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Bus HVAC energy consumption test method based on HVAC unit behavior

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ABSTRACT

This paper presents a test method for determination of energy consumption of bus HVAC unit. The energy consumption corresponds to a bus engine fuel consumption increase during the HVAC unit operation period. The HVAC unit energy consumption is determined from the unit input power, which is measured under several levels of bus engine speeds and at different levels of testing heat load in the laboratory environment. Since the bus engine fuel consumption is incrementally induced by powering an HVAC unit, the results are subsequently recalculated to the unit fuel consumption under the defined road cycles in terms of standardized diesel engine. The method is likewise applicable either for classic or electric HVAC units with a main consumer (compressor or high voltage alternator) mechanically driven directly from the bus engine and also for electric HVAC units supplied from an alternative electric energy source in case of hybrid or fully electric buses.

Méthode d'essai pour déterminer la consommation d'énergie d'un système de chauffage, de ventilation et de conditionnement d'air d'un bus fondée sur le comportement du système

Mots clés : bus ; système de chauffage ; de ventilation et de conditionnement d'air ; puissance d'entrée ; moteur standard ; consommation de carburant ; méthode d'essai

1. Introduction

Mobile HVAC systems in vehicles are important energy consumers. The influence of HVAC operation on the fuel consumption and emissions of passenger cars (M1 vehicles comprising no more than eight seats in addition to the driver's seat) has been discussed rather thoroughly during the last 10 years, see for example Benouali et al. (2003), Vermeulen et al.

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Nomenclature

c_R	specific fuel consumption [$L \cdot kW^{-1} \cdot h^{-1}$]
c_s	fuel consumption of a standard diesel engine [$g \cdot kW^{-1} \cdot h^{-1}$]
C	fuel consumption [$L \cdot h^{-1}$]
COP_{HVAC}	coefficient of performance for HVAC systems [–]
E	energy consumption [$kW \cdot h$]
f	power supply frequency [Hz]
I	electric fans current [A]
k	heat transfer coefficient [$W \cdot m^{-2} \cdot K^{-1}$]
m_E	specific mass of emissions reduced to the unit of energy or to 1 litter of fuel [$g \cdot kW^{-1} \cdot h^{-1}$, $g \cdot L^{-1}$]
M	torque [$N \cdot m$]
n	rotational speed [min^{-1}]
p	number of test periods [–]
P	input power [kW]
$\bar{P}$	mean input power [kW]
$\dot{Q}$	testing heat load [kW]
$\dot{Q}_{\%}$	relative heat load level [%]
$\dot{Q}_u$	HVAC unit cooling capacity [kW]
t	time [s, min, h]
t_B	standard average bus lifetime [year]
t_{RT}	time ratio [–]
T	temperature [°C]
S	heat transfer surface [m^2]
U	electric fans supply voltage [V]
Greek letters	
ϕ	price [$EUR \cdot L^{-1}$, $EUR \cdot kg^{-1}$]
ε	cost [EUR]
η	standard vehicle alternator efficiency [%]
λ	speed ratio between bus engine and the main consumer [-]
ρ	standard fuel density [$g \cdot L^{-1}$]
τ	standard average operating hours for bus HVAC units per year [$h \cdot year^{-1}$]
Subscripts and superscripts	
A	ambient
B	bus
BE	bus engine
C	main consumer (compressor or dedicated alternator) of HVAC unit
CO_2	carbon dioxide
D	diesel (fuel)
E	emission
F	electric fans of HVAC unit
I	inside
L	latent
max	maximal
min	minimal
nom	nominal
O	outside
OFF	turned OFF
ON	turned ON
P	period
R	road profile (specific profile described in Table 1 is marked with capital *R*)
S	sensible
(SP)	setpoint
t	lifetime
T	total
(TL)	testing line
(TLF)	testing line fan
U	HVAC unit

(2005), Weilenmann et al. (2005), Weilenmann et al. (2010), EU Commission Consultation Paper (2003), or Shecco Technology (2007). Nevertheless, literature review about related publications shows that commensurate attention is missing in case of bus air conditioning systems. We try to fill this gap by this paper.

The cooling capacity measurement of HVAC units is a common evaluation method, which is specified for example in ASHRAE 37 Standard (2009). HVAC unit cooling capacity at maximum compressor speed is typically used in order to compare the performance of bus or rail HVAC units. Air-conditioned buses are typically equipped with HVAC units that are powered by the variable speed bus engine and therefore the maximum cooling capacity is not practical for the recalculation of bus engine fuel consumption increase. The variable speed bus engine is usually operating at high speed for very short time, so it does not represent realistic operation conditions.

HVAC unit main consumer, compressor or dedicated alternator, is usually driven from the bus engine using a belt or by an electric or hydraulic power transmission and the compressor speed can either follow the bus engine speed or it can be practically independent on engine speed. Hence Ryska et al. (2000) introduced a comparison method for cooling performance evaluation of transport refrigeration and HVAC units during a vehicle operation with respect to different engine speeds.

Accordingly, it is necessary to calculate the HVAC unit energy 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, therefore the contribution of the HVAC unit to overall bus 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 fueled directly, this study describes a method how to determine the HVAC unit's contribution to the bus fuel consumption by means of the HVAC unit power input measured under defined conditions. Gained results are consequently used for recalculation of the bus engine fuel consumption increment while the HVAC unit is running. Proposed method is also applicable for energy consumption measurement of electric HVAC units supplied from an electric energy source of hybrid or fully electric buses. However, for this case the energy consumption of bus HVAC unit is not dependent on the particular bus engine speed.

2. Method

The new method and test apparatus were developed to compare energy consumption of bus HVAC unit at defined