Assessment of energy reduction potential of eco-driving and vehicle allocation measures in heavy-duty vehicle fleet

Rafael Franco Guerra Reis*
*Department of Mechanical Engineering, Instituto Superior Técnico,
University of Lisbon, Av. Rovisco Pais 1,
1049-001 Lisboa, Portugal; e-mail: rafaelfgreis@tecnico.ulisboa.pt

Abstract: In a context of increasing impacts related to freight transport, this work estimates the energy and environmental impacts of eco-driving, fleet management and alternative vehicle technologies. An experimental procedure and data processing method were implemented, to characterize the fuel consumption profiles of heavy-duty vehicles, based on real-world driving conditions. This resulted in the development of a tool to simulate the effect of eco-driving and vehicle allocation, evaluating the individual and combined impacts of those measures. This method was calibrated and validated by comparing estimates with real measurements, resulting in an error of 4,9% for the 19 trips measured with conventional Diesel vehicles. Eco-driving has a potential to reduce fuel consumption by 3.1%, with a trip duration increase of 0.3%. Vehicle allocation can reduce fuel consumption by 2.3% with an increase of 0.1% in trip duration. When combined, these measures provide a reduction of 5.6% in fuel consumption. The use of liquefied natural gas vehicles proved to be a viable option, emitting less CO_2 (-10.4%), CO (-21.8%), NO_x (-59.5%) and PM (-97.8%) than a diesel vehicle, with HC emissions increasing by 75.0%. As a result, the adoption of the presented solutions has great potential to increase fleet fuel efficiency, with the tools developed in this work providing important guidance towards a more rational fleet management.

Keywords: heavy-duty vehicles, diesel, natural gas, eco-driving, vehicle allocation, vehicle characterization, real-world driving conditions.

1. Introduction

It is a well-known fact that human activities, in particular those that involve fossil fuel combustion, are associated with the emission of pollutants. Some of these pollutants have local effects, decreasing the air quality, while some have global effects, called greenhouse gases (GHG), which cause global warming and climate change [1]. The transportation sector is one of the major contributors, being responsible for 19.6% of the GHG emissions in the EU in the year of 2012 [2]. Road transport has also an important role, being responsible for 74.9% of all goods delivered across the EU [3]. By being such an indispensable part of the economy, awareness on the energy and environmental impacts of this sector has increased, thus yielding a plethora of different measures attempting to reduce these impacts.

The benefits of decreasing fuel consumption go beyond the energy and environmental impacts, including financial benefits as well, since the amount of money spent on fuel decreases. While a better use of the current vehicles can improve fuel economy, progress in vehicle design is also important, with manufacturers providing vehicles that are more efficient and compliant with current EURO emission standards, that keep getting stricter with every iteration [4].

Besides technological improvements, some companies provide eco-driving training to their drivers in order to obtain fuel consumption reductions, which were found to be between 2,6% [5] to 20% [6], under real world driving conditions. Vehicle allocation and redistribution of the fleet can also contribute to decrease fuel consumption [7], though there’s a lack of studies surrounding this matter. Diesel vehicles, commonly used in freight transport, have been the only available option, but in recent years, natural gas powered alternatives have been developed, using liquefied natural gas (LNG) instead of diesel. These vehicles have lower GHG emissions, with studies claiming up to 20% reduction of tailpipe emissions [8].

In this context, this work aims at evaluating the energy and environmental impacts of the introduction of eco-driving behavior and vehicle allocation across the fleet, as well as the impacts of the use of LNG powered vehicles, under operational context. This work was performed as part of an internship at Transportes Paulo Duarte, which was done in the summer of 2015 under the project Galp202020, which is a result of the partnership between GALP ENERGIA and Instituto Superior Técnico.

2. Methodology

2.1 – Case Study

This work was performed during an internship during the summer of 2015 in the Portuguese company Transportes Paulo Duarte. This company has about 550 different vehicles covering about 65 million kilometers per year. Transportes Paulo Duarte is very active in the promotion of energy efficiency measures such as those studied in this paper, having acquired a LNG powered vehicle to test its potential and giving eco-driving lessons to its drivers, both through group lessons and in-vehicle individualized coaching with an instructor. The first step towards completing the proposed objectives was to choose which vehicles to study. Since it is not possible to analyze every vehicle the company owns, it was necessary to select vehicles that are both representative of the company's fleet and capable of covering different driving power outputs and fuel used. The vehicles studied in this work are presented in Table 1.

Table 1 - Vehicles studied

Vehicle	Manufacturer	Power output (hp)	Engine displacement (liters)	Age	Mileage (km)	Fuel	% fleet
1	Mercedes	440	12	5 years	850 000	Diesel	30
2					720 000		
3					650 000		
4		420		6 months	70 000		10
5	MAN	440			80 000		5
6	Volvo	400		5 years	800 000		15
7				7 years	1 000 000		
8	IVECO	330	7.8	1 year	150 000	LNG	~0

2.2 – STP Methodology

The experimental method used was defined following the operational restrictions in the field (such as unfeasibility of vehicle data collection through On-Board Diagnostic port or the installation of a fuel flow meter, due to confliction with manufacturer warranties). As a result, it was clear that the methodology to be designed could only use data collected through a non-invasive way, such as a portable laboratory (GPS device) and the fuel measurements provided by the fueling pump, during the refills.

Given the existing restrictions, the *Scaled Tractive Power* (STP) methodology [9] was used. This methodology was developed by the EPA [10] to estimate pollutant emissions rates for heavy-duty vehicles, but in this paper it is used in a slightly different way. STP was used to calculate the fuel consumption profile of heavy-duty vehicles, in a similar way as *Vehicle Specific Power* (VSP) has been used to estimate the fuel consumption profiles of passenger vehicles [11]. To use this methodology, it was crucial to collect and estimate the data presented in Table 2.

Table 2 - Data used in the vehicle characterization process

Variable	Measurement method	Calculation method	Measurement frequency
Speed	GPS with built-in barometric altimeter (GPSMap 76CSx from Garmin) that gathers vehicle location and elevation	Position variation every second	1 Hz
Acceleration		Speed variation every second	1 Hz
Slope		Ratio between elevation change and covered horizontal distance every second	1 Hz
Weight	Heavy-duty scale (manufacturer: Cachapuz; accuracy: 10 kg)	Value provided by the scale	Start and end of the trip
Trip fuel consumption	Vehicle refill	Value read at the fuel pump	End of the trip

An experimental procedure that fulfilled the requirements of the methodology adopted was developed and was strictly followed in every trip:

1- The vehicle was weighted after being loaded and fueled to the very top of the tank (not when the fuel pump stops) in order to have a reference point;
2- The GPS was turned on and given some time to establish a proper connection;
3- When the driver started the engine, the GPS was set to record data (position and altitude) and was kept turned on while the engine was on; and
4- At the end of the trip, the vehicle was weighted again (to know the weight after delivering the cargo) and it was refueled in the same pump up until the same level as before, while the value provided by the pump was recorded.

Table 3 presents information regarding trips and drivers studied for each vehicle.

Table 3 - Trips, vehicles and drivers

Vehicle	Trips	Service	Duration	Average speed (km/h)	% highway	% urban	% extra-urban	% ($\lvert slope \rvert > 4\%$)	Driver experience
1	1	**A**	4h06min	68.0	0	10	90	41.9	Trained / average experience
	2		3h59min	69.8	0	15	85	49.7	
	3		7h39min	72.7	0	5	95	19.2	
2	1	**B**	4h12min	71.3	0	5	95	45.2	Trained / average experience
	2		4h01min	74.2	10	5	85	52.9	
	3		8h04min	68.9	5	5	90	45.7	
3	1	**C**	4h13min	66.4	0	15	85	40.1	Trained / average experience
	2		4h09min	71.7	10	10	80	44.9	
	3		4h04min	74.2	10	10	80	52.8	
4	1	**D**	5h06min	68.0	0	10	90	38.7	Trained / Expert
	2		4h21min	78.0	0	5	95	22.2	
5	1	**E**	4h02min	69.7	5	5	90	21.9	No training / Rookie
	2		3h49min	72.9	5	5	90	18.7	
	3		4h11min	71.4	5	5	90	45.0	
6	1	**F**	1h54min	51.6	5	35	60	44.7	Trained / average experience
	2		3h49min	68.6	5	25	70	22.3	
7	1	**G**	3h04min	47.2	0	40	60	43.1	Trained / Expert
	2		3h49min	53.0	0	35	65	34.4	
	3		2h15min	60.7	5	35	60	52.6	
8	1	**H**	4h30min	58.0	10	10	80	43.1	Trained / average experience
	2		1h54min	51.6	10	5	85	34.4	
	3		1h31min	68.4	25	15	60	52.6	
	4		4h20min	49.7	20	10	70	43.1	

2.3 – Data processing

As previously mentioned STP was used as a measurement of the power being used by the vehicle. STP is given by equation 1 [9]:

$$STP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t(a_t + gsin\theta)}{f_{scale}} \qquad \text{(Eq. 1)}$$

Where:

STP_t = *scaled tractive power* at instant t in kW (scaled)
v_t = speed at instant t (m/s)

a_t = acceleration at instant t (m/s^2)
A = rolling resistance factor (kW.s/m)
B = rotating resistance factor (kW.s^2/m^2)
C = aerodynamic resistance factor (kW.s^3/m^3)
m = overall mass (metric tons)
f_{scale} = scale factor, a constant value of 17.1
g = gravitational acceleration (9.81 m/s^2)
$\sin\theta$ = slope (as a fraction)

The factors A, B and C used in this methodology are based on the work done by V.A. Petrushov and are presented in Table 4 [10].

Table 4 - factors A, B and C required to calculate STP

Factor (per metric ton)	**Heavy-duty vehicles (from 3.855 to 6.350 metric tons)**	**Heavy-duty vehicles (from 6.350 to 14.968 metric tons)**	**Heavy-duty Vehicles (above 14.968 metric tons)**	**Buses**
$\frac{A}{M}\left(\frac{kW.s/m}{1000\ kg}\right)$	0.0996	0.0875	0.0661	0.0643
$\frac{B}{M}\left(\frac{kW.s^2/m^2}{1000\ kg}\right)$	0	0	0	0
$\frac{C}{M}\left(\frac{kW.s^3/m^3}{1000\ kg}\right)$	$\frac{1.47}{mass(kg)} + 5.22\times10^{-5}$	$\frac{1.93}{mass(kg)} + 5.90\times10^{-5}$	$\frac{2.89}{mass(kg)} + 4.21\times10^{-5}$	$\frac{3.22}{mass(kg)} + 5.06\times10^{-5}$

For every trip, STP was calculated for every second and organized according to the modal distribution presented in Table 5:

Table 5 - Modal STP distribution

STP	**]- ∞,-59]**	**]-59,-58]**	**…**	**]-1,0[**	**0**	**]0,1[**	**…**	**[58,59[**	**[59, ∞[**
STP Class	-60	-59	…	-1	0	1	…	59	60

2.4 – Methodology to estimate fuel consumption profiles

Once every trip was processed and a modal STP distribution was obtained (like the one presented in Figure 1), it was possible to estimate fuel consumption profiles.

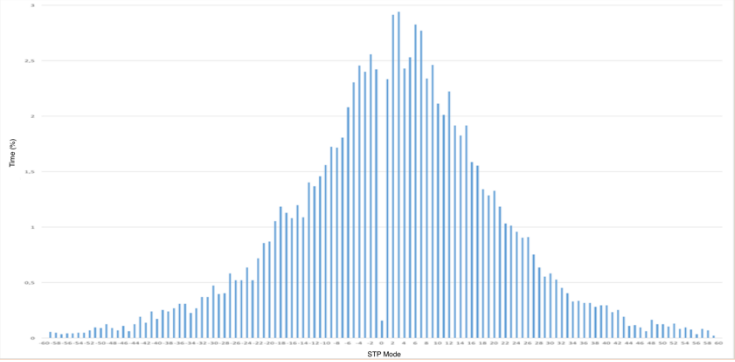

Figure 1 - Modal STP distribution for an example trip

It was assumed that the fuel consumption profile for this kind of vehicles is similar to those of passenger vehicles [11] and buses [12], presenting a similar trend to the one presented in Figure 2:

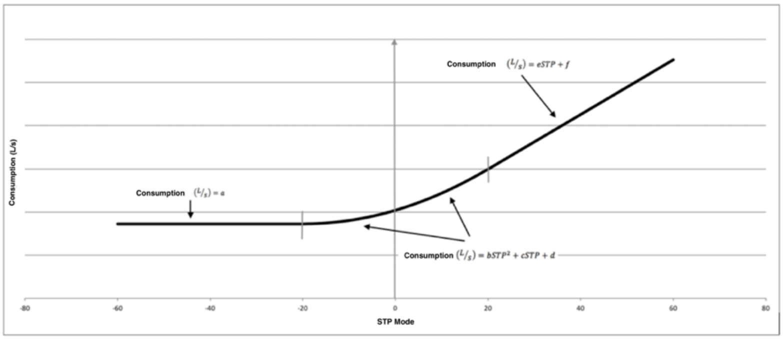

Figure 2 - Example of a typical fuel consumption profile (Adapted: Duarte, G [11])

For this particular case, given the lack of studies relating instant fuel consumption and modal STP distributions, it was necessary to use a trial and error process to find the continuity points between the 3 different equations required to characterize the fuel consumption profile. By varying those two points and using the resulting equation to estimate fuel consumption in validation trips it was concluded that the pair (-20,20) (skW) was the one providing better and more consistent estimates. To calculate the 6 variables, it was necessary to solve the 6 equation system presented in equation 2. From the continuity of the curve and the continuity of its derivative at STP = -20 and STP = 20, four equations were obtained (equations iii, iv, v and vi, respectively). The remaining two conditions are related the power distribution for two distinct driving cycles and to the total fuel consumption for each trip (equations i and ii).

$$\begin{cases} i)\ Fuel_{trip\ 1} = \sum_{-60}^{-21} a \times t_{STP} + \sum_{-20}^{-1} (bSTP^2 + cSTP + d) \times t_{STP} + \delta (bSTP^2 + cSTP + d) \times t_{STP=0} + \sum_{1}^{20} (bSTP^2 + cSTP + d) \times t_{STP} + \sum_{21}^{60} (eSTP + f) \times t_{STP} \\ ii)\ Fuel_{trip\ 2} = \sum_{-60}^{-21} a \times t_{STP} + \sum_{-20}^{-1} (bSTP^2 + cSTP + d) \times t_{STP} + \delta (bSTP^2 + cSTP + d) \times t_{STP=0} + \sum_{1}^{20} (bSTP^2 + cSTP + d) \times t_{STP} + \sum_{21}^{60} (eSTP + f) \times t_{STP} \\ iii)\ b \times (-20)^2 + c \times (-20) + d = a \\ iv)\ 2b \times (-20) + c = 0 \\ v)\ b \times 20^2 + c \times 20 + d = e \times 20 + f \\ vi)\ 2b \times 20 + c = e \end{cases}$$

(Eq. 2)

The value of δ, relative to the idle fuel consumption at STP=0, is calculated through an iterative process, starting with $\delta = 1$. For STP=0, fuel consumption is $\delta \times d = "fuel\ consumption\ at\ idle"$. The value of δ is calculated iteratively, by using typical idling fuel consumption value, which for this application was concluded to be $\delta = 0{,}22$.

2.5 – Numerical tool for eco-driving

The data used to characterize the different vehicles can also be used to quantify the impacts of energy efficiency measures. By developing a numeric tool in Matlab (R2014b) it was possible to adjust real world driving cycles, simulating the impact of eco-driving measures. First, the data collected from the trips with the company's best driver was studied, and the top speed and maximum instant acceleration limits were established, according with Table 6.

Table 6 - Maximum limits for speed and acceleration

	Downhill (slope < -4%)	Flat terrain (-4%< slope < 4%)	Uphill (slope > 4%)
Maximum velocity (km/h)	90	85	75
Maximum instant acceleration (m/s^2)	0.5	0.4	0.3

The numerical code developed reads the original data, compares the speed and acceleration (which are read from the original data on a distance basis instead of a time basis, due to the correcting of vehicle speed) with the limits presented before and, if the values go beyond these limits, the code corrects the original trip making sure the limits are not exceeded. This originates a new driving cycle that simulates the effect of a highly trained driver, which allows estimating a new fuel consumption for that trip.

Figure 3 presents a comparison between the modal STP distribution for the same trip, with the blue bars representing the original trip and the red bars representing the adjusted driving cycle, which takes into account the simulated effect of eco-driving. The distribution regarding the corrected trip (red) has a significantly smaller presence in the higher values of STP, where fuel consumption is higher, and is more concentrated in the lower values of STP, where fuel consumption is lower.

Using the fuel consumption profile (as presented on Section 2.4) of the vehicle used in that trip, combined with the modal STP distribution of the new adjusted driving cycle (that includes eco-driving), it is possible to estimate the energy impacts resulting from the introduction of eco-driving by comparing the fuel consumption with the original data.

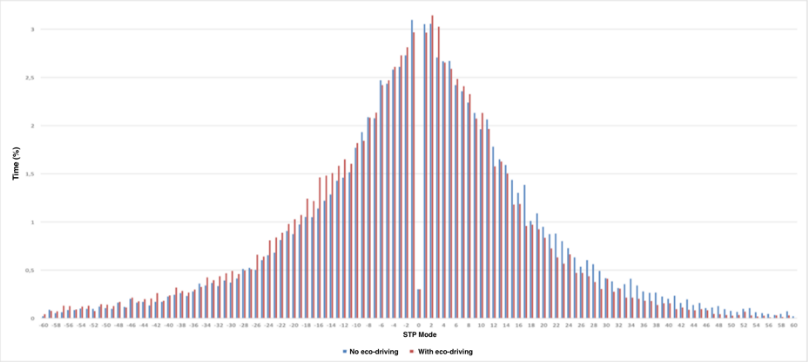

Figure 3 - Comparison between the original and adjusted STP distributions for the same trip

2.6 – Numerical tool for vehicle allocation

Since different vehicles have different fuel consumption profiles, it is possible that overall fuel consumption can be reduced by rearranging vehicle allocation through the operational requests. Using the STP distribution of every trip and the fuel consumption profile of every vehicle studied, it was possible to estimate the fuel consumption for each vehicle in each service. However, due to differences in vehicles' maximum power, it was necessary to correct the driving cycles according to that characteristic and use the proper STP distribution to estimate the correspondent fuel consumption. Consequently, the driving cycles were adjusted for the 4 levels of available power output (330, 400, 420 and 440 hp) available. As a result, a numeric tool was developed to estimate the power used at every second of driving, using equation 3. If the vehicle maximum power output is higher than the power required to keep up with the original cycle, the adjusted cycle remains the same as the original. When the maximum power output of the vehicle is lower than the power required to keep up with the original cycle, the code calculates the maximum acceleration possible, using the vehicle maximum power output as limit and uses that acceleration to adjust the original driving cycle.

$$power = \left(mg\lambda v + C_D \frac{1}{2}\rho v^2 A_f + m(a + g\sin\theta)\right).v \qquad (Eq.3)$$

Where:

$power$= power being used in that instant (W)
m = overall mass (kg)
g = gravity acceleration (9.81 m/s^2)
λ = rol resistance (constant value of 0.01)
v = instant speed (m/s)
C_D = drag coefficient (constant value of 0.6)
ρ = air density (1.25 kg/m^3)
A_f = frontal area (constant value of 10 m^2)
a = instant acceleration (m/s^2)
θ = slope

After adjusting each driving cycle to each vehicle, it was possible to use the new cycles and the fuel consumption profiles of the vehicles to estimate the fuel consumption of every vehicle for every trip. Using this information, it was possible to use Hungarian algorithm [13] to distribute the vehicles across the trips, without vehicle repetition, in order to minimize the overall fuel consumption. This value was compared with the original fuel consumption and its potential improvement was calculated.

2.7 – Numerical tool combining eco-driving and vehicle allocation

By using a code that adjusts the driving cycles, regarding both driver behavior (as shown in 2.5) and required power (as shown in 2.6), it was possible estimate fuel consumption values for every possible trip and vehicle combination, while taking into account the effect of eco-driving. This can then be used to find the best vehicle distribution, as done in 2.6, as well as to estimate possible fuel consumption reductions.

3 – Results

3.1 – Validation and vehicle characterization

Two different trips were needed to estimate the fuel consumption profile of a vehicle, as presented in section 2.4. When data was available from more than 2 trips performed with the same vehicle, more than one fuel consumption profile can be estimated. For every possible combination of 2 trips, the fuel consumption profile could be estimated and used to evaluate the fuel consumption of the remaining trips. Estimated values were compared to the real values and, for every vehicle, the pairs that yielded the lowest errors were selected. Table 7 presents the results of the validation process.

Table 7 - Results of the validation process

Vehicle	Trip	Measured fuel consumption (l)	Estimated fuel consumption (l)	Error (%)
1	2	74.5	78.8	5.8
2	3	158.0	149.9	-5.1
3	1	82.0	80.4	-1.9
5	1	86.0	81.6	-5.1
7	1	39.0	36.4	-6.7
8	2	34.1	24.1	-29.4
8	3	38.3	27.1	-29.2
Average Error				-10.2±12.6
Average of absolute errors				11.9±11.1
Average Error (Excluding vehicle 8)				-2.6±4.5
Average of absolute errors (Excluding vehicle 8)				4.9±1.6

Considering all the validation trips, the average error of -10.2%±12.6% indicates that estimates are not particularly accurate or precise. It was also found that there is a great disparity between errors relating vehicle 8 and the remaining vehicles. Excluding the errors introduced by vehicle 8, this method has proved to be capable of better estimates, as proven by the average error of -2.6%±4.5%% (average absolute error of 4.9%±1.6%) indicating that estimates are both accurate and precise. Errors observed in vehicle 8 (LNG) are much larger than on diesel vehicles because it has a pressurized fuel system which requires that gaseous LNG must be removed before liquid LNG is introduced in the tank during refueling. This gaseous mass of LNG is not consumed by the ICE, but is considered as having being consumed, since that gaseous mass is replaced by liquid LNG and that value is taken in consideration when reading the value presented by the pump after refueling is done. Therefore, real consumption is lower than the measured values (and closer to the estimated provided by this method).

The results of the characterization process are presented in Table 8, while Figure 4 shows the resulting fuel consumption profiles.

Table 8 - Results of the characterization process

			Vehicle							
			1	2	3	4	5	6	7	8
Coeficient	A	$(^{g}/_{s})$	3.12	3.30	3.26	2.95	3.96	2.47	2.49	3.45
	B	$\frac{(^{g}/_{s})}{(sKW)^2}$	2.13E-03	1.96E-03	1.79E-03	2.13E-03	1.53E-03	2.20E-03	2.27E-03	1.60E-03
	C	$\frac{(^{g}/_{s})}{sKW}$	8.47E-02	7.99E-02	7.17E-02	8.67E-02	6.13E-02	8.72E-02	8.95E-02	6.33E-02
	D	$(^{g}/_{s})$	3.97E+00	4.10E+00	3.98E+00	3.81E+00	4.57E+00	3.34	3.39	4.08
	E	$\frac{(^{g}/_{s})}{sKW}$	1.70E-01	1.60E-01	1.43E-01	1.73E-01	1.23E-01	1.74E-01	1.79E-01	1.27E-01
	F	$(^{g}/_{s})$	3.12E+00	3.30E+00	3.26E+00	2.95E+00	3.96E+00	2.47E+00	2.49E+00	3.45E+00

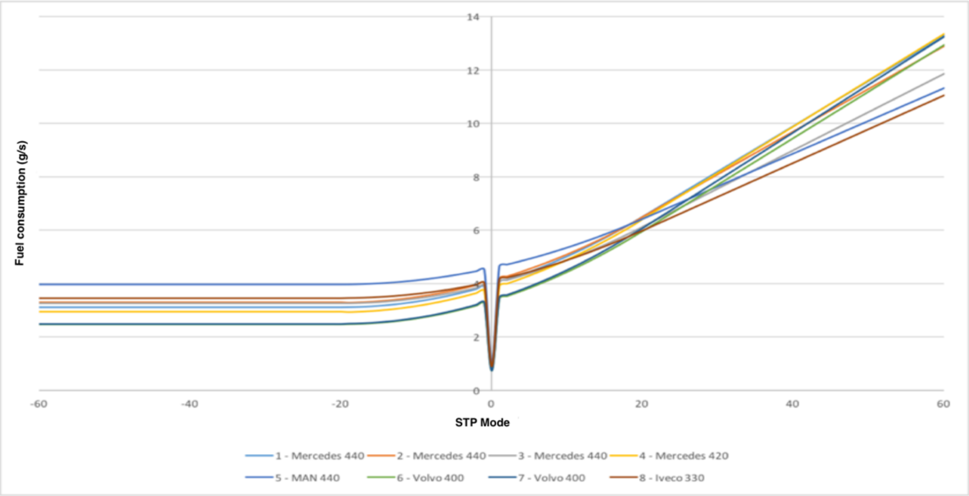

Figure 4 - Fuel consumption profiles

3.2 – Impacts of fuel efficiency measures

By using the methodologies described before, it was possible to estimate the potential benefits from the implementation of eco-driving policies, fleet allocation, eco-driving coupled with fleet allocation and the use of LNG powered vehicles.

Eco-Driving

The estimated benefits from eco-driving for each vehicle studied are presented in Table 9:

Table 9 - Results of the implementation of eco-driving behavior

Vehicle	Driver experience	Original consumption (l/100km)	Eco-driving consumption (l/100km)	Reduction (%)	Time increase (%)
1	Moderate	30.0	29.1	2.9	0.1
2	Moderate	25.4	24.8	2.4	0.1
3	Moderate	25.8	25.0	3.2	0.2
4	Expert	27.0	26.9	0.5	0.0
5	Rookie	28.1	25.5	9.3	1.2
6	Moderate	29.9	28.8	3.9	0.2
7	Expert	25.3	25.1	0.9	0.1
8	Moderate	25.1	24.8	1.6	0.2

The results show a direct relation between driver experience and the potential to reduce fuel consumption, with less experienced drivers showing a greater potential. The rookie driver, that did not have eco-driving lessons, shows a potential fuel consumption reduction of 9.3%, which is coherent with the 9.4% improvement obtained for a study performed with European drivers under real-world driving conditions with the same kind of training provided by Transportes Paulo Duarte [14].

It can also be seen that drivers who have been trained show improvements consistently lower than 4%. Expert drivers with complete training show improvements lower than 1%. It is also important to note that eco-driving has little to no effect on trip duration, with the least experienced driver showing the largest increase of just 1.2%. This can be explained by the fact that the most of the drivers had already been trained, the vehicles are fitted with a speed limiter and by the fact that there are usually very few interruptions (stop and acceleration events) once the trip starts. Overall there is a potential to reduce fleet fuel consumption by an average 3.1% with a trip duration increase of just 0.3%.

Allocation

Using the numeric tool developed to rearrange the way vehicles are currently distributed across services, it was possible to conclude that vehicles are not distributed in an optimal way. The distribution used, A1-B2-C3-D4-E5-F6-G7-H8 (where the numbers represent vehicles and the letters services), should be replaced by the optimal distribution **A7-B6-C3-D2-E8-F5-G1-H4**, which results in a 2.3% reduction in the overall fuel consumption, with a trip duration increase of

0.1%. It should be noted that vehicle 8, whose fuel consumption curve has the lower consumption in the higher STP values, is allocated to service E, with the rookie driver. This indicates that vehicles that have lower fuel consumption under higher power demands, are best suited for less experienced drivers. That way, vehicles that have higher fuel consumption when pushed hard are better suited for more experienced drivers that don't spend too much time under high power demand. This is the case of the resultant ideal allocation, with vehicle 2 being allocated to service D and vehicle 1 being allocated to service G, both vehicles 1 and 2 having high fuel consumption under high power demand being allocated to services with expert drivers.

Combination of eco-driving and vehicle allocation

When eco-driving is taken into consideration, the optimal allocation becomes **A7-B4-C8-D2-E3-F5-G1-H6** and the resulting fuel consumption is 5.6% lower than the case with no eco-driving and no vehicle allocation (0.3% trip duration increase).

LNG

Diesel vehicles have, on average, a fuel consumption of 27.6 l/100km (23.5 kg/100km), while the LNG powered vehicle proved to be capable of doing 24.4 kg/100km. This translates into a consumption of 13,4 MJ/km for the LNG vehicle and 10,6 MJ/km for an average diesel powered vehicle. This is due to the fact that diesel vehicles have a higher efficiency when under partial loads, therefore having a higher fuel efficiency [15]. However, despite the higher energy consumption, the LNG proved to be able to reduce emissions, as presented in the following summary.

Summary of adopted measures

Table 10 presents the average energy and environmental impacts of all the previous measures, calculated based on estimated fuel consumption reduction and emission factors for diesel [16] and natural gas [17]. Environmental benefits from eco-driving, allocation and the combination of both reflect the impact that these measures have on fuel consumption, with emission reduction being proportional (3.1% emission reduction for eco-driving, 2.3% for vehicle allocation and 5.6% for both combined, with mass reduction per 100km being presented in Table 10). LNG presents a different scenario, where some pollutants are reduced by varying amounts (from 10.4% and up to 97.8%) when compared to an average diesel vehicle, with THC emissions being 75.0% greater than those of a typical diesel vehicle.

Table 10 - Environmental impacts of the different measures

	Ecodriving	**Allocation**	**Ecodriving + Allocation**	**LNG powered vehicles**
Fuel (%)	-3.1	-2.3	-5.6	---
CO_2 (kg/100km)	-2.3	-1.7	-4.1	-7.7 (-10.4%)
CO (g/100km)	-5.5	-4.1	-9.9	-38.8 (-21.8%)
NO_x (g/100km)	-24.4	-18.0	-43.7	-465.7 (-59.5%)
THC (g/100km)	-1.4	-1.0	-2.5	+33.8 (+75.0%)
PM (g/100km)	-0.7	-0.5	-1.2	-21.6 (-97.8%)

4 – Conclusions

The energy and environmental impacts of energy efficiency measures were studied in this work, by evaluating the potential savings of eco-driving, fleet allocation and LNG powered vehicles. An experimental evaluation of 8 vehicles was performed during 23 trips and 93h of on-board data was collected under real world operating conditions. A method to simulate the performance of an experienced driver on driving dynamics was developed, allowing estimating the reduction in fuel consumption through an eco-driving program. A method to estimate and compare fuel consumption between different vehicles for the same trips was also created, allowing to redistribute and optimize the way vehicles are allocated in order to reduce overall fleet fuel consumption. Furthermore, the developed methodology allows characterizing energy consumption in heavy-duty vehicles in a non-intrusive way, without the need for expensive or complex equipment. This method, despite its simplicity, proved to be able to provide accurate estimates of fuel consumption (with an average estimation error of 4.9%).

The results indicate that eco-driving and vehicle allocation have the potential to reduce fuel consumption by 3.1% and 2.3%, respectively. When combined, that potential increases to 5.6%. In a fleet like the one studied, with ~200 vehicles covering an average of 150000 km/year each, the introduction of both solutions, could translate into a potential reduction of fuel consumption up to 394000 liters per year, saving the company up to 400000€ per year. The referred measures can also avoid the emission of 1230 metric tons of CO_2, along with 2970 kg of CO, 13110 kg of NO_x, 720 kg of hydrocarbons and 360 kg of particulate matter.

LNG powered vehicles were able to keep up with diesel vehicles, despite the lower power output, while being cheaper to run (0.22 €/km against 0.28€/km for an average diesel vehicle). The LNG vehicle, despite having a worse fuel economy than an average diesel vehicle, also can reduce emissions of every pollutant (CO_2 by 10.4%, CO by 21.8%, NO_x by 59.5% and PM by 97.8%), except for hydrocarbons, whose emissions exceed those of a diesel vehicle by 75.0%, possibly due to the incomplete combustion of methane.

To sum up, it is concluded that vehicle allocation combined with eco-driving programs has a significant potential to reduce fuel consumption and pollutant emissions in heavy-duty vehicle fleets and that the tools developed in this work provide important guidance towards better energy efficiency.

References

[1] T. R. Karl, "Modern global climate change," *Science,* 5 December 2003.

[2] EEA, "Pocketbook 2012," 2013. [Online]. Available: http://ec.europa.eu/transport/facts-fundings/statistics/doc/2012/pocketbook2012.pdf. [Accessed 23 February 2016].

[3] Eurostat, "Freight transport statistics," [Online]. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Freight_transport_statistics_-_modal_split. [Accessed 12 February 2016].

[4] ECOpoint Inc, "dieselnet.com," [Online]. Available: https://www.dieselnet.com/standards/eu/hd.php. [Accessed 12 November 2015].

[5] L. Boodlal and K. Chiang, "Study of the Impact of a Telematics System on Safe and Fuel-Efficient Driving in Trucks," 2014.

[6] H. Chaari and E. Ballot, Fuel consumption assessment in delivery tours to develop eco driving behaviour, 2012.

[7] K. Boriboonsomsin, "Reducing the carbon footprint of freight movement through eco-driving programs for heavy-duty trucks," National Center for Sustainable Transportation, 2015.

[8] J. Rosenfeld and M. D. Jackson, Life-cycle cost model and pollutant emissions estimator: Greenhouse gas and criteria pollutant emissions estimator, Cupertino, CA: TIAX, 2008.

[9] J. Yun, "Study of the driving cycle for heavy duty trucks in hilly terrain and its effects on calculated emissions, and comparison of two mobile emission models," 2012.

[10] EPA, "MOVES2010 Highway Vehicle - Population and Activity Data," 2010.

[11] G. Duarte, "A methodology to estimate vehicle fuel consumption and pollutant emissions in real-world driving based on certification data," 2013.

[12] H. Frey, H. Zhai, N. M. Rouphail, T. L. Farias and G. A. Gonçalves, "Comparing real-world fuel consumption for diesel- and hydrogen-fueled transit buses and implications for emissions," in *Transportation Research Part D*, Elsevier, 2007, pp. 281-291.

[13] H. Kuhn, "The Hungarian Method for the Assignment Problem," *Naval Search Logistics Quarterly 2,* 1955.

[14] B. Beusen and T. Denys, "Report on Monitoring Pilot Acitons," 31 May 2010.

[15] M J Bradley & Associates, "Comparison of Modern CNG, Diesel and Diesel Hybrid-Electric Transit Buses: Efficiency & Environmental Performance," 2013.

[16] L. Ntziachristos and Z. Samaras, "EMEP / EEA emission inventory guidebook 2013 update Sept 2014," 2014.

[17] H. Kristensen, "Energy Demand and Exhaust Gas Emissions of Marine Engines," 2012.