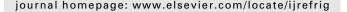
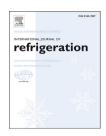




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Bus HVAC energy consumption test method based on HVAC unit behavior

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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.

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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
                                                                                  standard fuel density [g·L-1]
                                                                       ρ
                                                                                  standard average operating hours for bus HVAC
          specific fuel consumption [L \cdot kW^{-1} \cdot h^{-1}]
CR
                                                                                  units per year [h·year<sup>-1</sup>]
          fuel consumption of a standard diesel engine
c_s
          [g \cdot kW^{-1} \cdot h^{-1}]
                                                                       Subscripts and superscripts
С
          fuel consumption [L \cdot h^{-1}]
                                                                                  ambient
                                                                       Α
COP<sub>HVAC</sub> coefficient of performance for HVAC systems [-]
                                                                       В
                                                                                  hus
          energy consumption [kW·h]
                                                                       BE
                                                                                  bus engine
          power supply frequency [Hz]
                                                                       С
                                                                                  main consumer (compressor or dedicated
T
          electric fans current [A]
                                                                                  alternator) of HVAC unit
          heat transfer coefficient [W·m<sup>-2</sup>·K<sup>-1</sup>]
k
                                                                       CO_2
                                                                                  carbon dioxide
          specific mass of emissions reduced to the unit of
                                                                       D
                                                                                  diesel (fuel)
m_E
          energy or to 1 litter of fuel [g \cdot kW^{-1} \cdot h^{-1}, g \cdot L^{-1}]
                                                                       Ε
                                                                                  emission
                                                                       F
          torque [N·m]
                                                                                  electric fans of HVAC unit
M
          rotational speed [min<sup>-1</sup>]
                                                                       Ι
                                                                                  inside
n
          number of test periods [-]
                                                                       L
                                                                                  latent
р
P
          input power [kW]
                                                                       max
                                                                                  maximal
Ē
          mean input power [kW]
                                                                       min
                                                                                  minimal
ġ
          testing heat load [kW]
                                                                       nom
                                                                                  nominal
ġ"
          relative heat load level [%]
                                                                       0
                                                                                  outside
          HVAC unit cooling capacity [kW]
                                                                       OFF
                                                                                  turned OFF
Q_{u}
          time [s, min, h]
                                                                       ON
                                                                                  turned ON
t_B
          standard average bus lifetime [year]
                                                                       Р
                                                                                  period
t_{RT}
          time ratio [-]
                                                                       R
                                                                                  road profile (specific profile described in Table 1 is
Т
          temperature [°C]
                                                                                  marked with capital R)
S
          heat transfer surface [m<sup>2</sup>]
                                                                       S
                                                                                  sensible
U
          electric fans supply voltage [V]
                                                                       (SP)
                                                                                  setpoint
                                                                                  lifetime
                                                                       t
Greek letters
                                                                       т
                                                                                  total
          price [EUR·L<sup>-1</sup>, EUR·kg<sup>-1</sup>]
                                                                       (TL)
                                                                                  testing line
          cost [EUR]
                                                                       (TLF)
                                                                                  testing line fan
          standard vehicle alternator efficiency [%]
                                                                                  HVAC unit
          speed ratio between bus engine and the main
          consumer [-]
```

(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. Airconditioned 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

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