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Experimental assessment of the energy consumption of urban rail vehicles during stabling hours: influence of ambient temperature

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Abstract

Urban rail has widely recognised potential to reduce congestion and air pollution in metropolitan areas, given its high capacity and environmental performance. Nevertheless, growing capacity demands and rising energy costs may call for significant energy efficiency improvements in such systems. Energy consumed by stabled rolling stock has been traditionally overlooked in the scientific literature in favour of analysing traction loads, which generally account for the largest share of this consumption. Thus, this paper presents the methodology and results of an experimental investigation that aimed to assess the energy use of stabled vehicles in the Tyne and Wear Metro system (UK). It is revealed that approximately 11% of the rolling stock's total energy consumption is due to the operation of on-board auxiliaries when stabled, and investigation of these loads is therefore a worthwhile exercise. Heating is responsible for the greatest portion of this energy, and an empirical correlation between ambient temperature and power drawn is given. This could prove useful for a preliminary evaluation of further energy saving measures in this area. Even though this investigation focused on a particular metro system in a relatively cold region, its methodology may also be valid for other urban and main line railways operating in different climate conditions.

Keywords: urban rail; experimental investigation; energy consumption; on-board auxiliary systems, temperature dependence.

1. Introduction

Metropolitan transportation is responsible for about 25% of the CO₂ emissions caused by the transport sector in the European Union (EU) (European Commission, 2011), which approximately represents 8% of total greenhouse gas emissions in the EU (IEA & UIC, 2012). Furthermore, high levels of air pollution and congestion are major problems usually associated with urban mobility. Therefore, more efficient, reliable and environmentally friendly transport systems are key in dealing with increasing urbanisation, whilst reducing GHG emissions and enhancing living conditions in urban areas.

Urban rail is well placed to mitigate the impact of the problems associated with urban mobility because of its high capacity, safety, reliability and absence of local emissions (Vuchic, 2007). In addition, it typically has lower CO₂ emissions per passenger than competing transportation modes, although this is dependent on passenger load factors and the electricity generation mix (Chester & Horvath, 2009). Nevertheless, in a context characterised by rising energy costs and growing capacity demands, and where other modes such as automotive are making significant improvements in their environmental performance, it is critical that urban rail minimises its energy consumption while enhancing its service quality.

Energy use in railway systems is commonly classified into traction and non-traction loads. The former comprises the power required to operate the rolling stock across the system (including propulsion and on-board auxiliary systems), whereas the latter accounts for the energy utilised at stations, depots and other facilities in the system. On average, traction energy consumption generally represents between 70% and 90% of the total energy consumption in urban rail systems, of which around 20% is due to on-board auxiliaries (González-Gil, et al., currently under review). Hence, the majority of proposals to reduce energy consumption in railway systems have focused on the traction system itself, primarily by using regenerative braking (González-Gil, et al., 2013), applying energy-efficient driving strategies (De Martinis, et al., 2013), or improving the propulsion chain efficiency (Kondo, 2010). In turn, there has been relatively less focus on the on-board auxiliary systems.

Auxiliary power is required for two main purposes: control and cooling of vehicle systems, and comfort functions – these include heating, ventilation and air-conditioning (HVAC), lighting and information systems. HVAC equipment is generally responsible for the most significant part of this consumption, with a clear dependency on climate conditions. In the Oslo metro for instance, heating accounts for 78% of the auxiliary consumption, with 3% for control systems and the remaining 19% for other auxiliaries such as lighting and air supply (Struckl, et al., 2006). This corresponds to heating accounting for 28% of the vehicle consumption overall. In addition, variations of up to 38% in the total energy consumption were found between summer and winter months for a fleet of regional trains operating in Sweden (Andersson & Lukaszewicz, 2006).

On-board auxiliary systems remain partially or fully operative while trains are stabled in sidings or depots. This is principally to facilitate cleaning operations and to prevent damage to vulnerable components, for example any condensation in the air supply system freezing overnight. Furthermore, it is necessary to reach the desired comfort conditions (such as temperature) in vehicles before they enter service. Therefore, the operation of on-board auxiliaries while trains are out of service may account for a significant portion of the total energy consumption – for example general studies of Central and Northern Europe main line services estimated energy consumption of stabled trains to be around 10–15% of the system's total energy consumption (UIC, 2003), (Peckham, 2007). The scarcity of information and experimental data published in the academic literature – particularly for the case of urban rail – seems to call for more thorough investigations.

The main purpose of this paper is therefore to develop a deeper understanding and promote awareness of power consumed by rail vehicles while stabled. To achieve this, the outcomes of an experimental investigation aimed at assessing the energy use of stabled vehicles in the Tyne and Wear Metro (UK) are presented. The paper starts by briefly describing the Metro system, continues by explaining the research methodology and concludes by showing and discussing the main energy consumption results obtained for a single vehicle while stabled. Special emphasis is placed on examining the influence of ambient temperature upon the on-board auxiliaries' energy consumption. Although this paper focuses on an urban rail system as the specific case study, it is intended that the methodology described could be applied to all rail systems.

2. Introduction to the Tyne and Wear Metro system

2.1. General description and climate conditions

The Tyne and Wear (T&W) Metro is a light rail system centred on Newcastle upon Tyne in the north-east of England. First opened in 1980 as a 54 km route (of which 41 km had been adapted from existing heavy-rail tracks), currently the T&W Metro consists of a 78 km network that links the cities of Sunderland, Gateshead and Newcastle with the local airport and coastal regions. It is the second largest urban rail system in the UK (after London Underground), and the only one powered by an overhead 1500 V DC supply network. Further details on the T&W Metro can be found in (Howard, 1976), (Prickett, 1981), (Mackay, 1999) and (Pflitsch, et al., 2012).

The original rolling stock remains in service today, although it was refurbished between 1995 and 2000, and is currently undergoing life extension work to run until the mid-2020s. The fleet consists of ninety identical 28 m long twin-section articulated Metrocars built by Metro-Cammell; there are 68 seats, although around 300 passengers may be carried under crush load conditions. A single articulated Metrocar is carried on three two-axle bogies, with each outer bogie powered by a 185 kW series-wound DC monomotor, resistance-controlled by an air/oil camshaft. Braking is a combination

of rheostatic and spring applied/air released friction brakes. The typical train configuration consists of two Metrocars, although single unit operation is also possible.

Figure 1 illustrates the monthly average minimum and maximum temperatures in the Newcastle-upon-Tyne area for the period 1981–2010, together with the 20th and 80th percentiles (Met Office, 2013). The maximum average temperatures rarely exceed 19°C, whereas the minimum temperatures are normally above 0°C. Therefore, it is likely that heating is required in rolling stock throughout the whole year, whereas cooling will normally be unnecessary.

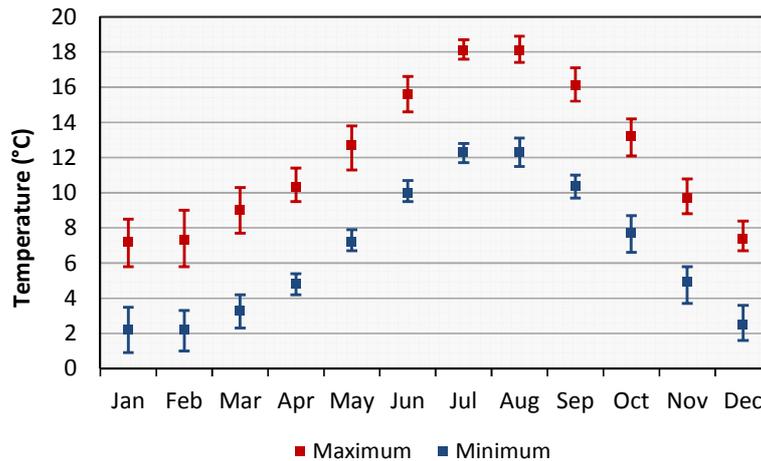


Figure 1 – Average monthly maximum and minimum temperatures in the Newcastle-upon-Tyne area

2.2. Vehicle auxiliary systems

The Metrocar’s auxiliaries basically comprise: heating, ventilation, air compressor, lighting and control systems.

Heating is primarily by waste heat recovery; i.e. warm air is ducted to the seat plinths from traction and braking resistors. When required to reach the target comfort temperature (nominally 21°C), this is complemented by two 15 kW auxiliary heaters (on/off regulation), which are directly connected to the 1500 V DC supply. Metrocars are not equipped with any active cooling system. Instead, the airflow from the resistors is automatically reversed when the saloon temperature exceeds the target point, thus helping to ventilate the train. Additionally, natural ventilation is possible via passenger-operated hopper windows.

The air compressor, which drives subsystems such as door actuators, air suspension and friction brakes, is directly linked to the 1500 V DC supply. Moreover, a motor alternator (MA) set converts 1500 V DC power into 415 V AC power, primarily for lighting and ventilation. The MA set is also used, via a transformer and rectifier, to charge batteries that feed emergency systems (e.g. emergency lighting) and other control circuits at 110 V DC. Figure 2 schematically illustrates the major electrical consumers in a Metrocar, with auxiliary loads in green and propulsion loads (which are to be

excluded from this study) in red. Note that in reality the equipment is distributed between both sections of the Metrocar.

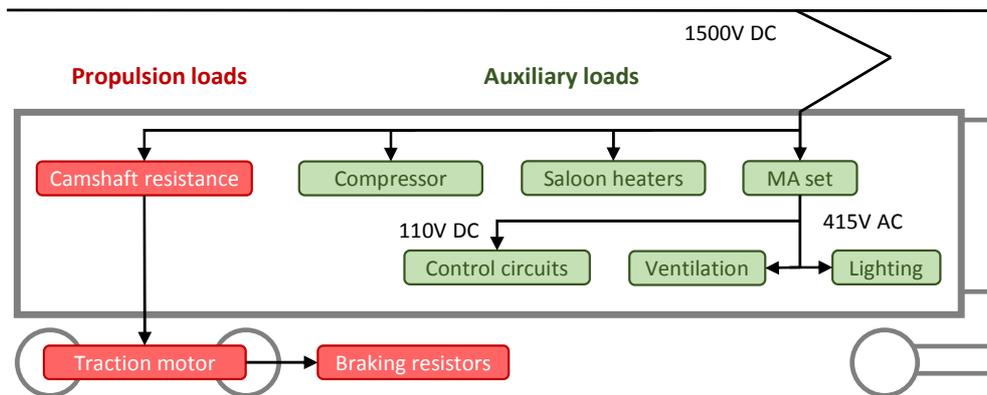


Figure 2 – Simplified illustration of Metrocar electrical circuits

2.3. Stabling

The T&W Metro has one depot located in Gosforth. Amongst other facilities, the site comprises: the running shed, where Metrocars are stabled between service duties; the inspection shop, where routine maintenance and light repairs are performed; and the lifting shop, where heavy duty repairs are carried out. Whereas the running shed is unsealed and unheated, both the inspection and lifting shops include a heating system that aims to keep the indoor air temperature around 15°C. Due to the fleet size, some vehicles have to be stabled outdoors, others will be in the inspection shop overnight for stabling and maintenance, and vehicles are also moved during the night as required.

In principle, all of the Metrocar’s auxiliary systems remain in operation when stabled, unless isolated from the overhead power supply for certain maintenance tasks. Among others, this means that the heating remains on to maintain the target interior temperature, which in this case is the same as in-service.

3. Methodology

3.1. Data collection

Data collected between 1st April 2012 and 31st March 2013 from an energy meter fitted to Metrocar number 4067 forms the basis for the analysis in this paper. Further instrumentation of the vehicle, such as vehicle subsystem metering or air temperature sensors, was not possible within the scope of the experimental programme. The following parameters were recorded every second: overhead line voltage, current and power drawn from the overhead line, output voltage from the MA set (for both the 425 V and 110 V circuits) and train speed. Field data were remotely downloaded in .csv format to computers in the depot offices, before being processed using Matlab and Microsoft Excel.

Historical climate data for the trial period were obtained from the weather station at Newcastle International Airport, which is located around 6 km from the depot in Gosforth (Weather Underground, 2013). This principally comprises ambient temperature, degree of cloudiness and wind speed. Global solar irradiance values were estimated by using the “very simple cloudy sky model” suggested by (Badescu, 1997). Solar position throughout the year was obtained using the algorithm proposed by (Reda & Andreas, 2004).

3.2. Data reduction

Although data is sampled by the energy meter every second, the basic time step selected to reduce experimental measurements for further analysis was of 30 minutes, since this is the sampling frequency of the available weather data. Note that this selection is also of the same order of magnitude as the typical thermal time constant of rail vehicles, reported to be around one hour by (Tomlinson, 1988). Thus, the distance travelled each second was summed within each 30 minute time step, and likewise the second-by-second power consumption was used to provide average power consumption data. If there was no movement within the 30 minutes, it was assumed that the Metrocar was stabled, as this time period is in excess of the typical turnaround times at terminal stations (5-15 minutes).

3.3. Data analysis

The data analysis methodology can be summarised as follows:

1. Calculating the total energy consumption of the unit for the whole experimental period, including running and stabling hours.
2. Determining the number of hours the vehicle was stabled, and the corresponding energy consumption for this period.
3. Investigating the relationship between ambient temperature and the vehicle’s energy consumption while stabled.
4. Examining factors that may influence the above relationship.
5. Analysing further experimental results to determine the breakdown of energy consumption between systems (including heating, lighting, air compressor and others).

4. Experimental results and discussion

This investigation involved collecting data during real operation of the metro system; hence, there were some unavoidable discontinuities in the measurements, mostly corresponding to the time where the unit was undergoing maintenance and the pantograph had been dropped. Some data were also corrupted in process of transmission to the depot. In total, there were 28 days out of 365 that could not be used for the purpose of this study.

4.1. Vehicle's total energy consumption

The total energy consumption of Metrocar 4067 during the 337 days of the trial period was 515,696 kWh, for a total travelled distance of around 130,000 km. Figure 3 illustrates the full data set for this period, with each point representing the distance travelled and energy consumed on a particular day, and the colour showing the average temperature of that day. As expected, the total energy consumption is proportional to distance travelled, with an additional offset on the y-axis that principally accounts for the auxiliaries' energy consumption, although other factors such as the driving style or traffic conditions may also have some influence. The general trend observed in the spread indicates that energy consumption is noticeably higher on colder days, which suggests that heating accounts for a substantial proportion of the auxiliaries' energy consumption. In fact, about 95% of the values lie within the range of 725 kWh per day, which on average corresponds to the auxiliary heaters' power of 30 kW.

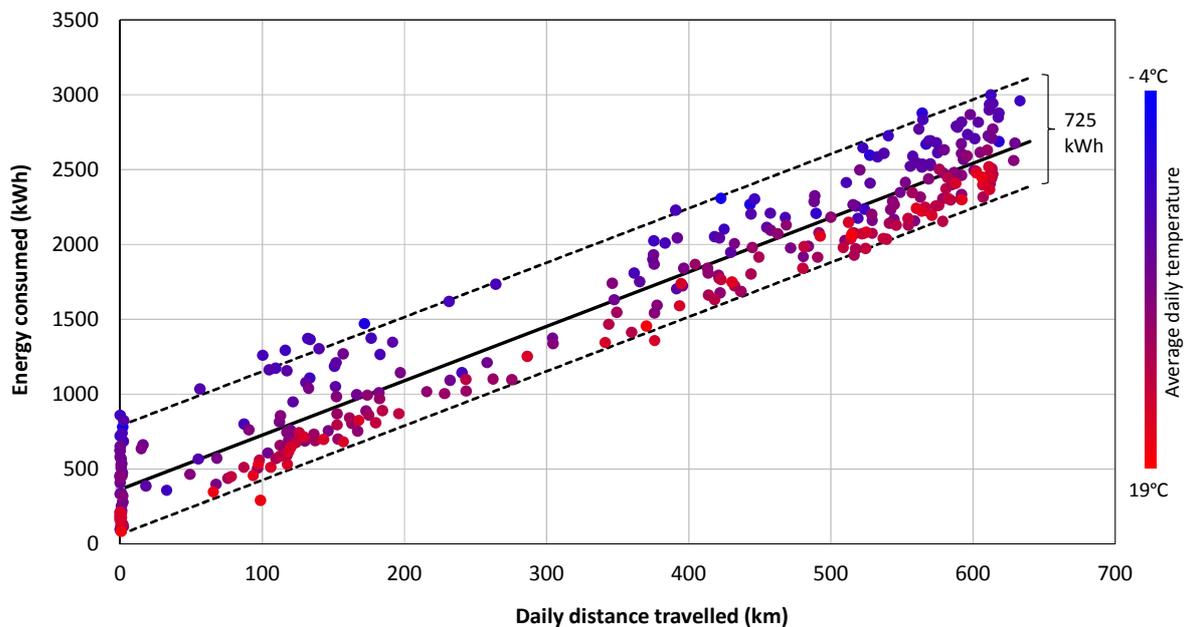


Figure 3 - Daily energy consumption of Metrocar 4067 during the trial period 2012-2013

4.2. Vehicle's energy consumption while stabled

4.2.1. Overall energy consumption and distribution of stabled time

Experimental data show that unit 4067 was stabled for 3,895 hours during the 337 days of the trial period, which represents about 48% of the total time. Figure 4 depicts the average daily distribution of time stabled for this unit; or in other words, it shows the probability of finding this Metrocar stabled at the depot at any time of the day during the trial period. The trend shown in this figure is representative of the timetable of T&W Metro, where peak time services are operational in both directions from approximately 7:00 to 10:00, and from 16:00 to 18:00. Note that vehicles may be moved around the depot at night, which accounts for the small percentage of time not stabled overnight.

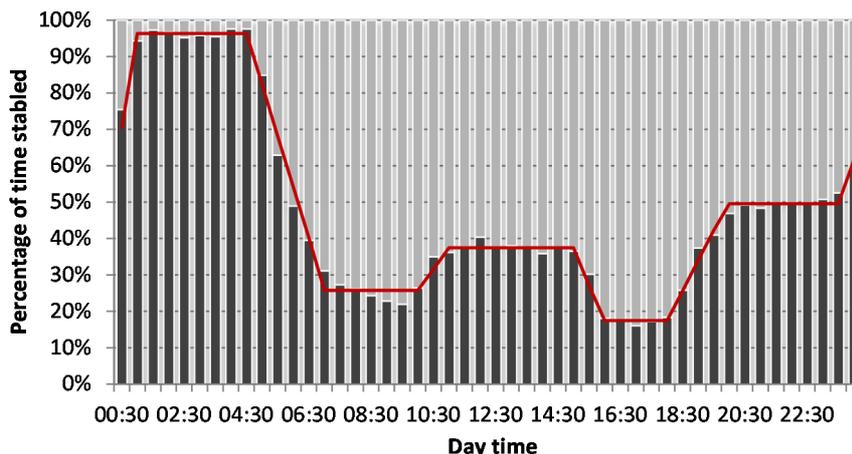


Figure 4 - Daily distribution of stabled time for Metrocar 4067 during the trial period 2012-2013

The energy consumed by unit 4067 while stabled was of 56,059 kWh for the whole trial period; i.e. an average of 166 kWh per day. This means that about 11% of the vehicle's total energy consumption occurred while stabled.

4.2.2. Influence of ambient temperature

In order to assess the contribution of each auxiliary system, energy consumption on those days where the Metrocar was stabled for the whole day were examined (these days correspond to the points on the y-axis in Figure 3). In this manner, the effects of remaining heat from brake resistors and other influencing factors associated with train operations were minimised.

Figure 5 compares the half-hourly averages of the Metrocar's power consumption and the ambient temperature for a day where it was always stabled (12th May 2012). A clear correlation between these variables may be observed, with higher power consumption at lower temperatures.

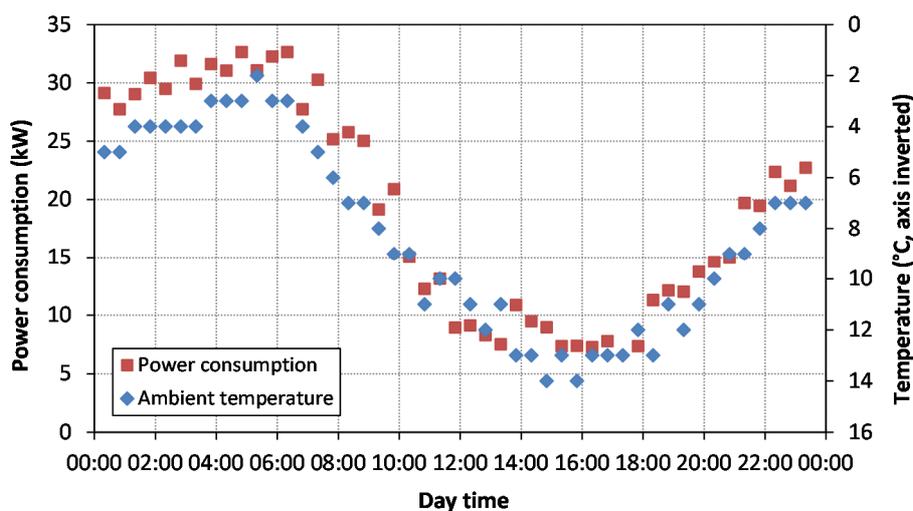


Figure 5 - Average power consumption of Metrocar 4067 on 12th May 2012

Figure 6 illustrates the power consumption results for a different day of the experimental campaign (15th April 2012). It can be observed that the power consumption initially varied with the ambient

temperature, similarly to that found for the previous example. However, after a period during which the unit was registered to move a few hundred metres, the power consumption remained nearly constant around 8 kW. This suggests that the heating was not needed any longer after the vehicle was shifted into an enclosed and heated building (refer to section 2.3). Note that the average power consumption for the period in which the vehicle moved was not plotted in Figure 6, as traction and auxiliary energy consumption cannot be separated in the measurements.

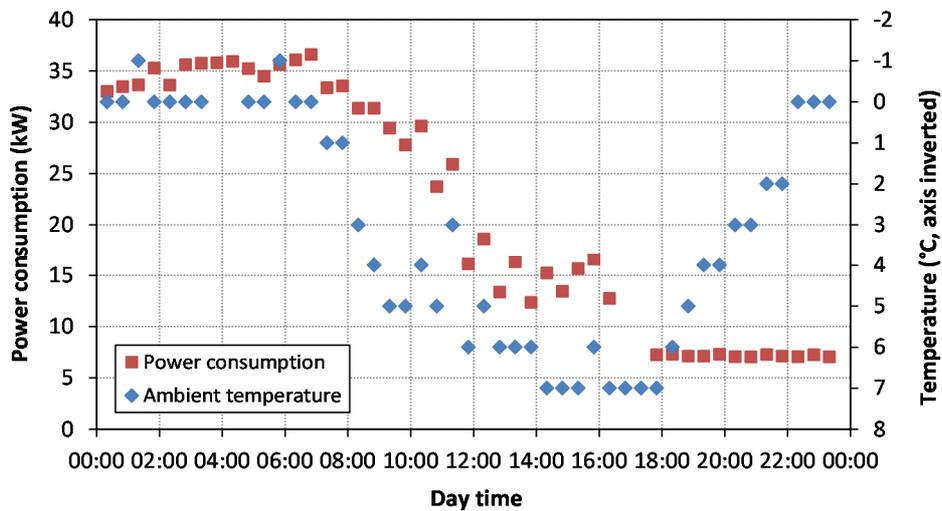


Figure 6 - Comparison of power-temperature relationship outside and inside depot shed (unit 4067, 15th April 2012)

In order to determine the relationship between ambient temperature and vehicle energy consumption while stabled, the results from 14 different days where it could be established with reasonable confidence that the Metrocar was stabled outdoors were combined; the pairs of temperature and power consumption for each half hour period are illustrated in Figure 7.

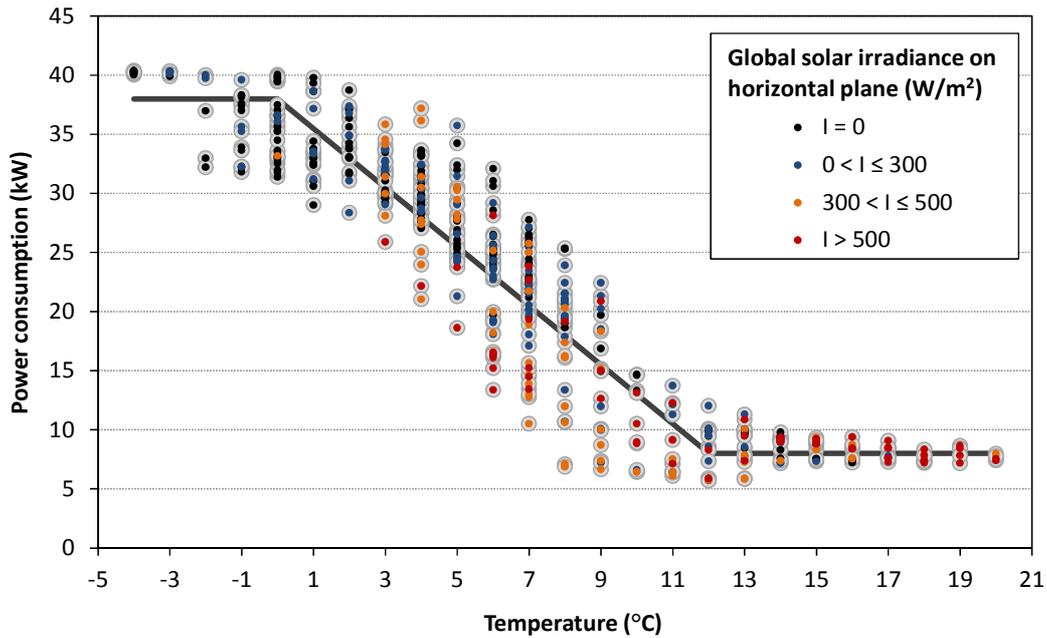


Figure 7 - Relationship between ambient temperature and power consumption for unit 4067 and influence of solar gains

At the highest and lowest temperatures, the power consumption is roughly independent of temperature, whereas an approximately linear relationship is observed in the central region of Figure 7. The empirical correlation that provided the best fit to these results is described by Equation (1), where P is the power consumption (in W) and T_a is the ambient temperature (in °C).

$$P = \begin{cases} 38000 & T_a < 0 \\ -2500T_a + 38000 & 0 \leq T_a \leq 12 \\ 8000 & T_a > 12 \end{cases} \quad (1)$$

The starting point for constructing a best fit line was to find the average power consumption in the tightly clustered region above 15°C where the heating is always off. The power consumption in the coldest region will then be about 30 kW above this value, as this is the rating of the auxiliary heaters. To obtain the relationship in the central region, a set of linear best fit lines to the data using different temperature pairs for the transitions to the region where heating is on intermittently were plotted, and it was found that using boundaries of 0°C and 12°C gave the best correlation to the data in this region, with an R^2 value of 0.8.

The global solar irradiance is also displayed on the graph (Figure 7); there appears to be an additional weak relationship whereby higher solar irradiance reduces the power consumption, independent of the ambient temperature. This, and other second order factors, are examined in more detail in section 4.2.3 below.

4.2.3. Discussion of the relationship between temperature and power consumption

It is proposed that the auxiliary power consumption illustrated in Figure 7 can be divided into two components: the heating, which is dependent on temperature, and other systems, which should have

an approximately constant power consumption when examined over half hour periods. There will also be second order effects (such as global solar irradiance mentioned above) that may increase the scatter in the results beyond what would be expected from experimental inaccuracies and errors alone. This section therefore examines three regions of Figure 7 defined by the temperatures, and the scatter.

High temperature region

At higher temperatures, the heaters should be off and the power consumption therefore constant; this is observed to happen at temperatures above 12–13°C in Figure 7, where the power consumption is around 8 kW in Figure 7. This figure is consistent with the power consumption in Figure 6 for when the Metrocar is assumed to be stabled within a heated building. To validate these findings, further data analysis and an independent set of experiments was carried out at the depot (this new experimental data was gathered from Unit 4088). Different auxiliary systems were switched on/off independently, and the variation in power drawn from the overhead line recorded, to compare against derived values:

- Compressor – second-by-second data from 12th August 2012 was inspected, and revealed power peaks of about 15 kW, lasting for around 12 seconds, at intervals of around 5 minutes, which represents a mean power draw of 0.6 kW. The experiment confirmed that these power peaks matched those observed when the compressor was running.
- Lighting – the main saloon lighting is provided by 38 fluorescent bulbs of 40 W each, and the measured power draw of 1.5 kW matches this.
- Other MA set circuits – the remaining circuits, which include ventilation fans, battery charger and control equipment, drew a mean power of 6 kW in the experiment.

Together, these figures provide excellent agreement with the previously derived overall value of a constant 8 kW of power for these auxiliary systems.

Low temperature region

At low temperatures, the heaters are permanently on and therefore consuming their maximum rated power of 30 kW (refer to section 2.2). This corresponds to temperatures below 0 °C in Equation (1) where the power consumption is no longer dependent on temperature.

Intermediate temperature region

At intermediate temperatures in the central region of Figure 7, an approximately linear relationship between temperature and power consumption may be observed. This is consistent with the general equation governing the steady heat demand in stabled rail vehicles without occupation and without solar load, simplified as follows (Ampofo, et al., 2004):

$$Q_{heat} = Q_{cond} + Q_{vent} - Q_{light} = \sum UA \cdot (T_i - T_a) + \dot{m}_{air} \cdot c_{p,air} \cdot (T_i - T_a) - Q_{light} \quad (2)$$

where Q_{cond} represents the heat losses through the vehicle's envelope, essentially due to conductive heat transfer; Q_{vent} is the heat load due to ventilation and air infiltration; Q_{light} represents the heat emitted by equipment within the vehicle such as lighting; U and A are the global heat transfer and the area of each surface forming the vehicle's envelope respectively; \dot{m}_{air} is the mass flow rate of air supply into the vehicle; $c_{p,air}$ is the ambient air specific heat; T_i and T_a are the indoor and ambient air temperatures respectively.

All variables in the right hand side of Equation (2) – except for T_a – should be practically constant when the vehicle is stabled at the depot, which means that the heating power consumption should be approximately linearly dependent on the ambient temperature. This would explain the linear trend found in the experimental data; however, there is a series of second order factors that equation (2) does not consider and that may affect the vehicle's thermal load.

~~The precise location of the transition points between the intermediate temperature region and low/high temperature regions was determined by finding the transition temperatures that provided the best fit to the data in the central region.~~

Scatter

Figure 7 nonetheless shows a significant spread in the experimental data from the proposed trend line, including a variation of up to about 15 kW in energy consumption for the same temperature on different days. This may be due to unpredictable causes such as fluctuations in the air temperature adjacent to the temperature sensor, the influence of adjacent buildings/vehicles, equipment reliability, or changeable boundary conditions (e.g. windows may be left open during night-time).

The effect of body thermal storage could also be suggested as a possible reason, although this effect has been identified to be very limited in the case of rail vehicles (Liu, et al., 2011), (Amri, et al., 2011). The influence of ambient air speed and incident solar radiation may play a more significant role yet (Ampofo, et al., 2004), (Li & Sun, 2013).

Higher ambient air velocities tend to increase the heat transfer through the vehicle's envelope, since this improves heat transfer coefficient U . However, this effect has been found to be rather limited in this particular case: preliminary calculations showed that wind speeds of 35 m/s (the highest value observed during the trial period) will only cause an increase of about 5% in the Metrocar's thermal load, in comparison with still conditions.

In turn, the influence of solar radiation appears to be stronger, as can be deduced from Figure 7. It is observed that most of the points below the trend line correspond to medium/high values of global solar irradiance (over 300 W/m² on a horizontal plane). Conversely, the majority of the points above the line correspond to little or no solar radiation. Furthermore, calculations made according to BS EN 14750-2 (2006) (BSI, 2006) have revealed that solar irradiance values of around 800 W/m² (the highest value observed during the trial period) may imply heat gains of up to 10 kW in vehicles

stabled outdoors. Therefore, it may be concluded that the variable incident solar radiation is a major reason for the scatter observed in Figure 7; this being particularly valid for ambient temperatures between 3°C and 12°C, where the range of solar irradiance values is wider.

4.2.4. Summary of the breakdown of energy consumption

As concluded above, auxiliaries' power consumption excluding heating may be considered fairly constant throughout the year, with an average value of 8 kW. Hence, considering the Metrocar was stabled for about 3,895 hours during the trial period (section 4.2.1), the energy consumption due to those systems can be estimated as 31,160 kWh. This means that heating was responsible for about 24,899 kWh, which represents nearly 45% of the vehicles' total consumption while stabled.

HVAC systems therefore play a key role in the auxiliary energy consumption of stabled Metrocars, with the ambient temperature being the main influencing factor in such consumption. Solar radiation – and to a less extent wind speed – may also have an influence depending on the location of the vehicle; that is, depending whether there are other vehicles or buildings adjacent providing shade or disrupting the wind. Moreover, there is a combination of other essentially unpredictable factors such as uncontrolled ambient air infiltration (e.g. through open windows) and fluctuations in local air temperature that can also have a significant effect on the consumption.

Figure 8 gives a graphical summary of the approximate energy consumption breakdown of stabled Metrocars, based on the results of section 4.2.3. Note that the energy consumptions depicted herein do not separate inefficiencies and energy losses within subsystems, which could not be evaluated in the present investigation.

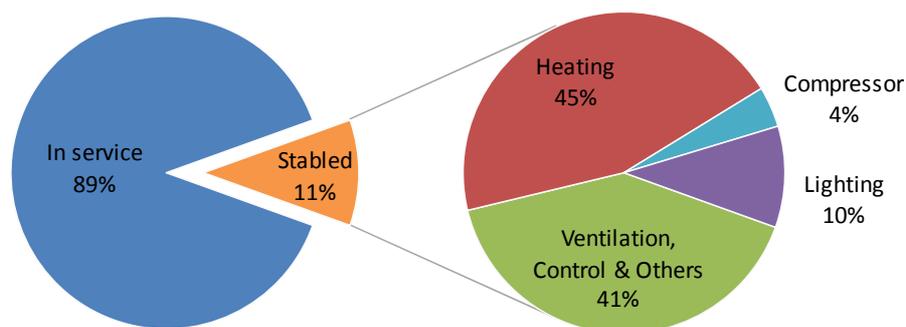


Figure 8 - Breakdown of main auxiliaries' energy consumption in stabled Metrocars

4.3. Uncertainty analysis

Table 1 shows the experimental uncertainties of the main variables used in this investigation. The values for both the power consumption and the distance travelled are directly drawn from the energy meter specifications, whereas the ambient temperature uncertainty is given by the weather data providers (Weather Underground, 2013).

Table 1 – Experimental uncertainties

Variable	Uncertainty
Power consumption	2%
Distance travelled	4%
Ambient temperature	$\pm 1^{\circ}\text{C}$

The uncertainties in Table 1 can account for some of the scatter in Figure 7, and the effects are not negligible when compared to the factors mentioned in section 4.2.3. Nonetheless, given the volume of data analysed, and the strength of the correlation between ambient temperature and power consumption, it is considered that the results presented in this paper are reasonably robust.

5. Conclusions

In order to investigate the energy use of stabled rolling stock in urban rail systems, power consumption and distance travelled by one of the 90 Metrocars forming the T&W Metro fleet were measured for one year. The following conclusions have been drawn from the analysis of the experimental data obtained:

It has been found that approximately 11% of the Metrocar's yearly energy consumption is accounted for by on-board auxiliary systems while the vehicle is stabled. Heating has been shown to be responsible for about 45% of this consumption, while the lighting and compressed air systems account for 10% and 4% respectively; other consumptions including fans and control circuits represent 41% of the total stabled energy consumption.

Ambient temperature has been identified as the main influencing factor on stabled vehicles' energy consumption, although solar radiation and wind speed may also have a notable influence depending upon the vehicle's location at depots.

A correlation between ambient temperature and the stabled vehicle's energy consumption has been obtained empirically. Although further experiments would be needed to develop a more accurate model, this correlation may be used as a preliminary tool in the evaluation of possible measures to minimise the energy consumed by stabled Metrocars. The results obtained for a single unit could be extrapolated to fleet level, as all the vehicles are of the same type/age and present similar duty cycles.

Ultimately, this paper has shown that the energy consumed by stabled vehicles is not negligible in comparison with energy consumed in service, and investigation of measures to reduce this consumption is a worthwhile exercise. Although the characteristics (and hence the specific results for the breakdown of energy use and the dependence on ambient temperature) will be different for

other urban and main line railway systems, this conclusion is likely to remain valid, and the methodology outlined in this paper can be applied to other systems.

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