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What Bus Operators Want: Emissions Mitigation and Water Management to Maintain Cleaner Fleets in Europe

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Abstract

For bus operators, predictive maintenance systems have become essential if the goal is to reduce garage costs. But advantages go beyond, since well-maintained fleets pollute less and well-timed maintenance mitigates waste production. The paper moves from this and describes two innovative dashboard functions embedded in a predictive maintenance software: one specifically designed to control emissions and the other to manage the amount of water needed for washing operations. The former is crucial, mainly when maintaining fleets composed by numerous pre-EURO VI vehicles. The latter represents a totally underestimated issue and for which there are no regulatory references. The paper describes the findings from some pilot cases on these dashboard functions, with the research goal to showcase examples of environmental best practice in the field of predictive maintenance.

Keywords: Bus; Water; Emissions; Predictive Maintenance.

1. Introduction

The advantages of predictive maintenance are well known in literature, and they are fast increasing thanks to relevance of Augmented Reality, Internet of Things, Machine Learning or Artificial Intelligence in the definition of software for this type of operations in the automotive sectors (Borro et al. 2021, Massaro et al. 2020, Killeen et al 2019, Prytz et al. 2015). Case studies in this field of telediagnostics also abound (Fan et al. 2015, Corazza et al. 2018, Raposo et al. 2019, Balbontin et al. 2022), all showcasing the possibility to decrease maintenance expenditures, improve reliability, optimize resources (Chardsutthi et al. 2010, Mckinley et al 2020). For bus operators taking advantage of predictive maintenance in their garages, the main driver is certainly operational, thus being possible to

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forecast or detect in real-time failures, rather than repairing them once they already occurred (conventional maintenance), or at a given time after the last garage check (preventive maintenance), resulting either in service disruptions or in garage operations scheduled according to practice rather than actual need, with unnecessary vehicles' stops.

But the operational concern, in the long run, might cast a shadow on the real potential of predictive maintenance, i.e., that of mitigating the negative environmental impacts generated by buses. Regular predictive maintenance contributes to slow down the fleets' obsolescence process, by improving lifecycles of mechanical parts and components. and optimizing replacement operations, with the final results to diminish the emission phenomena thanks to prolonged clean performance, and eventually reduced waste generation. Although these benefits were already demonstrated at a small scale, giving rise for larger applications (Corazza et al. 2021), a number of regular maintenance interventions are yet to be integrated within predictive operations either because still carried out according to the maintenance staff experience or simply because underestimated.

1.1. Structure of the paper

This means that environmental care can be an added value for predictive maintenance and that specific operations like emissions control and water management to wash vehicles could be regularly included, as the findings in this paper evidence. To this end, the problems of emissions generated by bus fleets and the water consumed to wash them are introduce in Section 2, stressing the relevance and the current underestimation of both. Section 3 describes the implementation of a predictive maintenance software with two innovative dashboard functions, designed to provide garage managers with real time data on the emissions generated by their fleets and directions on how to plan washing operations and reduce water consumption. Preliminary results are commented in Section 4, and conclusions drawn in Section 5 with the research goal to showcase examples of environmental sustainability best practice in the field of predictive maintenance and advance the research farther afield.

2. Two underestimated problems in bus fleets managements

Emissions generated by bus fleets and water consumption for washing operations are not accorded the place they deserve in the general maintenance practice at bus garage; reasons and corroborating facts for that are reported as follows.

2.1. Why bus fleets are obsolescing

In 2019, a supranational survey (UITP 2019) highlighted that EURO VI buses represented just the 15% of the investigated fleets and that engine conventionally-fuelled were still the major propulsion option. The recent pandemic did certainly not help the rejuvenating process which is still lagging behind because of reasons with distant roots, the first of which is the higher cost of cleaner vehicles (hybrid, electric, etc.) compared to that of diesel-fueled ones. Secondly, the lack of constant funding does not help to trigger a regular fleet turnover, with transit companies sometimes compelled to renovate just according to funding opportunities. Higher costs of cleaner vehicles might result into a paradox: given a funding opportunity, the amount of cleaner vehicles that can be purchased can be lower than that of the conventional ones, thwarting in the end the goal to rejuvenating fleets. The permanence of same engine standards without further restriction is one more cause of obsolescence, since "freezing" emissions' standards means, in the long run, an increase of fuel consumption and greenhouse gas emissions due to the longer exploitation of less efficient vehicles in the years to come (Keith at al. 2019).

Obsolescence is also fueled by a general misperception of the emission problems among the public and decision-makers. Since the beginning of the 2000s, the major environmentally-friendliness of transit over passenger cars has been evidenced by several national and supranational statistics; for example, in the U.S. the 2010 estimated average CO_2 emissions for transit buses accounted for 0.29 kg per Passenger Mile for transit buses vs 0.43 for private cars (Hodges 2010); in Europe, around 70% of the 2018 transport emissions were due to passenger cars and light-duty vehicles (Enzmann and Ringel 2020), with buses and minibuses accounting for just less than 10% (Statista 2021). Moreover, as widely reiterated, since efficient transit services might decrease the number of circulating private vehicles and contribute to the reduction in emissions (Pietrzak and Pietrzak 2020), the little attention paid to old buses is not surprising.

One more issue to consider it the bus operators' underestimation of the environmental consequences of managing old vehicles, which is generated by two typical situations: in case of small fleets, the operators' underestimation of the local fleets' potential in producing pollution; for larger fleets, their reluctance to estimate it when the amount of old-generation vehicles is big.

On the other hand, the efforts in the field of Research and Development - R&D are huge in shifting transit from being operated via conventional propulsion systems to electrification and cleaner fuels (Bousse et al. 2018, Musso and Corazza 2015, Smieszek et al. 2021). But this approach shows limitations, too, as this type of innovation is casting shadows on the potential provided by "maintenance" as an alternative to rejuvenate fleets, and retrofit instead of "buy new"; more specifically, the possibility to look elsewhere for saving resources and mitigating negative impacts, i.e.by optimizing already operational fleets and garage operations and reducing their costs, are left undisclosed.

A last point to consider is the problem of modelling emissions for old buses. Available models usually underestimate the mileage degradation factors for diesel buses, since this is based on very restricted mileage ranges (way below 200,000 km as higher limit). Actually, bus mileages in urban operations can easily reach 400,000 km and more, thus it is intuitive that the resulting simulations for the pollutant packages emitted by buses are far from real operational conditions.

2.2. Water consumption within bus management operations, an underestimated issue

As said, R&D efforts have been directed to reduce fuel consumption or replace this option with electrification or hybrid systems. Supranational and national regulations helped the process and the main driver in this process is to reduce operational costs. Not the same can be told for water. The fact that, according to the European Environmental Agency – EEA (2014, 2021), around 100 million people just in Europe are exposed to water stress and that the increasing water demand in the last 50 years went hand in hand with the decrease of available renewable water, which is now - 24% per capita, should lead to conclude that both water management and consumption are priorities for bus operators like that of fuel. On the contrary, water supplies, management and consumption seem to raise very little concerns, and this is also evidenced by the lack of statistics, recommendations and organized data at EU level about water consumed by the transport sector.

The daily per capita water consumption just for household activities, in Europe, is 144 liters, i.e. 0,144 cubic meters (EEA 2021), but in the first decade of the 2000s, the Organization for Economic Co-operation and Development - OECD estimated that the daily amount needed by North-Americans was between 335 and 380 liters, i.e. 0,335 and 0,380 cubic meters (Safewater 2017). This is not far from the water needed to wash a bus, around 300 liters (0,300 cubic meters) of fresh water, on average 4 times per week (Arriva 2019). Thus, during a week a European citizen consumes around 1008 liters vs 1200 liters required by a bus to be cleaned. Consequently, the annual water requirement per vehicle is around 62,400 liters and if this is applied to the 684,285 buses registered in 2020 in Europe (ACEA 2022), around 43 million m^3 of fresh water consumed are needed to wash the European bus fleet every year. In other words, one of the major public transport operators in Europe, with a fleet of 18,000 buses around Europe, consumes on average 1,123 million liters of fresh water per year, corresponding to the water volume of 450 olympic swimming pools.

As intuitive, water usage is directly linked to the amount of energy consumed to pump the water to wash the buses. If average data on water and energy consumption are assumed based on the above-mentioned major operator's practice, and according to the rate of 64.2 kWh needed to pump $1m^3$ water, the 18,000 vehicles require around 72 GWh/year to be washed. Translating such data at European level, for the previously estimated water consumption of 43 million m^3, the annual energy need would be of 2.77 TeraWh, to have the European bus fleet washed. Moreover, if converting this into CO_2eq emissions, for each cubic meter of water pumped, it could be calculated that 0.455 tCO_2eq are consumed (EPA 2021). Thus, at European level, it is safe to assume that 1,261$MtCO_2$eq are emitted yearly by the transport sector just to wash buses. Behind the underestimation of the water issue there is a regulatory problem. Emission mitigation and reduction are compulsory in any member states of the European Union and applied to every registered vehicle. Accordingly, the bus fleets' eco-conversion process is slowly progressing, coherently with very ambitious policy visions like, for example, the European Green Deal which aims at decarbonizing the transportation sector by 2050 (Haas and Sander 2020).

Moreover, unlike for emissions, there are no national or supranational regulations or standards on "cleaning" for public transport vehicles (e.g., on how many times a bus needs to be washed), and washing operations usually depend on garage practice.

In addition, given the lack of shared best practice or scientific references, operators have no clear views on different or new technologies either used or tested to save water during the washing process. One more factor which contributes to the underestimation of the water issue and also reveals a serious gap of awareness, knowledge and best practice sharing for water management.

3. Predictive maintenance advances towards more sustainable garage operations

From all of the above, some trends in the current bus operations and maintenance are clear: the renewal process is probably not fast and for some bus companies also unaffordable; the amount of old vehicles currently operating is not negligible; retrofitting and adapting can compensate both issues, and operators need efficient directions and tools to control operations in a way to meet the most advanced environmental requirements and save resources with the fleets they already manage. Predictive maintenance can play an important role in this if managers can forecast regular repair operations also according to a proper knowledge of the environmental impacts generated by their fleets. A predictive maintenance software, initially developed within a project funded by the European Commission (Corazza et al. 2018), and improved with two environmentally-friendly dashboard functions is a case in point to demonstrate that this can be done also with fleets where a large amount of old buses is still operational.

More specifically, the software's innovative dashboard functions are designed to calculate the emissions generated by buses (especially those with high mileage and protracted operational life), and manage water supplies for washing operations. Thus, these new dashboard functions are aimed at improving the quality of usual predictive maintenance applications by including the possibility to associate maintenance functions with data related to the consequent environmental benefits. A typical case is represented by transport companies that operate bus fleets with a large amount of pre-EURO IV vehicles, since they can take advantage of the new dashboard functions in two ways: i) by clearly understanding the pollution potential of old-generation vehicles, and ii) by considering additional areas in the field of the environmental safeguard like water management, also with clear benefits in terms of operations optimization and resource savings.

The software provides a dashboard with real-time tele-diagnostic facts and figures for prospective failure events and pollution assessment both based on real-time-monitored raw data and processed ones; it also provides meta-data (e.g., occurrence of specific anomalies or irregular events) necessary for the correct creation of the Training Set (i.e. materials the computer learns from, to process information). Emission data are made available thanks to an integrated emission model including all types of vehicles (per EURO-compliance, propulsion and fuel types, driving cycles, etc.) a bus fleet might be composed of. Further improvements enable to collect data on the vehicle performance, including those on the pollutants emitted, via CAN-Bus and sensors (typically, a Lo-Jack, installed in each vehicle associated with a SIM card to send data to the predictive maintenance system's cloud via 2G, 3G or 4G networks), to react in real time and propose concrete measures over a short horizon ("solving the issue") and in the far one ("programming for a better new planning"). The model is based on Artificial Intelligence techniques (Data-Driven), obtained from data networks (Enterprise Resource Planning - ERP software and sensors, such as Lo-Jacks) installed onboard. Thus, the model combines the management of static data (ERP, workshops, management) with real-time ones coming from the vehicles, and creates a single integrated platform capable not only of monitoring, but of carrying out real actions (implementations and decisions).

For what concerns the water management, the specific dashboard function collects the data via two sets of information on daily operations (data from the Fleet Management System dashboard function) and on the maintenance activities (Intelligent Garage System dashboard function). Information are integrated in the software scheduler where maintenance managers can check deadlines for any maintenance activity associated with a given fleet, including when to wash it.

Specifically, the dashboard function displays the prospective cleaning maintenance activities (e.g., weekly bus cleaning frequency), which usually are calculated just considering the cleaning frequency scheduled for a given type of vehicle (for example, weekly interior cleaning for an inter-urban bus, bi-weekly cleaning of its roof). In this case, the dashboard function provides an advanced forecast and optimizes washing operations, according to the real needs and real-time information on any given vehicle, including:

- Any activities that might require an unexpected, extra wash;
- Off time operations, when the bus is in the depot for some planned or unforeseen maintenance activity (i.e., for brakes or oil change);
- Planned downtime of the bus between trips, during the day.

These types of forecasts rely on the “Adaptive Cleaning Strategy Based on Generalized Load Recognition”, i.e. the innovative dashboard function’s smart algorithm, which goes beyond conventional schedules, recognizes different situations (operations, depot, maintenance times, etc.) and creates the right cleaning strategy, considering also unplanned events. The resulting adaptive scheduling of the fleet washing, by complying with the cleaning actual needs, enables not only to optimize operations but also to save resources, typically maintenance staff, energy and water.

In terms of the efficiency in water, this dashboard function is unique in this field. In fact, it has been designed and realized ad hoc to this end for the public transport operator. This function can take into account the daily changes of the fleet and internal operations that could affect the normal use of water causing an inefficiency. The dashboard manages three main performance area in parallel: i) the water optimization used for the fleet, ii) vice-versa, the optimization of the fleet when in daily service and in the depots to save water and, iii) the complete monitoring on water management.

Figure 1 describes two typical screenshots available for the Water Management dashboard function (a) and the Emission one (b).

Fig. 1. Screenshots of the two dashboard functions, water management (a) and emission (b)

4. Findings from the preliminary applications of the two dashboard functions

The two dashboard functions have been tested under a number of very different conditions in terms of operations (fleet size, amount and types of old-generation vehicles, routes, etc.), in several European urban areas in order to consider different topography features and climate conditions. The testing scenarios and the quality of the results (further described) achieved were also additional factors to assess the dashboard functions’ user-friendliness.

4.1. A multi-site test to assess emissions

The preliminary test to assess the emissions generated by a typical mixed-vehicle fleet (different EURO standards, and mileage) took place in Ravenna, involving a set of vehicles, compared to a control fleet and have a before-vs-during set of data. Results were beyond expectations, which led to fine-tune the emission dashboard function and test it again at two different urban areas, Olbia and Cuneo. The common trait among the three cities was the high number of pre-EURO IV buses in the local fleets. The results, for each city, were already presented elsewhere (Corazza 2018, Corazza 2021). However, comparison of the results achieved in the three test sites introduces more findings: i) each pollutant follows a different emission trend when vehicles with protracted mileage are considered, thus advancing the quality of both the tele-diagnostics thus far achieved in this field, and the simulation outputs, especially if compared to the most common models available in Europe; ii) the emission dashboard function also highlighted specific differences in the emission packages due to the types of operations performed.

Regarding such differences, in case of very high protracted mileage (i.e., > 160,000 km), NO_x emissions still increase, whereas the CO_2 ones stabilize; in turn, SO_x emissions trend decrease with the mileage, and actually quickly degrades after 80,000 km. PM emissions generation patterns are similar to the passenger cars', but beyond 160,000 km, the trend becomes exponential. Mileage or vehicle age do not affect ammonia emissions, generally produced in the in the cold-start stage and extremely dangerous since they give rise to $PM_{2.5.}$ It has been observed that ammonia emissions decrease when the temperatures raise. This shifts the attention on operations and their environmental conditions; for example, higher CO_2 emissions occur in case of hilly topography and higher temperatures (as presented for the case of Olbia and Cuneo in Corazza 2018, Corazza 2021). At the same time, high values detected in the NH_3 generation might reveal a cold-start problem. The implication for transit operators is clear: by associating emission trends with specific variables also old-generation buses can operate under acceptable environmental conditions. A knowledge of the service including factors like morphology, weather, engine's performance, travel patterns and mileage can help operators to redesign it and minimize negative impacts due to emissions, according to a simple concept: highly polluting vehicles can be associated with less challenging routes. For examples, older vehicles might be operated on routes with no or modest slopes, or during periods of the day when weather conditions do not contribute to raise emissions (for instance, in summer mornings at early hours or winter afternoons, when temperatures rapidly vary and when maintenance can be operated instead). Likewise, a proper knowledge of pollutants magnitude might help improving maintenance and can act as a telediagnostic support, since each pollutant might lead to a specific problem; for example, higher NO_x emissions can show exceeding temperatures during combustion, similarly for very high CO emissions which stress problems on the fuel burnt and high levels of SO_x which might indicate fuels unsuitable quality.

4.2. Experiences and different techniques to save water

After a first successful experience in Slovenia in 2016, the dashboard function on water management is currently under test at three different garages by the above-mentioned major transit operator, as part of a pre-trial within a project funded by the European Commission, due to start in the last quarter of 2022. The Slovenia case tested a new automatic bus washing plant with a rain harvesting system, which enabled to reduce the washing cycle within 6-8 minutes, with the 96% biodegradable detergents. The rain harvesting system covers 100 m^2 and is connected to two reservoirs which supply around 20% of the demand from the system. Any collected surplus water is redirected to oil separators for purification. In addition, the wash plant also includes a water recycling unit which captures used water for further washing cycles. This results in 50% lower water usage. The system has a return on investment of 9 years and saves annually 1.2 million liters of water. From these facts, the goal to reach around 90-95% of water saving efficiency is within reach and the three test sites where the water management dashboard function is currently applied were chosen to corroborate the feasibility at a larger scale.

The test sites are in Italy, the Netherlands, and Hungary, each testing a different innovative washing process, for a total of 680 buses involved. The washing technologies under test are respectively: i) wastewater treatment and recycling facility combined with a rainwater harvesting system; ii) simple wastewater treatment and recycling facility; and iii) waxing without water. The three countries have also been selected because they represent the three major different climate conditions in Europe, corresponding to different washing requirements. Currently, a Do-Something

Scenario (DoSS) has been built, with the three technologies expected to reach to different water saving goals; more specifically: rainwater harvesting with treatment and recycling of wastewater: - 92%, wastewater recycling: - 60% and waxing: - 98%. According to that, the expected average 84% decrease in the usage of fresh water for washing operations is going to account for 37.2 million liters saved over 30 months. At European level, by reaching 50% of the bus transport sector in 5 years (a potential fleet composed of 364,104 buses) this means 18 billion liters /year saved, corresponding to -42% of the total water used by transport sector. The 30-month DoSS also estimates further savings, i.e.: - 2.4 GWh of energy consumption, and - 1MtCO_2eq emissions in the three case studies. If the estimated emissions to wash the European fleets corresponding to 19,565 MtCO_2eq are considered over the same period, the implementation of the three innovative technologies will reduce by 5.5% the total Greenhouse Gases (GHG) emissions due to washing operations in Europe. In five years, it is possible to estimate a reduction of energy consumption as of 1,165 GWh and of – 529 MtCO_2eq GHG emissions, per year. All of the above also corresponds to a cost reduction of 152 million Euro.

5. Concluding remarks

The experiences and results above-reported might represent preliminary steps towards a paradigm shift in maintenance, with the environmental concern playing now the equal role the operational one did thus far. On the one hand, this could lead bus operators towards a full awareness of the environmental consequences of managing obsolescing fleets and adapt the service in a way to mitigate the resulting externalities (for example, by adapting the service in a way to associate obsolescing vehicles with less challenging operations under the emissions' point of view). On the other, it sheds a light on other maintenance operations which could generate savings, as the water management. In both cases, the two dashboard functions provide maintenance managers with tangible facts and figure about the possibility to pollute less and saving resources. This takes place by monitoring and modelling, and implies: in the case of washing operations, a shift from preventive-cleaning maintenance activities (conventionally, periodically pre-planned and associated to daily service), to predictive-cleaning maintenance ones (thus, when actually needed); in the case of the pollutant emissions assessment, to adjust operations and schedules in a way to have also vehicles with prolonged mileage performing with the least negative impacts. In both cases, the myth that saving resources and polluting less can be achieved only via new vehicles is debunked, being more avenues left to explore with the fleets already operational. The additional societal advantages are clear: the resulting more efficient management of the service generates among the passengers the perception of improved quality, thus increasing the transit attractiveness.

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