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An implemented Operative-TCO analysis to assess the company cost of hydrogen compared to diesel and CNG-fueled buses

Maxmilian Di Pasquale^a, Lorenzo Mario D'Angelo^b, Gino D'Ovidio^{b*}

^a*TUA SpA – Società Unica Abruzzese di Trasporto – Via San Luigi Orione, 4 – 65128 Pescara, Italy*

^b*University of L'Aquila – CITRAMS – Piazzale E. Pontieri, 1 – 67100 L'Aquila, Italy*

Abstract

In the context of the transport sector's decarbonization efforts, targeting zero direct emissions in urban areas by 2040, Local Public Transport (LPT) companies within the European Union (EU) are mandated with the task of fleet renewal, gradually replacing internal combustion engine (ICE) vehicles with electric vehicles, including those powered by hydrogen fuel cells electric (HFCE). Integrating novel vehicle technologies associated with the utilization of green energy carriers poses an additional challenge for LPT companies concerning the management of service production costs.

For economic evaluation purposes, an effective method relies on Total Cost of Ownership (TCO) analysis, which encompasses both fixed and variable costs associated with vehicles and their corresponding functional systems over their operational lifespan. However, TCO analysis fails to encompass a segment of company costs attributable to operational vehicle performance aspects. This paper proposes and elucidates an implementation of the Operative-TCO (OTCO) methodology, which additionally incorporates costs stemming from vehicle operational constraints, such as mileage range and energy recharging time, as a function of the service requirements along a designated route.

Utilizing data from the monitoring of an Italian LPT corporate fleet as a case study, the TCO and OTCO of green/grey-HFCE vehicles are computed in comparison to diesel and compressed natural gas (CNG) vehicles. The findings are presented and discussed in a comparative framework, inclusive of the assessment of emission-related costs.

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* Corresponding author. Tel.: +39-0862-434106; fax: +39-0862-434143

E-mail address: gino.dovidio@univaq.it

1. Introduction

Global warming represents a significant challenge for our planet, with anthropogenic greenhouse gas (GHG) emissions standing out as one of its primary causes. In response to this pressing issue, the European Union (EU) has enacted a series of initiatives and directives outlined in the Fit for 55 document [1]. These initiatives aim to achieve the following objectives: i) reducing GHG emissions by a minimum of 55% by 2030, relative to 1990 levels, and ii) attaining net zero emissions by 2050.

The transportation sector emerges as a prominent contributor to escalating GHG concentrations in the atmosphere, responsible for approximately one-quarter of total emissions within the EU [2]. Consequently, endeavors aimed at curtailing transportation emissions assume pivotal significance within the framework of decarbonization policies.

Crucial strategies and initiatives targeted at mitigating emissions from the transportation sector encompass [3]:

- a. Implementing actions and measures to bolster, optimize, and promote the utilization of public transportation at the expense of private vehicular transportation
- b. Substituting vehicles equipped with polluting engines with more efficient counterparts boasting near-zero direct emissions
- c. Encouraging widespread production and adoption of energy carriers derived from renewable sources.

In this context, Local Public Transport (LPT) companies play a crucial role, tasked with optimizing transportation services while transitioning to newer, less polluting vehicle alternatives.

However, it is noteworthy that the current engine configuration of LPT companies' fleets predominantly consists of vehicles with internal combustion engines (ICE), as exemplified by the Italian situation. As of 2022, the national bus fleet comprises approximately 41,800 vehicles with 88% diesel-powered, 9% natural gas, and 3% hybrid electric and battery electric (BE) vehicles. The adoption of zero-emission vehicles is steadily increasing, with a 30% rise compared to 2021 data [4].

LPT companies must soon take measures to modernize their fleets by replacing the predominant highly emissive internal combustion vehicles, particularly diesel and compressed natural gas (CNG) models, with direct zero-emission alternatives such as BE and hydrogen fuel cell electric (HFCE) vehicles.

On one hand, the integration of innovative vehicular technologies [5-8], combined with green energy sources, appears to be the most suitable and advantageous solution in the LPT sector [9]. On the other hand, this transition must also be carefully balanced from an economic standpoint, considering the increased expenses associated with technological and energy transitions. Nevertheless, it remains essential for LPT companies to address and analyze the economic aspects linked to meeting the requirements of this particular technology-energy transition phase.

When evaluating the economic aspect, a common practice involves conducting a Total Cost of Ownership (TCO) analysis. This method encompasses the expenses accrued by the LPT company throughout the vehicle's entire life cycle and functionally associated facilities. These costs can be divided into the following macro-categories:

1. Fixed costs (Fix) as they remain independent of the amount of transport service (km/y) produced
2. Variable costs (Var) as they vary in proportion to the amount of transport service (km/y) produced
3. External costs related to environmental impact are influenced by mileage and the type of vehicular technology employed.

The literature extensively discusses TCO analysis within the context of the LPT sector. This analysis enables the calculation of vehicle management costs over its operational lifespan, considering the performance characteristics of motorization options and corresponding energy carriers.

Several authors [10-12] have conducted comparative TCO analyses, primarily focusing on diesel and BE technologies. Findings indicate that currently, the TCO of BE buses exceeds that of diesel buses. However, projections suggest that over a lifecycle, the TCO of BE buses is expected to become lower than that of diesel buses by 2030, indicating potential economic advantages for BE buses in the future.

Despite their recent introduction, some authors have extended TCO analysis to include hydrogen-powered vehicles. Kim et al. estimated that currently, the TCO of hydrogen fuel cell electric (HFCE) buses surpasses that of diesel buses due to high purchase and hydrogen energy carrier costs. This differential is anticipated to persist until 2030 if the cost of green hydrogen remains unchanged [13].

While other authors [14-16] largely confirm these forecasted trends, they employ several methodological approaches. However, these analyses typically overlook LPT company costs related to vehicle performance limitations, such as mileage range and energy charging times, which influence vehicle operating costs by constraining commercial use.

To address this gap, we have proposed, in preliminary form, the Operative-TCO (OTCO) methodology, which

considers the vehicle mileage range [17].

This paper aims to advance this approach by incorporating vehicle energy recharging times as an operative factor. A case study applying the proposed OTCO analysis to diesel, CNG, and HFCE buses from a medium-sized Italian LPT company is presented.

The paper is structured as follows: Section 2 outlines the proposed OTCO analysis, Section 3 presents the case study analysis and results. Section 4 offers concluding remarks.

2. Methodology

For a specific vehicle fitted with the i -th motorization option, operating on the k -th public transport route of length L_k (km) and commercial speed S_k (km/h), the proposed analytical methodology relies on the computation of the $OTCO_i$, is detailed in equation (1):

$$OTCO_i = (1 + F_{o_i}) \cdot \sum_{c=1}^n Fix_i(I_{c_i}) + \sum_{o=1}^s Var_i(I_{o_i}) + \sum_{e=1}^u C_{e_i} \tag{1}$$

where:

- I_{c_i} and I_{o_i} denote the TCO_i Fix_i and Var_i cost items, respectively, associated with the i -th vehicular motorization option ($i=1 \dots n$, $c=1 \dots m$ and $o=1 \dots s$), as outlined in Tab. 1;
- C_{e_i} represents the TCO_i e -th type of environmental emission cost for the i -th vehicular motorization option ($e=1 \dots u$);
- F_{o_i} is the dimensionless operational factor for the i -th vehicular motorization option derived by relation (2):

$$F_{o_i} = F_{o_{1i}} + F_{o_{2i}} \tag{2}$$

In greater detail, the first factor $F_{o_{1i}}$ considers the P_{a_i} vehicular mileage range (km) per single energy charging operation for the i -th motorization, compared to its P_k daily operating mileage (km) on the k -th route, imposed by the public transport operation constraints, as follows (3):

$$F_{o_{1i}} = \frac{P_k - P_{a_i}}{P_k} \quad \text{with } 0 \leq F_{o_{1i}} \leq 1 \tag{3}$$

The term $(P_k - P_{a_i})$ in equation (3) takes on values as indicated in relation (4):

$$P_k - P_{a_i} = \begin{cases} 0 & \text{if } P_{a_i} \geq P_k \\ P_k - P_{a_i} & \text{if } P_{a_i} < P_k \end{cases} \tag{4}$$

The second factor $F_{o_{2i}}$ is defined by the relation (5). It takes into account the T_{r_i} energy recharging time (h) required for the vehicle equipped with the i -th motorization option, in comparison to the T_{e_k} daily duration time of providing public transport service on the k -th route.

$$F_{o_{2i}} = \frac{T_{r_i}}{T_{e_k}} = \frac{T_{r_i}}{\frac{P_k}{S_k}} \quad \text{with } 0 \leq F_{o_{2i}} \leq 1 \tag{5}$$

Table 1. TCO macro-categories of the i -th vehicular motorization

Macro-category	System component	Cost item	Symbol
Fixed costs	Bus	Depreciation	I_c
		Ordinary maintenance	
		Powertrain replacement cost	
		Property tax	
		Overhaul	
		Insurance	
TCO	Energy recharging facilities	Depreciation	
		Maintenance	
Variable costs	Bus	Extraordinary maintenance	I_o
		Energy consumption for traction	
		Lubricants	
		Tyres	
WTW emissions costs	Bus	CO ₂ equivalent (CO _{2e})	C_e

3. Case study

This section exemplifies the application of the OTCO methodology within a practical urban public transport context, utilizing empirical data from the year 2023 provided by Società Unica Abruzzese di Trasporto (TUA company), an Italian LPT middle-sized company.

Presently, the Company operates LPT services with a fleet of 820 buses, with nearly all (98%) powered by ICE, while the remaining (2%) are hybrid or BE-powered. Similar to many other national LPT operators, the company is committed to decarbonizing its service through the gradual replacement of polluting ICE vehicles with direct zero-emission vehicles (BE and HFCE) with short-medium-term objectives. The challenges encountered in this transition phase primarily revolve around economic sustainability rather than technological aspects.

To apply OTCO analysis to the company's operating context, the following main data are assumed:

- A city bus (12 m in length) with three different motorizations (Diesel, CNG, and high-efficiency HFCE). In addition, the following two types of fuels were considered for the HFCE vehicle, with the powertrain consisting of an electric motor powered by fuel cells (70 kW of power) and electrochemical batteries (45 kWh of capacity):
 - a. grey hydrogen (grey-H) generated from natural gas, or methane, using steam methane reforming with CO₂ released to the atmosphere. It accounts for 95% of world hydrogen production [18].
 - b. green hydrogen (green-H) produced by the electrolysis of water, using renewable electricity [19].
- An average annual bus mileage of 50,000 km.
- A depreciation time of 10 years for both the vehicle and energy charging facilities. Regarding residual economic values at the end of life, it is assumed zero value for buses and a value proportional to their use during their useful life for the replacement of components of the vehicle powertrain.
- A reference public transport route with 20 km/h of commercial speed (S_k), and 250 km of daily operating mileage (P_k) corresponding to 12.5 hours of daily operating time (T_{ek}).

Table 2 contains the main data used as a reference for the calculation.

It is important to acknowledge that the values assigned to the maintenance and replacement costs of the HFCE powertrain vehicle are indicative and lack empirical support. The same holds for the maintenance costs of the hydrogen charging facility. Additionally, the high costs associated with these aspects stem from the current stage of market introduction and testing of new technologies that have not yet reached mass industrial production. Therefore, these cost estimates must be interpreted cautiously, recognizing the uncertainties inherent in the current transition phase and the possibility of cost reductions as technology advances and economies of scale are realized.

However, it is expected in the medium term to drastically reduce the costs of both the purchase of the buses (and the facilities functional to them) and the production of green hydrogen [20, 21].

Figure 1 illustrates the price equilibrium thresholds for green hydrogen, set at €9.70/kg and €6.65/kg, respectively, corresponding to equivalent traction energy costs of HFCE buses compared to diesel and CNG ones.

Table 2. Main assumption data

System component	Item	Symbol	Motorization				Unit	Reference
			Diesel	CNG	Grey-HFCE	Green-HFCE		
Bus	Purchase cost	-	220	270	650		k€	
	Mileage range	P_{a_i}	450	380	420		km	
	Energy recharging time	T_{r_i}	0.08	0.2	0.2		h	
	Maintenance cost (ordinary + extraordinary)	-	20.1	25.7	15		k€/y	
	Powertrain replacement cost	-	3.1	3.4	2.2		k€/y	[22]
	Property tax	-	0.7	0.5	-		k€/y	
	Overhaul cost	-	0.14	0.14	0.14		k€/y	
	Insurance cost	-	2	2	3		k€/y	
	Energy consumption	-	0.41	0.38	0.06		l/km kg/km kg/km	
	Energy cost	-	1.4	1.04	2.03	13.7	€/l; €/kg; €/kg; €/kg	[22, 23, 24]
	Lubricants cost	-	1.125	1.125	0.563		k€/y	
	Tyres cost	-	1.35	1.35	1.35		k€/y	
Energy recharging facilities	Purchase cost	-	0.15	1.5	4		k€/bus	[22]
	Maintenance cost	-	0.2	0.3	4		k€/y	
Emissions	Well to wheel	WTW	1.363	1.185	0.99	-	kg CO ₂ e/km	[25,26]
	CO ₂ e cost	-			0.1		€/kg CO ₂ e	[27]

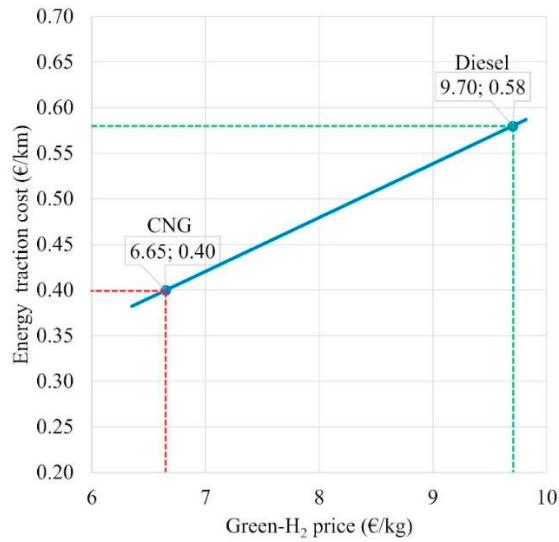


Fig. 1. Price equilibrium thresholds for green hydrogen at equivalent traction energy costs of HFCE buses compared to diesel and CNG ones

3.1 Results

Based on the assumptions outlined in Section 3 and considering an annual mileage of 50,000 km for the bus, Table 3 presents the TCO macro-cost categories and related cost items (€/km) for the Diesel, CNG, and HFCE vehicular motorizations.

Table 3. TCO macro-categories and cost items comparison for Diesel, CNG, and HFCE motorizations at 50,000 km yearly mileage per bus

Macro-category	System component	Cost item (€/km)	Diesel	CNG	Grey-HFCE	Green-HFCE	
TCO	Fixed costs	Bus	Depreciation	0.44	0.54	1.3	1.3
			Maintenance (ordinary)	0.08	0.13	0.12	0.12
			Powertrain replacement cost	0.06	0.07	0.04	0.04
			Property tax	0.014	0.010	-	-
			Overhaul	0.003	0.003	0.003	0.003
			Insurance	0.04	0.04	0.06	0.06
	Energy recharging facilities	Bus	Depreciation	0.003	0.03	0.08	0.08
			Maintenance	0.004	0.006	0.08	0.08
	Variable costs	Bus	Maintenance (extraordinary)	0.33	0.38	0.18	0.18
			Traction energy	0.58	0.40	0.12	0.82
			Lubricants	0.023	0.023	0.011	0.011
			Tyres	0.027	0.027	0.027	0.027
WTW emissions costs	Bus	CO ₂ e	0.14	0.12	0.07	-	

Table 4 lists the Operative factors, TCO and OTCO values for selected motorizations; results show that:

1. The selected vehicular motorizations exhibit similar operating coefficient values, suggesting that the HFCE vehicle, despite its innovative and non-polluting nature, possesses a comparable operational efficiency to current ICE vehicles.
2. OTCO value of green-HFCE is 37%, 35%, and 23% higher than those of diesel, CNG, and grey-HFCE, respectively.
3. For all vehicular motorizations selected, the OTCO values are slightly higher than TCO values with a range of 0.58% to 1.29%.

Table 4. Operative factors, Fixed and Variable costs, TCO and OTCO for the selected motorizations

Vehicular motorization	Operative factors				Fix	Var	TCO	OTCO	$(OTCO - TCO)$
	F_{o_1}	F_{o_2}	F_o	$(1 + F_o)$					
Diesel	0	0.007	0.007	1.007	0.64	0.96	1.73	1.74	0.58
CNG	0	0.016	0.016	1.016	0.83	0.83	1.78	1.79	0.75
Grey-HFCE	0	0.016	0.016	1.016	1.69	0.34	2.09	2.12	1.29
Green-HFCE	0	0.016	0.016	1.016	1.69	1.04	2.73	2.75	0.99

Figure 2a depicts, for the different vehicular motorizations examined, the values of the OTCO macro-categories at a bus yearly mileage of 50,000 km. Figure 2b shows, for the different vehicular engines considered, the values of OTCO as the annual bus mileage varies.

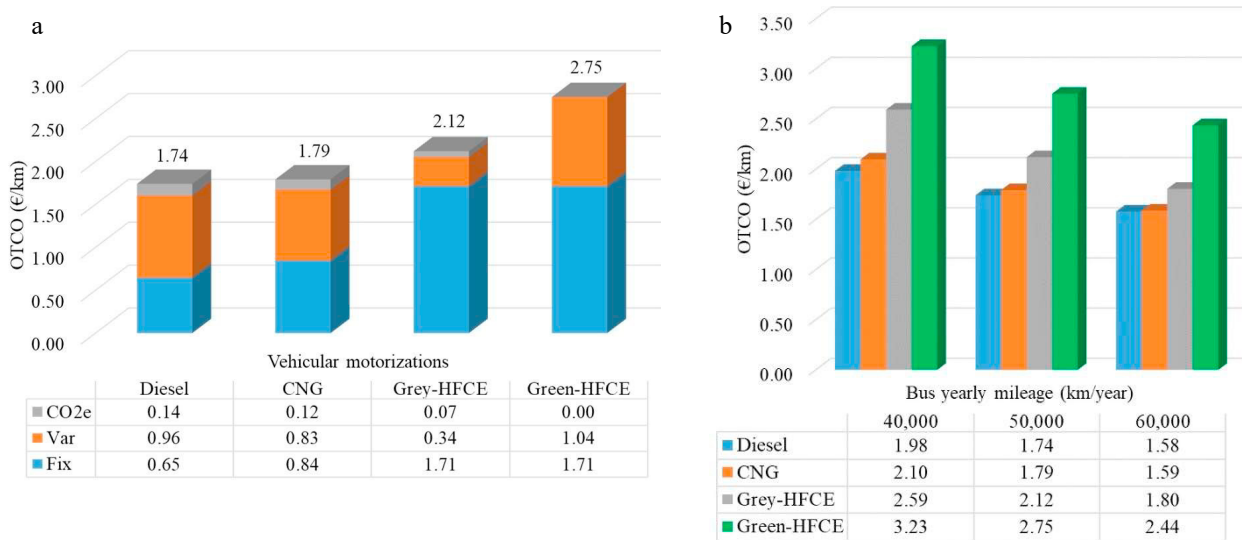


Fig. 2. (a) OTCO macro-categories for hydrogen, diesel and CNG fueled buses (bus yearly mileage of 50,000 km); (b) OTCO values for hydrogen, diesel and CNG fueled buses by varying bus yearly mileage.

4. Conclusion

This paper introduced and applied an Operative-Total Cost of Ownership (OTCO) analysis, which, in contrast to the standard Total Cost of Ownership (TCO), incorporates company costs arising from vehicle performance limitations related to both mileage range and energy recharging time, about the requirements of public transportation service operations.

Using data collected from monitoring an Italian Local Public Transport corporate fleet as a case study, the TCO and OTCO analyses were conducted within the company's operational context. This involved considering a city bus (1 m in length), three different powertrains (Diesel, CNG, and HFCE), and an average annual bus mileage of 50,000 km. Grey and green hydrogen types were also considered for fuelling HFCE vehicles.

The results indicate that presently:

- The selected vehicular motorizations exhibit similar operating coefficient values, suggesting that the HFCE powertrain, despite its innovative and non-polluting nature, possesses comparable operational efficiency to current Internal Combustion Engine (ICE) vehicles.
- The OTCO value of green-HFCE is 37%, 35%, and 23% higher than those of diesel, CNG, and grey-HFCE respectively.
- For all vehicular motorizations selected, the OTCO values are slightly higher than TCO values, ranging from 0.58% to 1.29%.

The disparities in OTCO values between HFCE and ICE motorizations are attributed to the additional costs of new vehicle configurations associated with the current phase of experimentation and technology-energy transition.

Therefore, these cost estimates must be interpreted with caution, recognizing the uncertainties inherent in the current transition phase and the possibility of cost reductions as technology advances and economies of scale are realized.

Looking toward the near future, it is expected that the purchase cost of both HFCE vehicles and green hydrogen will be drastically reduced, leading to corresponding decreases in fixed and variable costs.

Future applications of OTCO analysis will extend to the comparative evaluation of battery-electric vehicles.

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