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# Optimal bus fleet management strategy for emissions reduction

Lu Li, Hong K. Lo *, Xuekai Cen

*Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong, China*

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A B S T R A C T

Transportation is a major cause for environmental degradation via exhaust emissions. For many transit-oriented metropolitan areas, bus trips often constitute a sizeable mode share. Managing the bus fleet, in particular updating buses to comply with the newer emissions standards, therefore, can have a substantial impact on transportation-induced air quality. This paper presents the approach of remaining life additional benefit–cost (RLABC) analysis for maximising the total net benefit by either early-retiring or retrofitting the current bus fleet within their lifespans. By referring to the net benefits for different bus types estimated by RLABC analysis, the most beneficial management scheme for the current bus fleet can be identified. Optimal bus fleet management (BFM) models based on the RLABC analysis for the operator and the government are developed. Then a government subsidy plan is produced to achieve win–win solutions, which will offer efficient and flexible management schemes. To illustrate the approach, the largest bus company in Hong Kong, which carries more than 23% of the total trips in Hong Kong, is taken as a case study example. Instead of adopting a fixed retirement plan, such as replacing buses at the age of 17 as is currently practised, the proposed method develops an optimal BFM scheme that progressively phases out buses or retrofits them. This study produces promising results to demonstrate the large benefit of this approach for optimal bus fleet management.



## Introduction

Road transportation is a major source for environmental degradation via exhaust emissions, causing considerable damage to human health and the ecosystem. According to Zegras (2007), four major areas can be considered to tackle vehicular greenhouse gas (GHG) emissions: activities, mode share, fuel intensity, and fuel type. In the context of Asian and European countries, where public transport is prevalent, how to manage the bus fleet to make it environmentally efficient is an important endeavour.

Numerous studies have been conducted on vehicle fleet management. In the early days, the notion of "repair limit" was proposed, describing that the asset should be replaced when its repair cost exceeds a certain amount (Drinkwater and Hastings, 1967). Since then, the approach was extended to consider imperfect repair or cumulative repair-cost (e.g. Nguyen and Murthy, 1981; Beichelt, 1982; Dohi et al., 2000). These models tend to focus on the cost of one single repair, without considering the prospect for the whole system. And overall budgetary constraints were generally not taken into account. Subsequently, the parallel machine replacement problem (PMRP) was introduced by Jones et al. (1991), with the idea of minimizing the total replacement cost for a finite population of economically interdependent machines over the

* Corresponding author. Tel.: +852 2358 8742; fax: +852 2358 1534.
*E-mail address:* cehklo@ust.hk (H.K. Lo).

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planning horizon. It offered two rules to replace the fleet, including the No-Splitting Rule – in any stage machines of the same age are either all kept or all replaced, and the Older Cluster Replacement Rule – a machine is replaced only if all older machines are replaced. Karabakal et al. (1994) described another PMRP for replacing multiple assets under capital rationing. McClurg and Chand (2002) developed a forward-time dynamic programming algorithm to better solve the PMRP. All of these studies are for deterministic PMPP with non-increasing marginal costs. To extend the consideration for the stochastic case, Childress and Durango-Cohen (2005) formulated a linear program to find optimal replacement policies for the infinite-horizon stochastic PMRP. These studies have taken into account many factors which affect machine replacement, such as purchase cost, operating and maintenance cost, salvage value, and budget constraint. For the vehicle replacement problem, however, the important factor of vehicular emissions has not been fully considered, which may make a big difference in the replacement decision.

In recent years, as the environmental problems become increasingly acute, green fleet management strategies for emissions reduction have attracted much attention. Cook and Straten (2001) conducted a benefit–cost analysis for replacing the existing bus fleet in North California by alternative-fueled buses. The study found that although natural gas buses offered substantial benefits of emissions reduction, a considerable amount of capital cost was needed to upgrade the facilities for buses using alternative fuels. The point is that it is essential to consider the benefit of emissions reduction alongside the life-cycle costs of bus-fleet replacement. Dill (2004) provided a more accurate estimate of emissions reduction by changing the assumptions from a voluntary accelerated vehicle retirement program. It pointed out that incentives from the government will have a strong impact on the quality of vehicles to be retired. Gao and Stasko (2009) developed an integer program to minimize the net present value of the retrofit/replacement costs under budget and emission constraints. Later Stasko and Gao (2010) updated their approach to minimize the operational costs and penalties for emissions produced under capital budget constraints. Retrofit is incorporated as an alternate method for reducing emissions. Nevertheless, the purchase and resale costs of the new bus were not taken into consideration, which may result in an aggressive replacement plan. On the other hand, as the purchase cost is much larger than the other costs, if the purchase cost is directly added to the objective function, then the opposite may occur, i.e. early replacement will likely not happen. How the purchase costs of replacement buses should be incorporated appropriately, therefore, remains an important question. In terms of complying with emission regulations, Stasko and Gao (2012) developed a model to predict the expected cost of compliance, giving guidance to regulators and fleet managers. It presented an approximate dynamic programming approach for making vehicle purchase, resale, and retrofit decisions in a fleet setting with stochastic maintenance and repair costs and vehicle failures. The model formulation is oriented toward the objective of emissions reduction by making all the buses reach the standard in an efficient way.

This paper proposes a novel approach called remaining life additional benefit–cost (RLABC) analysis to maximise the net benefit of managing the bus fleet within their lifespans for the common good of society. A bus fleet management (BFM) model based on the RLABC analysis is developed, which is arguably more realistic as it considers the additional net benefits generated by changing the BFM plans from their fixed retirement age, while considering the purchase, resale, retrofit, and operation costs, emission factors, as well as the budget constraints. The conventional BFM scheme typically takes into account the actual expenses, and leaves out certain indirect benefits and costs, which would lead to decisions that do not address the complete picture. The proposed approach here can tactfully alleviate the misgiving of the purchase cost issue by taking into account the indirect additional benefits and costs, as will be explained in Section 'Methodology'. Besides, the private bus company will develop its management scheme for profit maximisation, not emissions reduction. To include this perspective of the private operator, a management model based on remaining life additional cost analysis is developed, which purely minimizes the actual additional cost while ignoring the additional benefits from emissions reduction. Based on the optimal management schemes generated by these two models, we develop a government subsidy plan to investigate what kind of subsidy to the private operator would provide sufficient incentive for it to implement the optimal BFM scheme that includes the objective of emissions reduction. Such an approach is arguably more realistic, as it considers both the government's objective to reduce emissions and the private bus company's objective to maximise profit.

In this study, we consider six main types of emissions as a function of speed and emission standards, and convert them into monetary form by their corresponding external costs. To illustrate the methodology, we apply it to the biggest bus company in Hong Kong in the context of Euro IV franchised buses replacement a few years ago. Nevertheless, the methodology developed is applicable for a general context. The outline of this paper is as follows: Section 'Methodology' presents the methodology; Section 'Case study – Hong Kong' depicts the implementation of the methodology to the Hong Kong case study; and finally, Section 'Concluding remarks' provides some concluding remarks.

## Methodology

### *Remaining life additional benefit–cost (RLABC) analysis*

#### *Description of RLABC analysis*

Early retiring or retrofitting the bus fleet before their nominal retirement age will generate additional benefit and cost. The question is how to strike a balance between the benefits of reduction in external costs arising from emissions and