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Improving the environmental performance of bus fleets in Europe

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Abstract

Predictive Maintenance Systems (PdM) for bus fleets are gaining momentum among transit operators in Europe, although two major issues in this practice are still not fully addressed in mitigating negative impacts on the environment: emissions control and water management. To this end, the paper presents some innovative Dashboard Functions (DF) for a specific PdM, based on a software, already developed within a project funded by the European Commission (EBSF_2), with the goal to optimize predictive maintenance at bus garages. The first DF is aimed at assessing the emissions generated by buses, especially when fleets are composed by pre-EURO VI vehicles (one in three buses in the world is still pre EURO IV). The second DF is focused on the water management and control for washing buses: an underestimated issue, but still relevant in pursuing sustainability, since according to garage practice a vehicle needs around 300 litres of fresh water to be cleaned, typically 4 times a week, which multiplied by the almost 700,000 units which compose the European fleets generate 43 million m^3 of yearly water requirement. The paper describes the results from the assessment of both emissions and water in the software, with a special focus, for the former, on the problem of obsolescing vehicles and their components specifically contributing to the emissions phenomenon; for the latter, in turn, the paper focuses on the application of different washing technology. The research goal is to advance scientific knowledge further afield and provide examples of best practices in the field of PdM implementation for bus fleets.

Keywords: Predictive Maintenance; Water; Emissions; Bus

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1. Introductory considerations

Predictive Maintenance Systems - PdM for bus fleets are consolidating in garage operations of many transit operators, mostly to plan spare parts substitutions, repair operations, prevent breakdowns and manage the generated waste. Advantages are largely described in literature: increased productivity and reliability, optimization of resources (Chardsutthi et al. 2010, Massaro et al. 2020, Killeen et al. 2019), decreased maintenance costs, cleaner performance (Corazza et al. 2018, Mckinley et al 2020). The automotive sector is the arena for very advanced technologies specifically based on Augmented Reality (Borro et al. 2021), Internet of Things and Machine Learning (Massaro et al. 2020, Killeen et al 2019), or Artificial Intelligence - AI (Prytz et al. 2015), thanks to algorithms designed to solve typical faults on engines, gearboxes, batteries, wheelsets, etc. (Theissler et al 2021, Carvalho et al. 2019). Several interesting case studies (Raposo et al. 2019, Balbontin et al. 2022, Fan et al. 2015) evidence the availability of solutions in the field of tele-diagnostics to maintain and/or timely replace vehicles' specific, wearable parts and components (typically tires, valves, cables, etc.) and ensure the fleets efficiency.

The approach behind, nevertheless, is still merely associated with the possibility to reduce the amount and the severity of failures due to missed or delayed maintenance interventions; to order spare parts in advance and have them promptly available, all with the ultimate goal to optimize operations. Consequently, the operators' common concern when resorting to PdM seems to be purely operational: avoid service disruptions, and this seems to be mostly dealt with traditional procedures, i.e via general maintenance processes based on event detection (e.g. maintenance when a failure occurs), or preventive (e.g. maintenance based on the elapsed time since the last maintenance check), whereas the gist of PdM enables the possibility to intervene when failures either can be detected through appropriate sensors networks, or forecast by AI algorithms detecting patterns of future failures.

This means that most of the PdM potential is still underexploited, especially in terms of environmental impacts. Regular maintenance helps to slow down the fleets' obsolescence process, improving lifecycles of mechanical parts and components. and optimizing replacement operations, thus mitigating the emission phenomena thanks to prolonged clean performance, and eventually reducing waste. Although these benefits were already demonstrated at a small scale, giving rise for larger applications (Corazza et al. 2021), some regular maintenance operations are yet to be integrated within PdM either because still carried out according to the maintenance staff experience or simply because underestimated.

2. The environmental concerns can lead towards advanced Predictive Maintenance Systems

Environmental care and safeguard can steer maintenance at bus garages towards even cleaner performance for vehicles by including, within the PdM process, specific operations to mitigate negative impacts on the environment, and namely emissions control and water management, as further elaborated.

2.1. Emissions generated by bus fleets

Vehicular emissions management and/or mitigation is central in transport policies worldwide. Although the focus mostly lies on passenger cars, the need to control emissions generated by bus fleets is not secondary, if related to the not negligible amount of obsolescing vehicles still in operation. A 2019 worldwide survey stressed that EURO VI buses account for just around 15% of the investigated fleets and that conventional fuels are still prevailing as energy choices (UITP 2019). Fleets' obsolescence is a phenomenon doomed to last for several reasons; among these, the higher cost of cleaner vehicles (hybrid, electric, etc.) compared to that of diesel-fueled ones; poor availability of funding; and eventually the general local administrations propensity to "innovate" rather than "renovate" when it comes to transit.

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 Carbon Dioxide 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).

Although, as widely reiterated, efficient transit services might decrease the number of circulating private vehicles, thus contributing to the reduction in emissions (Pietrzak and Pietrzak 2020), the underestimation of the emission problem for buses, especially among the decision makers, is still an unsolved issue.

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, from supranational to local levels (Bousse et al. 2018, Musso and Corazza 2015, Smieszek et al. 2021). Such process has caused limitations, too, as this type of innovation, in this instance is: i) casting shadows on the potential provided by "maintenance" as an alternative to rejuvenate fleets, and operate "green"; ii) prioritizing products rather than process, by placing major emphasis on the benefits derived from the introduction of novelties (vehicles, components and technologies), rather than on those associated with the regular preservation of what already operational; and iii) neglecting additional areas for saving and eco-improving operations, as the water issue. Paradoxically, "innovation" as such is also often evaluated resorting to "traditional schemes": assessment of fuel and energy saving generated by given new items (vehicles, engines, auxiliaries, gearboxes, driving styles, etc.), translated into costs reduction and emission mitigation. This approach certainly supports public transport operators when deciding about the fleets renewal process, but does not help in looking elsewhere for saving resources and mitigating negative impacts, i.e. already operational fleets and garage operations and their costs. Last to consider, when innovation higher costs are acknowledged, operators' willingness to update is thwarted.

2.2. Water requirements to wash bus fleets

Water management and consumption seem to raise minor concerns, not only among transport operators but also decision-makers and researchers. This is such an underestimated problem that neither statistics, recommendations or guidelines nor organized data at EU level are available about water consumed by the transport sector.

This does not mean that water management and consumption are minor issues. According to the European Environmental Agency - EEA, around 100 million people just in Europe are exposed to water stress. The increasing water demand in the last 50 years went hand in hand with the decrease in availability of renewable water, which is now - 24% per capita. Climatic changes are also behind that, as demonstrated by the recent repeated drought phenomena and, more in general, the detected net drop in precipitation in Europe (EEA 2014). More affected areas are in the Mediterranean (EEA 2021), but European northern regions are starting to experience water scarcity, as well. The daily per capita water consumption, solely related to household activities, in Europe is 144 litres (EEA 201), but in the first decade of the 2000s, the Organisation for Economic Co-operation and Development - OECD estimated that the daily amount needed by North-Americans was between 335 and 380 litres (Safewater 2017). This is not far from the water needed to wash a bus, around 300 litres of fresh water, on average 4 times per week (Arriva 2019). Thus, during a week a European citizen consumes around 1008 litres vs 1200 litres required by a bus to be cleaned. Consequently, the annual water requirement per vehicle is around 62,400 litres 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 fleet every year. In other words, one of the major public transport operator in Europe, Arriva, with a fleet of 18,000 buses around Europe, consumes on average 1,123 million litres of fresh water per year, enough to fill 450 olympic swimming pools.

Obviously, 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 Arriva'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 1,261MtCO_2eq 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 (EU) 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 decarbonising the transportation sector by 2050 (Haas and Sander 2020).

On the contrary, water management is still treated as a side problem. Moreover, unlike for emissions, there are no national or supranational regulations on "cleaning" standards for public transport vehicles (e.g., on how many times a bus needs to be washed), and washing operations usually depend on garage practice. And there are neither specific directions on how transport companies have to mitigate water consumption nor standardized references (not even from the public health field). Public transport operators use all kinds of water saving solutions they consider appropriate for each depot without any clear benchmark or best practice, at EU or member state levels. Directions on water management are given at company level or more frequently at depot level. Companies' coordinated water management plans are often missing, too.

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. Saving and mitigating through Predictive Maintenance

A real paradigm shift is therefore needed to achieve full sustainability in the field of public transport, with PdM playing a relevant role in helping transit operators' decisions whether to "buy new", "retrofit and adapt", "maintain and preserve", thus advancing the environmental consciousness by conveying the idea that emission mitigation and cost savings might be achieved via the less expensive optimization of other resources, and not just via cleaner engines. In line with such direction, a PdM software initially developed in within a project funded by the European Commission (Corazza et al. 2018) has been improved providing bus managers with solutions to mitigate the emission and the water problems. To this end, the software's new Dashboard Functions (DF) are aimed at: i) assessing the emissions generated by buses, especially when fleets are composed by obsolescing vehicles; and ii) managing water supplies for washing buses. The new DF are aimed at improving the PdM quality by including the possibility to associate maintenance functions with data related to the consequent environmental benefits. More specifically, transport companies that operate bus fleets with a large amount of pre-EURO IV vehicles can take advantage of the new DF in two ways: i) by clearly understanding the pollution potential of old-generation vehicles (a crucial aspect for those companies where a total conversion of the fleet would be unaffordable, and thus expected to keep on managing vehicles with a protracted operational life); 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.

3.1. Monitoring air Pollutants: The Emission Dashboard Function

The above-mentioned PdM 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. Unlike other models, this one considers the level of obsolescence of a given vehicle via the mileage degradation factor specifically designed for diesel buses, which is a key parameter in highlighting their polluting potential (Corazza et al 2021). Further improvements under study and test concern the possibility 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 PdM 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 AI 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). Maintenance managers, via the dashboard, can acknowledge both past events and current status of the vehicle and get information in real time on the emissions generated, as in the screenshot in Figure 1.

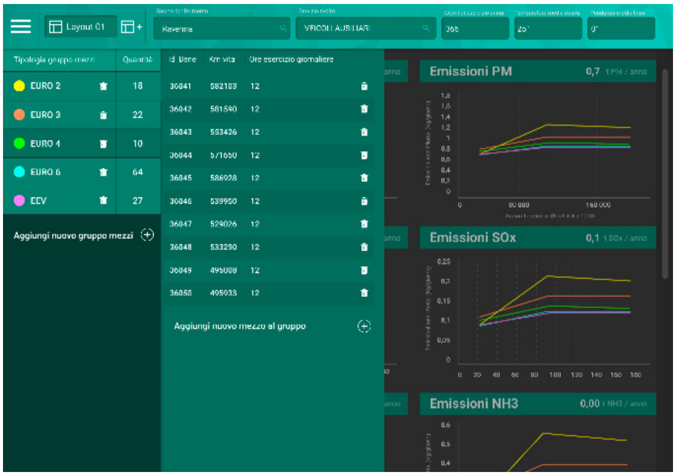

Fig. 1. Emission Dashboard Function

3.2. An additional Dashboard Function to manage water supplies

Data for the water management in this dedicated DF are gathered through two sets of information on daily operations (data from the Fleet Management System DF) and on the maintenance activities (Intelligent Garage System DF). 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 (Figure 2).

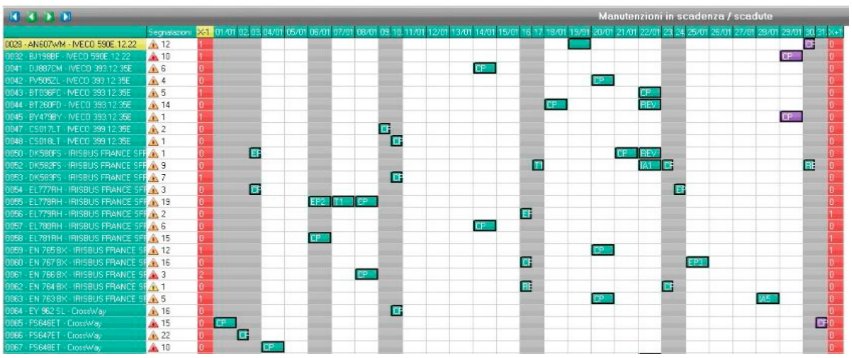

Fig. 2. Water Management Dashboard Function

Specifically, the DF 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 DF 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 forecast rely on the “Adaptive Cleaning Strategy Based on Generalized Load Recognition”, i.e. the innovative DF’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 resultin, innovative 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.

4. Testing scenarios and preliminary outcomes

Tests for both DF have been extensively carried out, as further described, with the two-pronged goal to assess the software reliability and its user-friendliness among operators. To this end, different testing scenarios have been designed, with the additional goal to test the software under very different local conditions (local topography, fleet size, environmental conditions, etc.).

4.1. A benchmark test to assess emissions

Initially, the emission assessment, by applying the above-mentioned integrated algorithm, took place in three different real operational scenarios, involving the transit fleets of three middle-size Italian cities, all with a large amount of servicing pre-EURO IV buses, i.e. in Ravenna, Olbia and Cuneo.
Ravenna was the first scenario and can be considered a sort of pre-trial since only a small amount of vehicles were involved. Results achieved were promising and enabled to upscale the tests in Olbia and Cuneo, again successfully validating the process. The results, at city level, have been already presented elsewhere (Corazza 2018, Corazza 2021). A benchmark among the three case studies, however, presents two novel 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 new DF also highlighted specific differences in the emission packages due to the types of operations performed.
For the latter, in case of very high protracted mileage (i.e. > 160,000 km), NOx emissions still increase, whereas the CO_2 ones stabilize; in turn, SOx 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. At the same time, high values detected in the NH_3 generation might reveal a cold-start problem. The implication for transit operators are 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 NOx 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. Water Management

The water management DF is being trialled at three different Arriva garages, following up successful experiences started in 2016, in Slovenia. Here, a new automatic bus washing plant was opened, and integrated 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. Moreover, 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 litres of water. From these facts, the goal to reach around 90-95% of water saving efficiency is within reach and the three test sites the DF is applied to serve as a feasibility trial. The three 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 condition 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 litres 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 litres /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.
The DF is designed to provide maintenance managers with facts and figures on the expected improvements in terms of water and energy savings, and actual expenditures, so to enable operations optimization, by simply entering data on local operations and context.

5. Conclusions

From all of the above it is clear that these experiences represent the first steps towards a more comprehensive vision on negative impacts mitigation and pave the way towards more opportunities to save resources for bus operators. It also stresses that there are fields like the management of obsolescing bus fleets or water supplies which are still underestimated or less considered, partly because of the lack of appropriate regulations (e.g. on water management) and partly because of the poor awareness among operators and decision-makers on their potential in coping with externalities (for example, by saving and reducing emissions through advanced maintenance processes and adapting the service in a way to associate obsolescing vehicles with less challenging operations under the emissions' point of view).
For what specifically concerns the two DF, their relevance does not only rely on the possibility to manage maintenance operations via tele-diagnostics and optimize the service; more important, the two DF provide maintenance managers with tangible information 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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