-4%. Figure 4 further illustrates that the most widespread engine operation regimes in Israeli driving patterns are at “motoring” and “full load” modes. This fact validates the previously discussed finding about the aggressiveness of the local driving style.

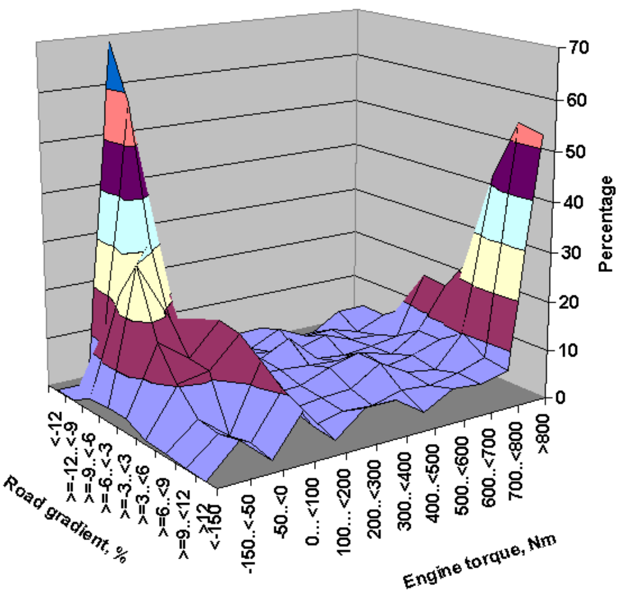

Figure 4: Share of bus engine torque utilization vs. road gradient.

Figure 5 demonstrates utilization of torque and engine speed values in the real-world bus driving on the hilly route (2a+2b). The areas, which were attributed as controlled by the ESC test cycle, are bounded by dotted lines (actual test points are marked by circles). Calculation results show that about 33% of the total operation time, the bus engine runs on modes, which are found outside of the

ESC controlled areas. About 23% of the total operation time the engine runs in motoring mode.

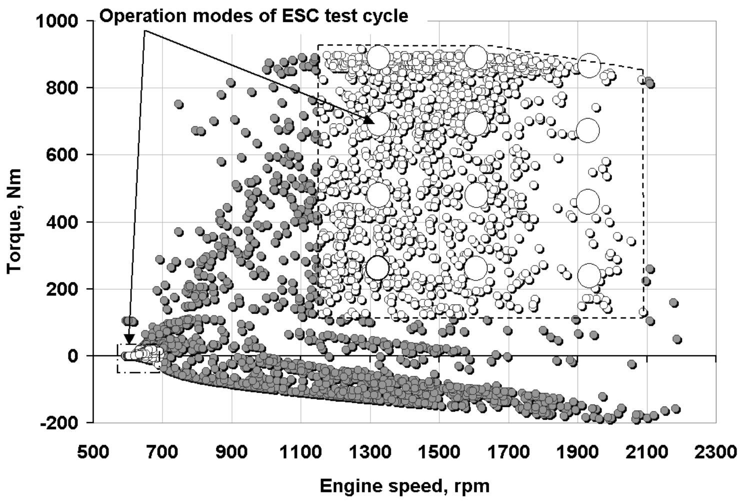

Figure 5: Example of torque values utilization versus engine speed.

Effects of air conditioning

Experiments aimed at estimation of AC effects were carried out on bus route 5. The driving behavior was studied during two summer months (July, August), when the AC system was almost permanently switched-on, and during two winter months (January, February), when it was not used. Data of bus fuel consumption (FC) were received from the bus operator and processed for the above-mentioned periods. Average FC values that were obtained for AC-on and AC-off periods are 65 and 59 l/100 km, respectively. The difference of 10% may be attributed mainly to the effects of AC system operation on engine power demand. It may be assumed that real effects of AC operation on urban bus FC is even greater, due to the negative influence on winter FC of longer lighting times, wet roads etc.

In order to estimate more accurately the AC influence on the bus engine power, the AC system power demand was evaluated according to the method described in chapter 2. Values of AC power were calculated on second-by-second basis for all measured driving patterns, when the AC system was switched-on. Then, weighted average values were calculated. It was found that the average power consumed by the AC system during urban bus driving on route 5 is about 11.5% of the average engine power demand. The mechanical power consumed by the AC at engine idle mode is more than 6.5 kW.

Conclusions

Comparison of measured driving patterns with available driving cycles shows that these cycles cover about the whole range of traffic situations and of the measured driving patterns. Driving cycles that show better resemblance to the measured driving behavior of buses in Israel are: Dutch Urban Bus Cycle, both Munich and Stuttgart driving cycles. There is no available driving cycle, which could describe suitably congested city center bus driving patterns. Development of an appropriate representative driving cycle for this traffic situation is certainly useful.

From comparison of the Belgian (Turnhout) and Israeli bus driving patterns, the following observations can be made: much higher percentage of stop time in Israel compared to Belgium was measured, together with lower levels of average and maximal accelerations, and higher percentage of cruising in Belgian driving patterns. The driving pattern measured in Brussels is closer to the Israeli measurements, but also here lower maximal acceleration/deceleration values and higher percentage of cruising were observed. This illustrates the more aggressive driving style of Israeli bus drivers. The results show that the most widespread engine operation regimes in Israeli driving patterns are at “motoring” and “full load” modes. A ‘driving dynamics factor’ was suggested, in order to describe the driving dynamics effects on engine power demand. It was found that the DDF value gives a better measure of how much power is used compared to RPA or speed*accelerations values.

For bus driving patterns in congested city centers, the problems of light-off or insufficient regeneration of aftertreatment devices may arise, due to the low exhaust gas temperatures. In the winter season the percentage of driving time with EGTs > 225 ^{o}C is about 1.7 times lower compared to summer driving. The share of maximal torque utilization rises from about 15 to about 55% with the increase of road gradient from –3…3% to values of more than 9%.

It was found from a limited study of one urban bus equipped by one specific AC system, that the AC switching-on leads to rise of 11.5% in average power demand and about 10% in fuel consumption. The mechanical power consumed by the AC at engine-idle mode is over 6.5 kW. Detailed study of AC effects on driving behavior and emissions of buses and other heavy-duty vehicles, as also mentioned in the COST 319 Action, is needed.

Acknowledgments

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