EX-ANTE EVALUATION OF OPTIMAL MIXED TRANSIT FLEET MANAGEMENT PLANS

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ABSTRACT
Transit operators are gradually incorporating hybrid and electric vehicles in existing conventional-drive and natural gas fleets, in an effort to improve carbon-footprint of transit services. Naturally, there are significant trade-offs in terms of purchase, operation and management costs between the various propulsion systems, which complicate fleet replacement and vehicle purchase decisions for agencies. To that end, the objective of this study is to provide an ex-ante evaluation of bus fleet management plans in cases of fleets with mixed propulsion technologies. An integer programming model is exploited for that purpose, seeking to minimize the total cost of purchasing, operating and selling buses, under various fiscal and operational constraints. A realistic data set from various sources is collected and a thorough scenario analysis is performed to assess the various trade-offs between different propulsion technologies. Results show that the largest reduction in the fleet management cost stems from favorable conditions for the purchase of more fuel-efficient types of buses, such as electric and natural gas buses.

Keywords: *resource allocation, bus replacement, fleet management, integer programming*

INTRODUCTION

Sustainability in urban transportation is undeniably one of the main concerns of the 21st century. Since the Kyoto Protocol, environmental directives and policy initiatives have been put forward to ensure that the carbon footprint of road transport sector is decreased (*1*). Given the number of passenger-miles traveled each year by buses, deploying alternative fuel vehicles in public transportation fleets has the potential to greatly reduce transportation-related environmental impacts (*2*). In this context, public transport operators have begun to introduce environmental friendly bus fleets. In the past 15 years, many public transport authorities worldwide have adopted natural gas (NG) buses to limit air pollutants emitted by bus fleets (*3*,*4*), with compressed NG bus purchases accounting for 20%–25% of U.S. transit bus sales (*5*). Hybrid diesel-electric and electric propulsion technologies have also emerged as alternative options for transit fleets. Indeed, hybrid diesel-electric vehicles are already used by several agencies (*4, 6-8*). Further, electric vehicle demonstration projects are underway in several cities both in the US (*9,10*) and Europe (*11*). As a consequence of the adoption of new vehicle types, transit agencies are called to operate mixed bus fleets, as hybrid and electric vehicles are gradually incorporated in existing diesel and natural gas fleets (*12*).

The simultaneous presence of different vehicle types naturally complicates fleet management strategies. In general, transit operators are faced with multiple decisions regarding fleet management, such as when and how many buses to sell or purchase. The problem is complex even in the case of homogeneous fleets, as decisions for a certain year affect the performance of the operator in the following years (*13*). Further, the provision of high-quality service to passengers and the minimization of financial cost constitute conflicting objectives both of which affect fleet replacement strategies. On the one hand, the purchase of new vehicles enhances the level of service quality and the public image of the operator, thus affecting long-term financial viability (*14*). On the other hand, operators want to make the most out of the capital investment in vehicles by exhausting vehicle age limits, while budget constraints naturally apply as well (*15*). Further complicating relevant decisions, the condition of buses is also obviously linked with maintenance and operating costs, as the latter rise with vehicle age (*16*). The associated fleet replacement problem arising for operators must thus aim to reconcile conflicting goals in an efficient manner.

Nevertheless, bus replacement decisions for transit agencies are typically based on rules of the thumb and fixed replacement schedules (*14, 17*). In mixed fleets, however, the trade-offs between the various technologies must be taken into consideration within an optimization framework, as purchase, maintenance and operating costs vary across different technologies and thus, largely affect optimal replacement strategies (*17*). Moreover, existing literature on optimal transit fleet maintenance has not yet addressed the incorporation of natural gas and electric propulsion vehicles in transit fleets. In this context, this work aims to determine the optimal fleet management plan for a transit operator, considering four propulsion technologies: diesel, hybrid, natural gas, and electric. The problem is realistically modeled based on a wide data collection from research studies, practice reports, policy briefs, and online databases and solved using integer programming. The model can be used by transit operators to assist in management decisions during their transition from conventional to alternative fuel fleets.

The remainder of this manuscript is organized as follows: The following section reviews the literature on fleet management models, focusing on mixed fleets. Subsequently, the mathematical formulation is provided. The application of the model is then described in detail and a thorough sensitivity analysis is performed. Finally, key findings are discussed.

BACKGROUND

In the relevant literature, the problem that formally describes the decision-making process faced by transit agencies with respect to vehicle replacement is referred to as fleet replacement problem (*14*). Over the years, several studies have devised relevant fleet management models, which consider decisions regarding the timing of salvaging old vehicles and purchasing new vehicles, the types and number of vehicles to replace/purchase and which maintenance actions to take (*13- 20*).

Simms et al. (*13*) were the first to propose an optimization model for bus fleet management. A combination of dynamic and linear programming was used to determine the number of buses to buy/sell and the timing of the sale. Similarly, Keles and Hartman (*14*) proposed an integer programming formulation for transit fleet management, considering various operating factors and different bus manufacturers. Khasnabis et al. (*18*) presented an asset management strategy for US state Departments of Transportation to optimally select between purchasing new buses and rebuilding existing buses and to fairly distribute available funds among transit agencies. In the same context, Matthew et al. (*19*) proposed a non-linear optimization problem to maximize the total weighted average remaining life of a conventional transit fleet considering bus replacement, remanufacturing and rehabilitation. Building upon this work, Mishra et al. (*20*) modified the optimization problem to minimize the net present cost of the financial investment of the operator. A few other studies attempted to estimate the optimal point in time to replace a bus. In this direction, Boudart and Figliozzi (*15*) developed an integer optimization model to determine the optimal timing for bus replacement, taking into account emissions, maintenance costs, salvage value and vehicle utilization. Similarly, Riechi et al. (*16*) proposed a methodology combining Monte Carlo simulation and life cycle cost analysis using real data from a small Spanish transit operator to determine the optimal timing of replacement.

These studies, however, considered conventional diesel vehicle fleets. A few studies have addressed management and replacement decisions in the context of heterogeneous fleets featuring various propulsion technologies. Nevertheless, the majority of these studies have so far dealt with commercial vehicle fleets. In this line of research, Figliozzi et al. (*21*) proposed an integer programming vehicle replacement model for private vehicle fleets considering diesel, hybrid, plug in hybrids and electric vehicles and fiscal policies such as emissions trading and taxes. Similarly, Feng and Figliozzi (*22*) proposed an integer programming model for commercial vehicles considering electric motor and diesel trucks. Recently, Ansaripoor et al. (*23*) presented a stochastic mixed integer programming model for fleet management considering fossil fuel and electric vehicles. Economic parameters such as fuel and CO_2 price were treated as stochastic variables and the goal of the proposed model was to minimize the total expected cost and financial risk. In the only approach to consider multiple fuel technologies for transit operators, Feng and Filgiozzi (*17*) presented an optimal bus fleet replacement model using real world data from a transit operator in Seattle, considering diesel and hybrid diesel vehicles.

To the best of the authors' knowledge, there is no study dealing with fleet replacement decisions in the context of transit fleet management which considers NG and electric vehicles. This fact is all the more surprising, considering that NG vehicles are widely used in public transport (*3, 5*), while electrification of bus networks is in the works in many cities worldwide (*9-11*). To that end, the present study extends an existing formulation to incorporate CNG, hybrid, electric and diesel buses in an optimal fleet management model. A rigorous data collection is conducted in order to realistically model the problem at hand and investigate the various trade-offs between alternative technologies.

PROBLEM FORMULATION

A deterministic problem formulation is adopted. The various economic parameters are treated as known functions of time (*22*) and a thorough sensitivity analysis is performed later on to estimate their effect on model results. The mathematical model is borrowed from (*17*,*21*,*22*) and extended to consider fleet size requirements for transit operators. Adding fleet size constraints was necessary since the vehicle utilization constraint might be satisfied by a smaller number of vehicles, yet passenger demand may not be satisfied in such a scenario. Let:

X_{ijk}: the number of type-*k* buses of age *i* in operation at year *j*

Y_{ijk}: the number of type-*k* buses of age *i* sold at year *j*

P_{jk}: the number of type *k* buses purchased at year *j*

$k \in K = \{1,2,\ldots K\}$: Bus type

$i \in A_k = \{0,1,\ldots,A_k\}$: age of *k*-type bus

$j \in T = \{0,1,2,\ldots,T\}$: year within planning horizon

v_k : cost for bus of type *k*

b_j: purchase budget for year *j*

o_{ijk}: energy cost/km for type-*k* bus of age *i* at year *j*

dr: depreciation rate of money

s_{ik}: sale revenue for type-*k* bus of age *i*

m_{ik}: maintenance cost for type-*k* bus of age *i*

u_{ik}: utilization (in km) for type-*k* bus of age *i*

h_{ik}: initial number of type-*k* buses of age *i*

d_j: Minimum number of km per year

F_{max} maximum fleet size

F_{min} minimum fleet size

e_{ik}: CO_2 emissions for type-*k* bus of age *i*

ec: cost per CO_2-ton

The problem is then defined as follows:

$$\min \sum_{j=0}^{T-1}\sum_{k=1}^{K} v_k \cdot P_{jk} \cdot (1+dr)^{-j} - \sum_{i=1}^{A_k}\sum_{j=0}^{T-1}\sum_{k=1}^{K} s_{ik} \cdot Y_{ijk} \cdot (1+dr)^{-j} + \sum_{i=1}^{A_k-1}\sum_{j=0}^{T-1}\sum_{k=1}^{K} (o_{ijk} + m_{ik} + ec \cdot e_{ik}) \cdot u_{ik} \cdot (1+dr)^{-j} \cdot X_{ijk} \quad (1)$$

s.t.

$$\sum_{k=1}^{A_{k-1}} v_k \cdot P_{jk} \le b_j \quad \forall \text{ j} \in \{0,1,\ldots,T-1\} \quad (2)$$

$$\sum_{i=0}^{A_{k-1}}\sum_{k=1}^{K} u_{ik} \cdot X_{ijk} \ge \text{d}_j \quad \forall \text{ j} \in \{0,1,\ldots,T\} \quad (3)$$

$$\text{F}_{\max} \ge \sum_{i=0}^{A_{k-1}}\sum_{k=1}^{K} X_{ijk} \ge \text{F}_{\min} \quad \forall \text{ j} \in \{0,1,\ldots,T\} \quad (4)$$

$$P_{jk} = X_{0jk} \quad \forall \text{ j} \in \{1,2,\ldots,T\} \quad (5)$$

$$P_{0k} + h_{0k} = X_{00k} \quad \forall \text{ k} \in K \quad (6)$$

$$X_{i0k} + Y_{i0k} = h_{ik} \quad \forall \text{ k} \in K \ \ \forall \text{ i} \in \{1,2,..A_k\} \quad (7)$$

$$X_{(i-1)(j-1)k} = Y_{ijk} + X_{ijk} \quad \forall \text{ k} \in K \ \ \forall \text{ i} \in \{1,2,..A_k\} \ \forall \text{ j} \in \{1,2,..T\} \quad (8)$$

$$X_{A_k jk} = 0 \quad \forall \text{ j} \in \{1,2,\ldots,T\} \ \forall \text{ k} \in K \quad (9)$$

$$Y_{0jk} = 0 \quad \forall \text{ j} \in \{0,1,\ldots,T\} \ \forall \text{ k} \in K \quad (10)$$

$$P_{jk}, X_{ijk}, Y_{ijk} \quad \in I = \{0,1,2.....\} \quad (11)$$

The objective function minimizes the discounted sum of purchasing (first term), salvage revenue (second term), operation, maintenance, and emissions' cost (third term) over the planning horizon. Eq. (2) reflects the annual budget constraint for new vehicle purchases. Eq. (3) states that total distance traveled each year must exceed the minimum requirement. Eq. (4) restricts the total number of vehicles used annually within the fleet size limits for the operator. Eq. (5) states that all new vehicles must be used right away. Eqs. (6) and (7) ensure the conservation of vehicles for year 0 and subsequent years, respectively. Eq. (8) states that each available vehicle must be either used or sold in the following year. Eq. (9) states that no vehicle can be used beyond its maximum age. Eq. (10) states that a new vehicle (of age 0) cannot be sold. Finally, Eq. (11) specifies the form of the decision variables.

APPLICATION

The model was applied for the case of a transit operator in a large urban area, considering diesel, hybrid, natural gas (NG) and electric (E) buses. The relevant assumptions and numerical values for the various parameters involved in the calculation process are addressed next.

Assumptions

This section presents the calculation of operating costs, salvage values as well as vehicle utilization.

Energy cost: The energy cost estimation for each bus type *k* was estimated according to the following equations (*22*):

$$o_{ijk} = \frac{f_{cj}}{f_{ik}} \quad (12)$$

$$f_{cj} = f_{c0} \cdot (1 + fr_c)^j \quad (13)$$

Where *c* the fuel type, f_{cj}: fuel cost in €/lt or in €/KWh, fr_c: fuel price inflation rate, f_{ik}: motor efficiency for type-*k* bus of age *i* in km/KWh or km/lt

The price inflation rate is assumed to be 3.5% for diesel and natural gas and 1.8% for electricity (*24*). Further, an annual reduction rate of 1% in motor efficiency was assumed due to increasing vehicle age (*25*).

Vehicle utilization: Adopting a similar approach to Feng and Filgiozzi (*24*), the following equation was used to compute the utilization for each bus based on age:

$$u_{ik} = t_k - 500 \cdot i \quad (14)$$

Where t_k is the annual average distance traveled per type-*k* vehicle and *i* the bus age.

Salvage price: The sale revenue from a used bus is a function of both vehicle use and age. An exponential function was used for salvage price. The following equation applies (*26*):

$$s_{ik} = v_k \cdot (1 - \theta_k)^i \quad (15)$$

Where v_k the purchase cost and θ_k a coefficient for vehicle utilization equal to 15% (*26*)

Maintenance cost: Annual increase rates of 2.5% and 1.5% were assumed for the maintenance cost of diesel buses and remaining bus types, respectively (*27*).

Data Collection

A thorough data collection process was followed to estimate the parameter values. Relevant figures from research studies (*1-3, 28-31*), practice reports (*4-10, 25, 12, 32-36*) and online databases (*37-39*) have been collected and average values have been computed for the input values (Table 1).

TABLE 1 Parameter values

Average parameter values	Bus type: Diesel	Hybrid	CNG	EV	General
k	1	2	3	4	
c	1	1	2	3	
Energy cost €/km (o_{ijk})	0,80	0,63	0,51	0,24	
Maintenance cost €/km. (m_{ik})	0,35	0,29	0,30	0,29	
Motor efficiency €/lt ($f_{ik}, k\neq 4$)	1,6	2,1	1,6	-	
Electric Motor efficiency €/kwh (f_{i4})	-	-	-	0,82	
CO_2 emissions kg/km (e_{ik})	2,290	1,722	1,732	0,124	
Fuel cost €/lt ($f_{c0}, c\neq 3$)	1,30	1,30	0,51	-	
Electricity cost €/kwh (f_{c0})	-	-	-	0,20	
Average annual km traveled (t_k)	55,000	50,000	55,000	50,000	
Purchase cost (€) (v_k)	236,841	394,004	333,954	538,500	
Minimum fleet size (F_{min})					1,000
Maximum fleet size (F_{max})					2,000
Minimum annual km (d_j)					70 mil.
Max age for all types (A_k)					15
Depreciation rate (dr)					1.5%
Annual budget (b_j)					100 mil.
Initial number of vehicles ($\sum_i h_{ik}$)	600	375	450	225	1,650
Initial number of vehicles of age i (h_{ik} for all i)	40	25	30	15	

Results

The model was implemented in *OpenSolver*^{TM} , which uses the branch-and-cut method. The case study presented refers to the Athens transit operator, for which minimum and maximum fleet size requirements have been estimated. Since no emissions' tax is used in Athens, the emissions' cost will be considered zero in all but one scenarios. The number of decision variables is 2,480 and the model takes less than 1 minute to run on a 4GHz personal laptop with 8GB of RAM.

Basic Scenario

This section presents the results for the parameter values shown in Table 1. The overall fleet management cost over the 20-year planning horizon is approximately 1 billion €. The average bus age is 6.4 for diesel vehicles, 10.2 years for hybrid vehicles, 7 for NG vehicles and 7.8 for electric vehicles. Vehicle utilization percentages per type are shown in Figures 1 and 2.

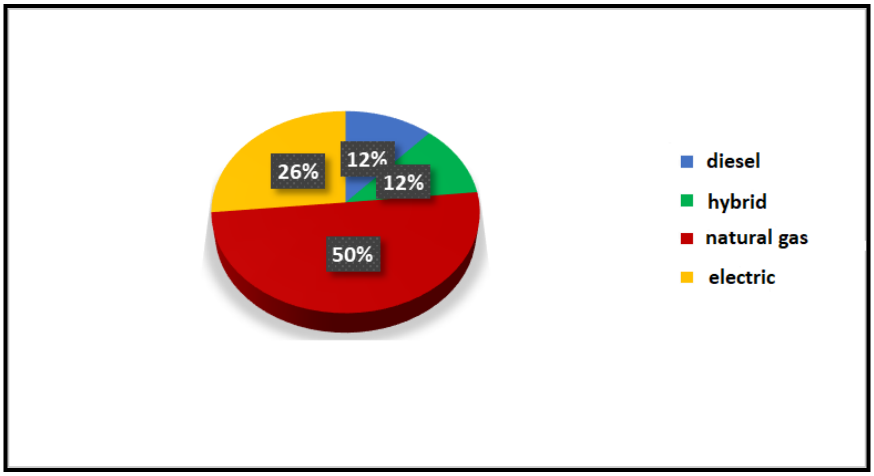


FIGURE 1 Usage Share for each bus type

As can be seen in Figure 1, out of all the vehicles used, 50% are natural gas vehicles, 26% are electric, 12% are hybrid and 12% are diesel. This is reasonable considering the comparatively low natural gas and vehicle purchase price and in accordance with applied practice (*3*,*5*). According to Figure 2, out of all buses sold, 33% run on NG, 30% on diesel vehicles, 19% use electricity and 18% are hybrid. Notably, most of the diesel buses originally in the fleet are sold. In total, 58% of new buses are natural gas vehicles, 31% are electric, 11% are conventional, while no hybrid vehicles are bought. The latter may be attributed to the high purchase price and high fuel cost associated with hybrid vehicles.

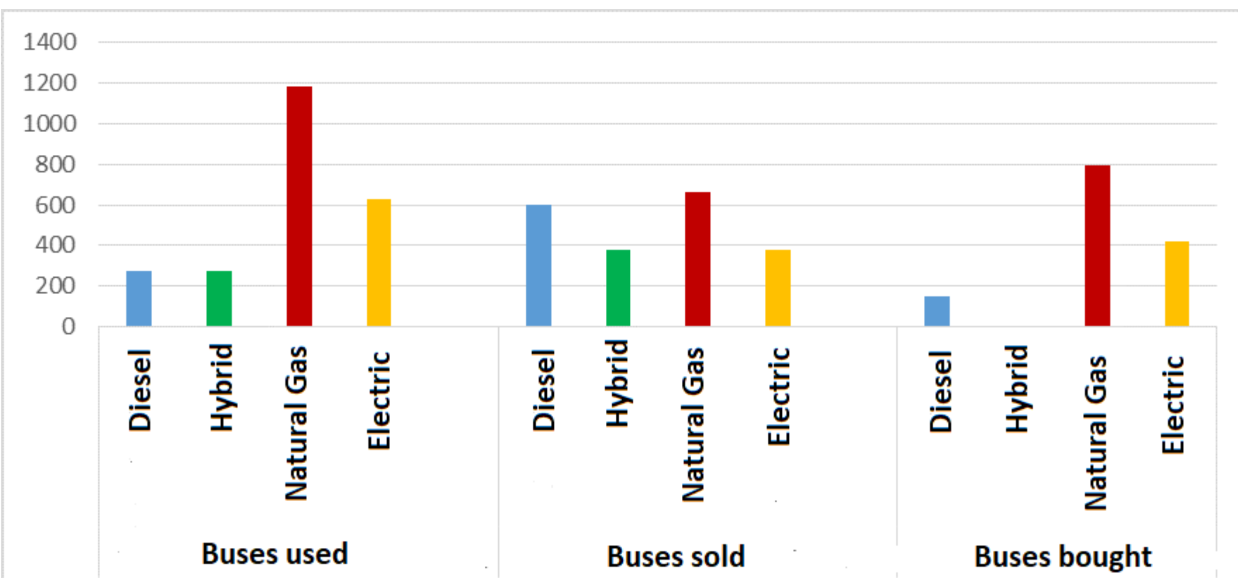
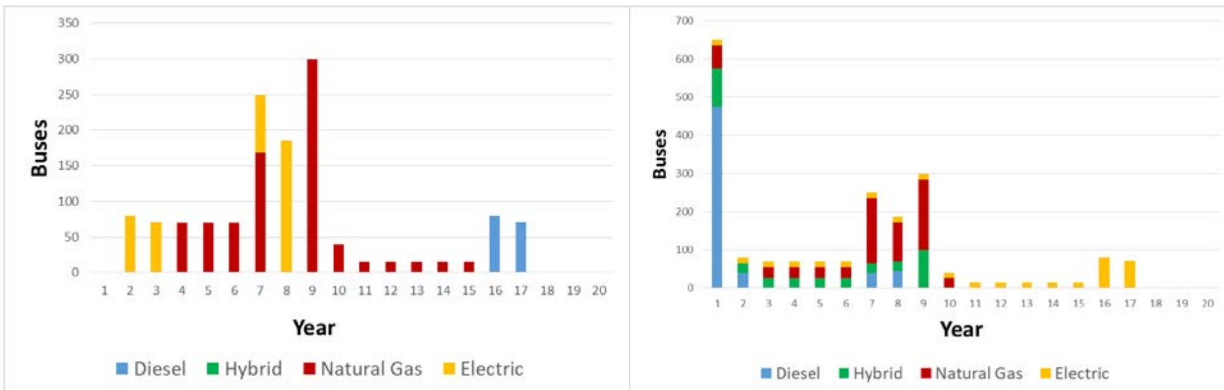


FIGURE 2 Total number of vehicles used, sold and bought per type

Figure 3 shows the vehicles sold and bought per type for every year of the planning horizon. In terms of new vehicles purchased, natural gas vehicles are bought during most of the planning horizon (years 4-15), electric vehicles are bought in the earlier years (2,3,7,8), whereas diesel vehicles are only bought at years 16, 17. The majority of diesel vehicles in the initial fleet (79%)

are sold in the first year, while hybrid and NG vehicle sales occur until year 9 and 10, respectively. After year 10, only electric vehicles are sold (until year 17), which is explained by their higher salvage value compared to other types.



(a) (b)

FIGURE 3 Number of vehicles bought (a) and sold (b) each year per type

Scenario Analysis

An extensive scenario analysis is performed considering four main parameters: purchase and energy cost for each bus type, emissions' cost and annual budget. These are further described in the following subsections.

Purchase Cost

Reasonably, the initial cost for each vehicle type is a crucial factor for the number of vehicles purchased of each type. For this reason, 8 scenarios are explored, where the purchase cost for each vehicle type is decreased/increased by 30% (low cost/high cost). Scenarios S_2 and S_3 correspond to low (-30%) and high (+30%) diesel vehicle costs, respectively. Similarly, S_4 and S_5 reflect low and high hybrid vehicle cost; S_6 and S_7 low and high NG vehicle cost and S_8, S_9 low and high electric vehicle cost, respectively.

Fuel/ Energy Cost

Naturally, fuel costs are the main driver of operating costs. To explore the effect of energy cost, 6 scenarios are developed. Scenarios S_{10} and S_{11} reflect low (-30%) and high (+30%) diesel cost, scenarios S_{12} and S_{13} low and high natural gas costs and scenarios S_{14} and S_{15} low and high electricity costs, respectively.

Emission's cost

Scenario S_{16} considers the social cost of CO_2 emissions, which may be seen as the imposition of an emissions' tax. In this case, the emissions' cost was assumed as 100€/ CO_2 -ton, similar to (*15,40,41*).

Budget constraint
Scenario S_{17} represents a reduced annual budget of 40 million euros.

Results for all scenarios are shown in Table 2.

TABLE 2 Total number of vehicles used per scenario

	Buses Used				Average vehicle age			
	Diesel	Hybrid	NG	Electric	Diesel	Hybrid	NG	Electric
1. Basic Scenario	276	275	1,183	627	6.4	10.2	7	7.8
2. Low Diesel bus Cost	660	275	516	994	3.9	10.6	8.5	7.7
3. High Diesel bus Cost	100	300	1,477	485	10.3	9.8	6.8	7.9
4. Low Hybrid bus cost	80	1,710	360	210	10	6.9	9.3	9.7
5. High Hybrid bus cost	335	240	1,125	651	6.7	10.6	7.1	7.8
6. Low NG bus cost	40	275	1,920	195	1	10.5	6.9	10.2
7. High NG bus cost	620	285	360	1,165	5	10.2	10.2	7.4
8. Low E bus cost	40	185	300	1,825	1	10.6	10.4	6.5
9. High E bus cost	160	270	1,728	180	10.3	9.8	6.9	10.2
10. Low diesel price	796	999	270	180	6.4	7.6	10.2	9.5
11. High diesel price	40	175	1,319	806	1	10.6	6.4	7.7
12. Low NG price	40	275	1,920	195	1	10.6	6.8	10.2
13. High NG price	620	300	340	1,165	5.1	10.2	10.2	7.4
14. Low electricity price	344	300	622	1,149	2.8	10.2	7.6	7.5
15. High electricity price	160	255	1,715	195	10.3	10.1	6.9	7.4
16. Emissions' tax	205	275	695	1,185	2.1	10.1	6.9	7.4
17. 40 mil. budget	354	275	1,175	551	3.8	10.4	7	8

As a general point, as expected, in any scenario where the purchase cost of a certain bus type is reduced, the number of respective vehicles used increases and vice versa, while average vehicle age also drops (S_4, S_6, S_8). The most notable rise in the number of vehicles in response to a lower purchase price is noted in the case of hybrid vehicles (up by 522%), followed by electric vehicles (+192%). These figures underline the relative advantage of hybrid and electric vehicles in terms of operating and maintenance costs and the issue of high capital cost which hinders their wider adoption. Similarly, for lower NG bus prices, the corresponding usage share increases by 62% (S_6) with the total NG vehicle number reaching the value of 1,920. Likewise, for low diesel bus purchase cost, 139% more conventional vehicles are used (S_2), yet their total number (666) is still much lower than in the other fuel cases.

In cases with higher purchase costs, average vehicle ages rise, as older vehicles are kept in operation for more years. Particularly, in Scenarios S_3 and S_7, the average age for diesel and NG vehicles rises by 63% and 46%, respectively. Scenarios with reduced energy prices also provide useful insights. In the case of low electricity price, electric vehicles are preferred whereas in the majority of scenarios, NG vehicles comprise the largest proportion of the fleet. Further, the reduction in diesel price increases the number of diesel and hybrid vehicles by 188% and 263%, respectively. In the case of an emissions' tax, the number of electric vehicles naturally grows by 89%, while the count of diesel buses drops by 26%. Finally, the drastic cut in the budget for new purchases does not greatly impact the vehicle totals per type, except for the 28% increase in the number of diesel buses, which are used in the place of electric buses. Overall, it may be observed that in scenarios where alternative fuel and bus prices are reduced, a very small percentage of diesel vehicles are retained and sold after 1 year (S_6, S_8, S_{11}, S_{12}).

Figure 4 shows the total number of vehicles per type for each scenario reflecting changes in purchase or fuel costs (Scenarios 2-15). So, for each bus type, the total number of corresponding vehicles utilized is plotted for five scenarios: low vehicle purchase cost, low fuel cost, basic scenario, high purchase cost and high fuel cost.

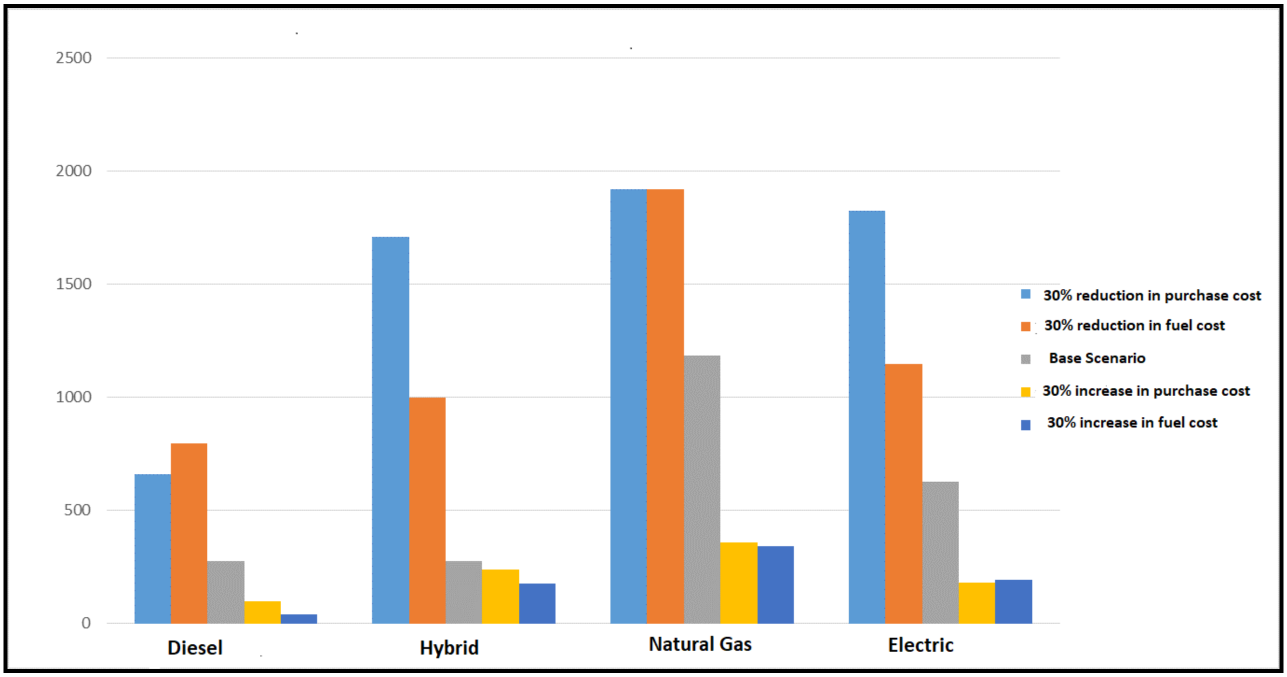


FIGURE 4 Total number of vehicles used per cost scenario

Several useful observations arise from Figure 4. First of all, a reduction in purchase cost has a larger effect on the number of vehicles bought in the case of hybrid and electric vehicles, which is explained by the high purchase prices of these types. For NG vehicles, a 30% reduction in purchase cost has the same effect as a 30% reduction in NG price in terms of the number of vehicles used. For diesel vehicles, a 30% reduction in fuel cost leads to more diesel buses used than a reduction in purchase cost. This finding is also considered reasonable, since diesel buses are comparatively cheaper than other types, while diesel price is high compared to NG and electricity.

A similar analysis is conducted for the number of vehicles purchased per type in response to changes in fuel and purchase costs (Figure 5). With respect to vehicles purchased, a 30% increase either in the initial purchase cost or in the fuel price deters the purchase of any vehicles of the corresponding type. For any vehicle type, a 30% reduction in purchase or fuel cost leads to an increase in the number of vehicles bought; the effect of the former is proportionally larger than the latter with the exception of natural gas vehicles, where the same number of buses are bought in both cases. Particularly for hybrid vehicles, if initial cost dropped by 30%, approximately 1,400 vehicles would be bought and hybrids would comprise the majority of the buses used (also see

Table 2), in contrast to the base case where no hybrid buses are bought. These results are shown in Figure 5.

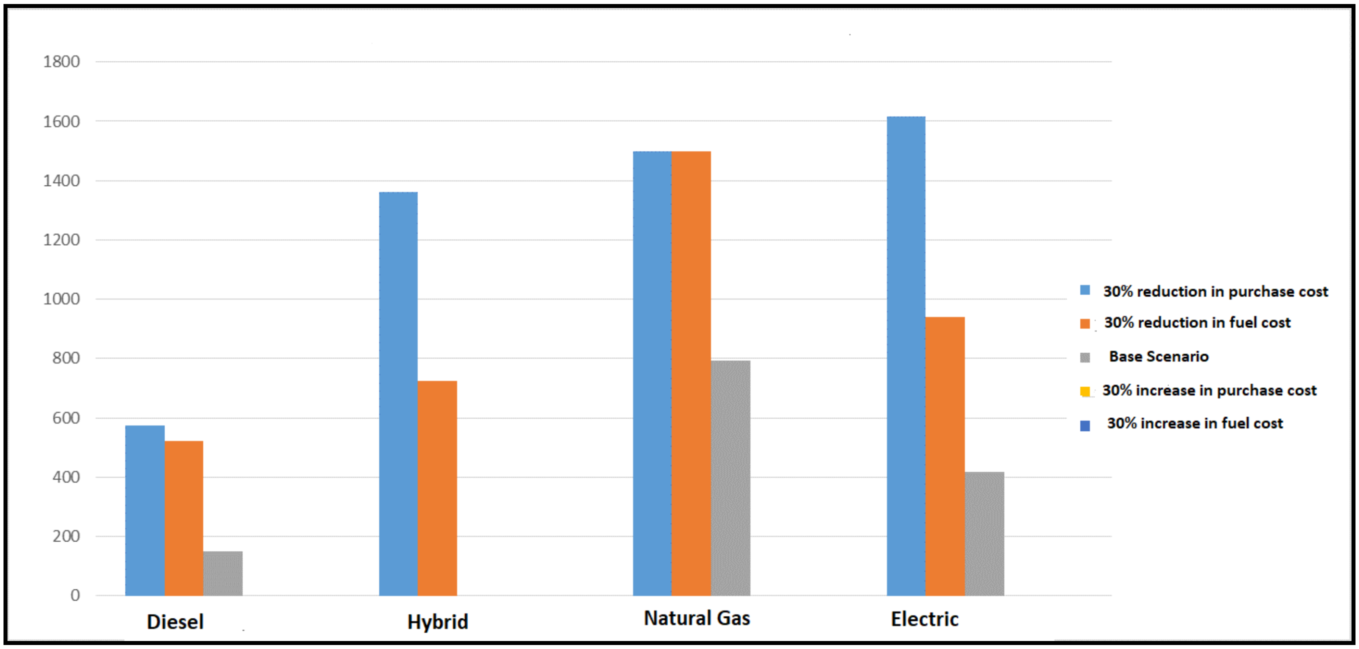
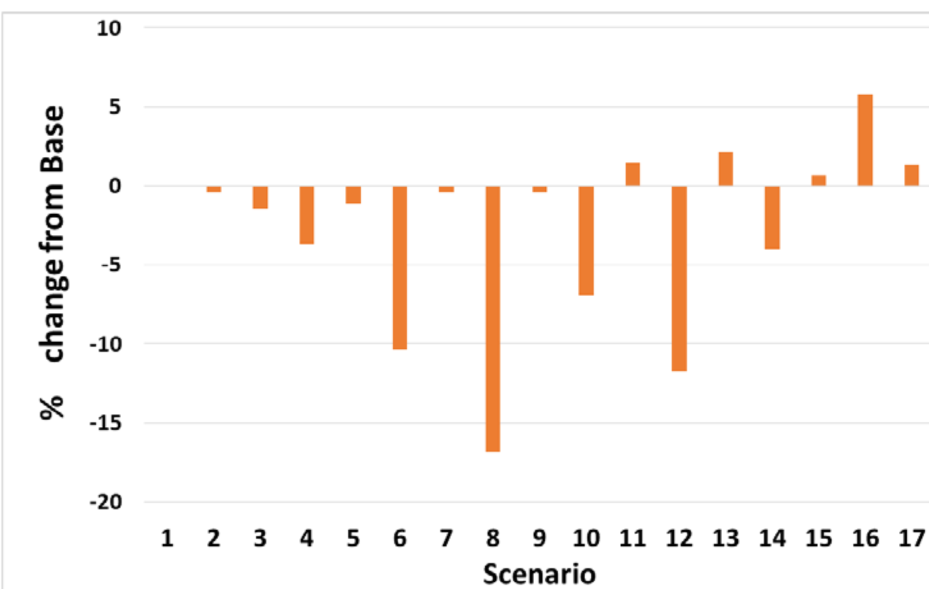


FIGURE 5 Effect of purchase and fuel cost on vehicles bought per type

Important conclusions may be drawn by comparing the total management cost among the different scenarios. Figure 6 presents the percentage change in total cost over the entire planning horizon compared to the basic scenario.



1. Basic Scenario
2. Low Diesel bus Cost
3. High Diesel bus Cost
4. Low Hybrid bus cost
5. High Hybrid bus cost
6. Low NG bus cost
7. High NG bus cost
8. Low Electric bus cost
9. High Electric bus cost
10. Low diesel price
11. High diesel price
12. Low NG price
13. High NG price
14. Low electricity price
15. High electricity price
16. Emissions' tax
17. 40 mil. budget

FIGURE 6 Percentage change in total cost from Basic Scenario

As may be observed in Figure 6, Scenario 8, i.e. a 30% lower electric vehicle price results in the lowest total fleet management cost. Similarly, a 30% reduction in natural gas price and a 30%

reduction in NG vehicles' cost also yield significant cost savings. Smaller improvements in terms of cost are attained in S_4, S_{10}, S_{14} which correspond to 30% lower purchase cost for hybrid buses, 30% lower diesel and 30% lower electricity price. On the other hand, in the case of lower diesel bus price (S_2), 30 % higher natural gas bus (S_7) or higher electric bus prices (S_9), the change in total cost is negligible. This may be explained by the fact that fewer diesel buses are used anyway, while if NG bus costs sharply rise, a mix of diesel and electric buses are utilized instead and vice versa. Moreover, the imposition of an emissions' tax raises the total cost, as non-electric vehicles (11% of the fleet) are taxed. Lastly, the 60% budget reduction leads to a 1% increase in overall cost (S_{17}), which is attributed to the increased operating and maintenance costs of older vehicles.

DISCUSSION

The incorporation of alternative fuel vehicles, spurred by a series of sustainability-related policy initiatives, creates new challenges for the operators. Indeed, decisions regarding optimal replacement strategies for fleets consisting of multiple vehicle types are complex and greatly affect management costs. To that end, this study realistically models the fleet management problem for a transit operator with a mixed fleet consisting of diesel, natural gas, hybrid and electric buses. The extensive analysis conducted in this study provides various useful insights for the management of heterogeneous fleets and underlines the comparative strengths and weaknesses of the various vehicle types. A few key findings are summarized in this section.

First and foremost, the analysis shows that hybrid and electric vehicles are advantageous in terms of operation and maintenance costs, yet high purchase costs limit their wider adoption by agencies. Further, in any case where the purchase or fuel price for an alternative fuel vehicle is reduced, the number of diesel buses used sharply drops. These observations give rise to policy questions with respect to the provision of "green fleet" incentives, as operators would have to largely increase their budget in order to switch to fully electric fleets. With respect to fuel prices, a 30% increase prohibits new bus purchases regardless of vehicle type, while changes in diesel price largely affect buy/sell decisions for diesel buses. These observations also imply that operators would financially benefit from switching to other fuels in the long run in response to rising diesel prices.

Moreover, purchase and operating costs affect the age of vehicles in the fleet, which are important for the public image of the operator. In all cases, reduced fuel or vehicle prices for a specific type lead to a larger number of new bus purchases, as buying new vehicles is preferred to incurring high maintenance costs for older vehicles in this case. Naturally, the reduction in purchase prices directly leads to reduced average fleet ages per type, as more new vehicles are incorporated in the fleet. On the contrary, a 30% rise in diesel bus prices leads to a 63% increase in average vehicle age, as few new diesel vehicles are bought and those originally in the fleet are retained for more years.

Lastly, changes in fiscal policy, either internal or external, naturally alter the management plan. For instance, a 60% budget cut would lead to a higher share of diesel vehicles in the fleet, as these constitute the cheapest option in terms of purchase costs. In contrast, an emissions' tax would bring about a drastic reduction in the count of conventional and NG vehicles, as well as in the average fleet age. However, an increase in the total cost is noted in this case, since budget constraints prevent the operation of an exclusively electric fleet of this size, thus other vehicles are taxed. In terms of total management cost, scenarios where the prices of non-diesel vehicles and energy sources are lower produce favorable solutions, which implies that financial incentives/ subsidies for the acquisition and operation of environmentally friendlier vehicles would also benefit the operator in terms of cost in the long term.

Author Contribution Statement

The authors confirm contribution to the paper as follows: study conception and design: Konstantinos Kepaptsoglou Author, George Yannis Author; data collection: Ilias Laios Author; analysis and interpretation of results: Christina Iliopoulou Author, Ilias Laios Author, Konstantinos Kepaptsoglou Author, George Yannis Author; draft manuscript preparation: Christina Iliopoulou Author, Konstantinos Kepaptsoglou Author. All authors reviewed the results and approved the final version of the manuscript.

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