FUEL CONSUMPTION MEASUREMENT OF BUS HVAC UNITS

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ABSTRACT

This study presents a new test method for determination of energy consumption of bus HVAC units. The energy consumption corresponds to a bus engine fuel consumption increase during the operation period of the HVAC unit. The bus engine fuel consumption incrementally induced by powering an HVAC unit is determined from the HVAC unit total input power measured under four levels of bus engine speeds and at three levels of total heat load in the laboratory environment. The tested HVAC unit operates in automatic temperature control mode for one hour after reaching setpoint for each test condition. The results are subsequently recalculated to the HVAC unit fuel consumption under the defined road cycles. Therefore, the fuel consumption data gained in this way can give a true picture of real operating conditions.

1. INTRODUCTION

The cooling capacity measurement of HVAC units is a common method, which is specified in ANSI/ASHRAE 37-2009 Standard [1]. Unit cooling capacity at maximum compressor speed is typically used to compare the performance of bus or rail HVAC units. However, the maximum cooling capacity is not practical for recalculating the bus engine fuel consumption increase due to operating the HVAC unit. Most air-conditioned buses are equipped with HVAC units that are powered by the bus engine, either with the compressor driven directly from the engine using a belt or with electric or hydraulic power transmission. In this case, the bus engine speed and thereby the compressor speed varies depending on the bus operating conditions, especially in city traffic. Therefore, a comparison method of transport refrigeration and HVAC units for cooling performance evaluation during a vehicle operation with respect to different engine speeds was introduced in [2].

It is also necessary to calculate the HVAC unit fuel consumption as a function of bus engine speed to effectively compare bus HVAC unit efficiency. The bus engine does not run at a uniform speed, so the contribution of the HVAC unit to overall fuel consumption must be determined by means of an operating profile based on variation of the engine speed. Since bus engine powered HVAC equipment is not fuelled directly, this paper describes a method to determine the HVAC unit’s contribution to the bus fuel consumption by means of the HVAC unit power input measured under specific conditions. Results are used to recalculate the bus engine fuel consumption increment when the HVAC unit is in the operation.

2. METHOD

The described method and test apparatus were developed to compare energy consumption under realistic bus HVAC unit operating conditions and in order to avoid the drawbacks of calculating the unit energy consumption from standard cooling capacity test results aimed only at nominal performance. Bus engine fuel consumption increases during HVAC unit operation which is controlling the bus interior temperature setpoint. The measurement is performed at steady state conditions after the setpoint is reached and the pull down mode is excluded from this test. The measurement procedure considers the steady state operating conditions of bus HVAC unit and excludes other influences such as the particular bus, engine type, and driver’s style. Therefore, the HVAC unit energy consumption is determined from the unit total input power
measurement under the specific conditions in the laboratory system. The results are subsequently recalculated to the HVAC unit diesel consumption by means of a standard specific fuel consumption of the standard diesel engine [4] under the defined road cycles.

2.1. Test setup

The fuel consumption test setup is different than the standard cooling capacity test setup. During the nominal cooling capacity test the HVAC unit is manually switched ON with its evaporator and condenser blowers operating in high speed mode. Therefore, the compressor power input $P_C$ and the fan input power $P_F$ is measured at the maximum operating condition. During the fuel consumption test, the HVAC unit operates for a time interval $T_P$ (e.g. 1 hour) in automatic temperature control mode, in which the compressor works in the ON-OFF regime, and the evaporator and condenser fans work at various levels of speed according to the adjusted heat load level $Q_{\%}$ at defined temperature setpoint $T_S$ and constant ambient temperature $T_A$. As a consequence, the measured HVAC unit power input $P$ corresponds more to the unit power consumption in reality.

In order to represent the bus internal volume, an air-duct testing line with internal volume 50 m$^3$ was designed in IR ETC Prague lab. The testing line was built for large and tourist buses, but the dimensions can be modified for smaller or larger buses. The new air-duct line was added to the measurement system for HVAC unit air-flow and cooling capacity testing. The fuel consumption test can follow the standard cooling capacity test and the HVAC unit installation remains without any change.

Figure 1 illustrates the complete test system developed for the fuel consumption test. The HVAC unit is installed in the hot room with controlled ambient temperature $T_A$. The unit operates in automatic control mode with setpoint temperature $T_S$ under the testing heat load level $Q_{\%}$. The test unit is connected with the testing line in the test room, which represents the internal volume of the bus. The testing heat load $Q_{\%}$ is generated in the “bus model” test line in order to represent a realistic heat load for the test unit. The testing heat load $Q_{\%}$ corresponds to on-road operation of the HVAC unit and it is defined as a percentage from nominal cooling capacity $Q_0$ at maximum compressor speed of the HVAC unit.

![Figure 1: Schema of the new testing system for fuel consumption measurement of bus HVAC units.](image-url)
2.2. Test conditions

Testing heat load $\dot{Q}_\%$ is described in Eq. (1) and consists of two thermal components, latent heat load $\dot{Q}_L$ and sensible heat load $\dot{Q}_S$.

$$\dot{Q}_\% = \dot{Q}_L + \dot{Q}_S$$  \hspace{1cm} (1)

Latent heat load $\dot{Q}_L$, which is associated with humidity produced by passengers in the bus, is simulated by a latent heat source (boiling water), which is installed in the mixing room. The latent heat load $\dot{Q}_L$ is defined as 10 % of the maximum cooling capacity $\dot{Q}_0$, which represents a presumed number of passengers. This definition is based on the assumption that the size of the test HVAC unit is directly proportional to the expected number of passengers. The sensible heat load $\dot{Q}_S$ corresponds to heat gains due to heat transfer via bus walls, solar radiation and from passengers. The fresh air load and infiltration due to door opening are not simulated. The power input $P_S$ of the sensible heat load source, which is installed in the testing air-duct line, is controlled depending upon the required testing heat load $\dot{Q}_\%$, latent heat load $\dot{Q}_L$, duct test line heat gains $\dot{Q}_G$ and duct line fan input power $P_f$ as described in Eq. (2).

$$P_S = \dot{Q}_\% - \dot{Q}_L - \dot{Q}_G - P_f$$  \hspace{1cm} (2)

The sensible heat load $\dot{Q}_S$ is maintained constant and independent of the test system changes which are caused by the automatic ON-OFF control of the HVAC unit. The duct line fan input power $P_f$ is monitored as a function of $f_1$, where $f_1$ is the variable supply frequency of the fan. The test line heat gain $\dot{Q}_G$ is calculated by means of Eq. (3) from the inside temperature $T_i$ and the outside temperature $T_o$, the heat transfer surface $S_L$, and the heat transfer coefficient $k_L$ of the test line.

$$\dot{Q}_G = k_L \times S_L \times (T_o - T_i)$$  \hspace{1cm} (3)

The test unit is automatically switched ON and OFF under the testing heat load levels $\dot{Q}_\%$. The unit power consumption $P$ is measured at three testing heat load levels e.g. $\dot{Q}_{30\%}$, $\dot{Q}_{40\%}$, $\dot{Q}_{50\%}$, which are defined as a percentage from maximum cooling capacity $\dot{Q}_0$. The maximum heat load $\dot{Q}_{M\%}$ is estimated in advance by means of cooling capacity measurement at the temperature conditions $T_A = 35 \, ^\circ C$, $T_S = 27 \, ^\circ C$ and relative humidity 50 % for idle bus engine speed $n_B = 500 \, \text{RPM}$. Subsequently, the HVAC unit power consumption as a function of heat load $P = P(\dot{Q}_\%)$ can be calculated.

Compressor power curves are derived through testing on a component level test system where torque $M$ is measured at constant rotational speed $n_C$. Bus engine speed $n_B$ is based on bus road cycles [3] under real conditions. Four bus engine speeds $n_B$ are defined at 500 RPM, 1000 RPM, 1500 RPM, and 1900 RPM according to Thermo King’s standard road profile. The speed ratio $\lambda$ between engine and compressor is set according to the real installation. For example, if the speed ratio is defined as $\lambda = 1.3$, the test compressor speed $n_C$ is adjusted to 650 RPM, 1300 RPM, 1950 RPM, and 2470 RPM. The evaporator and condenser fan speed profiles are not defined because the fan’s speed is set by the unit controller. Their power consumption $P_f$ is added to the compressor power consumption $P_C$.

Fuel test temperature conditions are based on Thermo King standard temperature conditions used for cooling capacity tests. The ambient temperature $T_A$ is 35 °C and HVAC unit controller setpoint temperature $T_S$ is adjusted to 27 °C. The relative humidity is influenced by the latent heat $\dot{Q}_L$ and varies with compressor ON-OFF cycling. However, temperature verification tests indicate that temperature level setting have a negligible effect on the fuel test results. The selection of temperature points below or above Thermo King standard conditions has insignificant impact on HVAC unit power consumption $P$. Therefore, the method is not limited to the particular temperature conditions and can be applied in general for various temperature points.
3. RESULTS

3.1. Test data output - power consumption determination

Figure 2 illustrates a model diagram of the measured compressor operation in ON-OFF cycles.

\[
P_C = 2\pi n M \tag{7}
\]

\[
\overline{P}_C = P_C \times T_R \tag{8}
\]

\[
P_F = U I \tag{9}
\]

The test period \(T_P\) is described in Eq. (4) and consists of time \(T_{ON}\) and time \(T_{OFF}\), for which compressor is switched ON and OFF. The total unit operation time during the fuel test time \(T_T\) is calculated from the number \(p\) of measured periods and the period time \(T_P\) as depicted in Eq. (5). The next step is calculating the time ratio \(T_R\) between overall compressor ON time \(T_{ON}\) and total unit operation time \(T_T\). See Eq. (6).

\[
T_P = T_{ON} + T_{OFF} \tag{4}
\]

\[
T_T = T_P \times p \tag{5}
\]

\[
T_R = (\sum T_{ON}) / T_T \tag{6}
\]

The instantaneous compressor input power \(P_C\) is calculated from the rotational speed \(n\) and torque \(M\) as shown in Eq. (7). Mean compressor input power \(\overline{P}_C\) is calculated by means of Eq. (8) from instant compressor input power \(P_C\) and the time ratio \(T_R\). HVAC unit electric fan and blower input power is calculated from measured supply voltage \(U\) and measured current \(I\) as shown in Eq. (9).

The compressor mean power consumption \(\overline{P}_C\) and fan power consumption \(P_F\) as a function of heat load level \(Q_{\%}\) is determined for each bus engine speed \(n_B\). An example of test results is shown in Figure 3. The next step is to determine the analytical functions of compressor power consumption \(\overline{P}_C\) and fan power consumption \(P_F\) at bus engine speed \(n_B\) for each heat load \(Q_{\%}\) for subsequent calculations of compressor and fan power at bus speeds defined by the particular bus road profile. The example of recalculated real test data is shown in Figure 4.
Figure 3: Test data example of compressor and fans power consumption as a function of heat load.

Figure 4: Example of recalculated data of compressor and fans power consumption vs. bus engine speed.

3.2. Recalculation to the energy consumption according to the bus road profile

The bus road profile is based on engine speed during bus operation. Typical bus engine speeds $n_{BR}$ and cycles durations $t_R$ were selected for Thermo King (TK) standard road profile, which consists of a mix of real cycles (City Bus Duty C.B.D., Idle, High idle, Arterial and Commuter Cycle). TK Road profile, summarized in Table 1, is employed for the next calculations.

The test data are recalculated based upon the compressor and fan power consumption $P_{CR}$ and $P_{FR}$ related to the TK road profile bus speeds $n_{BR}$ for each of the tested heat load level $Q_\%$. The test data may be recalculated according to any other road profile and for other heat load levels. An example of compressor and fans power consumption at TK bus engine speeds is shown in Table 2.

<table>
<thead>
<tr>
<th>Bus cycle:</th>
<th>Idle</th>
<th>High idle</th>
<th>C.B.D.</th>
<th>Arterial</th>
<th>Commuter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus Engine Speed $n_{BR}$ [RPM]</td>
<td>500</td>
<td>1000</td>
<td>1250</td>
<td>1700</td>
<td>1850</td>
</tr>
<tr>
<td>Duration $t_R$ [s]:</td>
<td>701</td>
<td>300</td>
<td>1197,0</td>
<td>375,2</td>
<td>257,0</td>
</tr>
<tr>
<td>Route [km]:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Thermo King road profile bus engine speeds definition
Table 2: Example of compressor and fans power consumption at TK road profile bus engine speeds

<table>
<thead>
<tr>
<th>Relative Heat Load Level [%]</th>
<th>Bus Engine Speed $n_{BR}$ [RPM]</th>
<th>Compressor Power Consumption $P_{CR}$ at TK standard BUS speeds [kW]</th>
<th>Fans Power Consumption $P_{FR}$ at TK standard BUS speeds [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
<td>1,4 2,1 2,4 3,0 3,1</td>
<td>30 0,9 0,7 0,6 0,6</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>1,7 2,6 3,2 4,2 4,4</td>
<td>40 1,0 0,8 0,7 0,7</td>
</tr>
<tr>
<td></td>
<td>1250</td>
<td>2,4 3,4 4,1 5,1 5,3</td>
<td>50 1,2 0,9 0,8 0,8</td>
</tr>
<tr>
<td></td>
<td>1700</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1850</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compressor and fan power consumptions $P_{CR}$ and $P_{FR}$ at the TK Road profile are recalculated to the compressor and fan energy consumption $E_{CR}$ and $E_{FR}$ at overall the TK Road Profile, which lasts 0.79 hour. For HVAC unit energy consumption over a one-hour period $E_{CR}^{th}$ and $E_{FR}^{th}$ the data are recalculated for compressor and fan energy consumption, $E_{CR}^{th}$ and $E_{FR}^{th}$ respectively, at TK road profile for each of heat load level $Q_{th}$. An example of the test data recalculation is shown in Figure 5. The vehicle powered HVAC units usually take electric current of the vehicle alternator to drive electric fans. Therefore, the vehicle alternator efficiency must be included to the calculation of fans energy consumption $E_{FR}^{th}$. Reasonable alternator efficiency estimation is defined as standard vehicle alternator efficiency $\varepsilon = 50 \%$ in [4].

Figure 5: Example of compressor, fans and total HVAC unit energy consumption at TK Road Profile

### 3.3. Bus fuel consumption increase at the HVAC unit operation lifetime

The data are finally recalculated as shown in Eq. (10). The one-hour HVAC unit diesel consumption $C_{R}^{th}$ at the TK Road Profile is dependent on the one-hour HVAC unit energy consumption at the TK Road Profile $E_{R}^{th}$, the fuel consumption of a typical diesel engine $c_s$ (165 g/(kW.h), and the diesel fuel density $\rho$ (836 g/l), which are defined in [4].

$$C_{R}^{th} = \frac{(E_{R}^{th} \times c_s)}{\rho}$$  \hspace{1cm} (10)

The one-hour HVAC unit diesel consumption $C_{R}^{th}$ at the TK road profile can express the fuel consumption $C_{R}$ per HVAC unit lifetime at the same road profile by means of defining bus lifetime $t_B$ and average annual operating time $\tau$, see Eq. (11). An example of HVAC unit diesel consumption at the TK road profile per unit lifetime is shown in Table 3 with $t_B = 12$ years and $\tau = 2000$ h / y.

$$C_{R} = C_{R}^{th} \times t_B \times \tau$$  \hspace{1cm} (11)
Table 3: Example of an HVAC unit fuel consumption at TK road profile per HVAC unit lifetime

<table>
<thead>
<tr>
<th>Nominal cooling capacity ( \hat{Q}_0 ) [kW]</th>
<th>Relative Heat Load Level [%]</th>
<th>Heat Load ( Q_{%} ) [kW]</th>
<th>One Hour Fuel Consumption ( C_R^{1h} ) [l/h]</th>
<th>Fuel consumption per HVAC unit lifetime ( C_R ) [l]</th>
<th>Specific One Hour Fuel Consumption ( c_R ) [l/(kW. h)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>30</td>
<td>7,5</td>
<td>0,93</td>
<td>22 421</td>
<td>0,108</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>10,0</td>
<td>1,06</td>
<td>25 386</td>
<td>0,107</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>12,5</td>
<td>1,30</td>
<td>31 315</td>
<td>0,105</td>
</tr>
</tbody>
</table>

Specific one-hour fuel consumption \( c_R \), which is given in the last column of Table 3, represents an eligible value for economy comparison of different bus HVAC units. It is calculated as one-hour fuel consumption \( C_R^{1h} \) [l/h] divided by the corresponding heat load \( \hat{Q}_0 \) [kW] as shown in Eq. (12)

\[
c_R = \frac{C_R^{1h}}{\hat{Q}_0}
\]

(12)

3.4. Determination of comparative parameters

The final results of the fuel consumption test for an adequate comparison of the HVAC units are defined by means of two parameters. The first parameter is one-hour specific fuel consumption at the particular road profile \( c_R \) and the second parameter is called the maximum allowed heat load \( \hat{Q}_A \). The determination of the maximum allowed heat load for the HVAC unit at the road profile is an important part of the fuel test procedure for correct interpretation of test results. The maximum allowed heat load \( \hat{Q}_A \) is defined as a percentage from the nominal cooling capacity \( \hat{Q}_0 \) and it means limiting the heat load to the point where the HVAC unit is still able to maintain the temperature setpoint at given conditions and at the range of particular road profiles. This implies if the HVAC unit is running at mean compressor speed corresponding to the mean bus engine speed at the road profile, then a maximum heat load limit exists for maintaining the required setpoint. The mean bus engine speed \( \bar{n}_{BR} \) at the TK Road Profile is calculated according to Table 1 from the bus engine speeds \( n_{BR} \) and corresponding cycle duration \( t_R \), see Eq. (13). For the TK Road Profile is \( \bar{n}_{BR} = 1150 \) RPM, but in general its value is strongly dependent on the definition of particular road profile.

\[
\bar{n}_{BR} = \frac{\sum (n_{BR} \times t_R)}{\sum t_R}
\]

(13)

If the heat load \( \hat{Q}_0 \) would be greater than the maximum allowed heat load \( \hat{Q}_A \) at \( \bar{n}_{BR} \), the fuel test result is not correct above the point of the maximum allowed heat load \( \hat{Q}_A \), because the internal bus temperature \( T_B \) is increasing above the allowed setpoint offset (see Figure 6). For the regular comparison of the HVAC units we defined 40% from nominal cooling capacity \( \hat{Q}_0 \) as a comparison heat load \( \hat{Q}_{40\%} \) for the fuel consumption recalculations. The value of \( \hat{Q}_{40\%} \) corresponds to the average HVAC unit’s heat load of real buses during their operation in middle Europe. However, the test results might be recalculated to the fuel consumption at any other requested heat load \( \hat{Q}_{\%} \) below the maximum allowed heat load \( \hat{Q}_A \).

Figure 6: Maximal allowed heat load illustration on real example of the measured data.
4. DISCUSSION

The entering into force of EC Directive 2009/33/EC [5] results in new requirements to get comparable energy consumption data in order to calculate operational lifetime costs of bus vehicles. The operational lifetime cost of the energy consumption of a bus HVAC unit might be calculated based on test results obtained by means of the presented test method. Additionally, the results can be added to the operational lifetime costs of the whole bus in order to compare energy requirements of buses equipped with various types of HVAC units. In terms of applicability to different kinds of HVAC units, the method will be submitted as a draft for the standardized test procedure to the International Association of Public Transport (UITP). The UITP organization is active in proposing standardized tests for fuel consumption measurement of entire buses by means of the “SORT project”, Standardized On-Road Tests cycles [3]. The final fuel consumption test results might have the following format as depicted in Table 4.

Table 4: Example of the fuel consumption test data recalculated according to the Directive 2009/33/EC.

<table>
<thead>
<tr>
<th>Diesel price without tax</th>
<th>663.86</th>
<th>EUR/1000 litres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of emissions per overall HVAC unit operation</td>
<td>EUR 16 853</td>
<td></td>
</tr>
<tr>
<td>Cost of CO₂ emission</td>
<td>EUR 2 696</td>
<td></td>
</tr>
<tr>
<td>Cost of NOx emission</td>
<td>EUR 1 132</td>
<td></td>
</tr>
<tr>
<td>Cost of PM emission</td>
<td>EUR 71</td>
<td></td>
</tr>
<tr>
<td>Specific one hour fuel consumption</td>
<td>l/(kW.h) 0.107</td>
<td></td>
</tr>
<tr>
<td>Standard heat load (40% of maximal cooling capacity)</td>
<td>kW 9.92</td>
<td></td>
</tr>
<tr>
<td>Standard one hour fuel consumption of HVAC unit</td>
<td>l/h 1.058</td>
<td></td>
</tr>
<tr>
<td>Fuel consumption per overall HVAC unit operation hours</td>
<td>l 25 386</td>
<td></td>
</tr>
<tr>
<td>Produced emission of CO₂ per overall HVAC unit operation</td>
<td>t 77.0</td>
<td></td>
</tr>
<tr>
<td>Maximal allowed heat load</td>
<td>kW 18.3</td>
<td></td>
</tr>
<tr>
<td>Cost of CO₂ emission</td>
<td>EUR 2 696</td>
<td></td>
</tr>
<tr>
<td>Cost of NOx emission</td>
<td>EUR 1 132</td>
<td></td>
</tr>
<tr>
<td>Cost of PM emission</td>
<td>EUR 71</td>
<td></td>
</tr>
<tr>
<td>Specific one hour fuel consumption</td>
<td>l/(kW.h) 0.107</td>
<td></td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

This paper presents the new test method and examples of the test results focused on fuel consumption determination during the operation period of vehicle powered bus HVAC units. The principle of fuel consumption test consists in the HVAC unit power consumption measurement at various compressor speeds and under the heat loads corresponding to the real bus operation. The tested HVAC unit works in automatic temperature control mode with adjusted setpoint temperature at controlled ambient temperature through a test period from reaching the requested setpoint. The test results are recalculated to the HVAC unit fuel consumption under defined road cycles. The test system is based on simulation of real bus HVAC units operating conditions in the laboratory environment in order to get comparable test data for various kinds of bus HVAC units. Therefore, the method is planned to be submitted as a draft of the standardized test procedure to the International Association of Public Transport UITP for the next phase of the ‘SORT’ project. Additionally, in order to express and compare energy requirements together with road transport emissions of buses equipped by various brands of HVAC units, these fuel consumption test data can be used for calculations of the operational lifetime costs as requested by European Directive 2009/33/EC.

6. REFERENCES