Fuel-efficient driving in the context of urban waste-collection: a Spanish case study

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Abstract

While diesel use represents one of the most important costs of the waste-collection process, the impact of eco-driving practices in this context has been surprisingly little addressed so far. Here, we present the results obtained by implementing eco-driving through the installation of in-board driving-assistance devices in a Spanish waste-collection fleet. Driving parameters and diesel use were monitored for over a year on 67 vehicles. An average fuel consumption decrease of 7.45 % was observed, ranging from 1.86 % to 11.50 % according to the type of vehicle and to its waste-collection mechanism. Waste-transfer trucks that were not performing stop-and-go cycles displayed the highest values of fuel savings. In addition, eco-driving benefits obtained through real-time feedback did not tend to get lost over time, as fuel consumption remained remarkably steady. An average difference of only -0.45 % between the first and the last month of monitoring was observed. After 14 months, an economic and environmental assessment of eco-driving implementation in the fleet was carried out. Nearly 120,000 liters of diesel were economized, leading to substantial financial savings and to a significant exhaust emission decrease that was theoretically quantified in terms of CO_2, CO, HC, NOx and PM. Overall, our results tend to show a highly positive environmental and economic impact of fuel-efficient driving in the waste-collection context.

Keywords

Eco-driving; waste-collection; refuse trucks; real-time feedback; fuel savings

1. Introduction

Road traffic is by far one of the largest contributors to the massive daily release of greenhouse gas (GHG) and to overall atmospheric pollution. In particular, heavy-duty vehicles such as trucks, buses or refuse lorries represent only a small fraction of the vehicle population (< 5 % in many countries), but account for a major part of total exhaust emissions (Wagner and Rutherford, 2013). Currently, most of heavy-duty fleets are still equipped with diesel engines due to their high efficiency, durability, reliability and low-operation costs (Reşitoğlu et al, 2014). Diesel emissions are therefore considered as one of the main actors responsible of atmospheric pollution and global carbon dioxide emissions. Moreover, they are a source of major health concerns due to their adverse effects on the human body. The main pollutants arising from diesel engine exhaust gas are carbon dioxide (CO_2), carbon monoxide (CO), fine particulate matter (PM), nitrogen oxides (NOx) and hydrocarbons (HC), originating either from incomplete fuel oxidation or from oxidation of non-combustible species (Khair and Majewski, 2006).

In this context, ecological considerations and rising fuel prices have led to worldwide initiatives to decrease fuel consumption. One of the main initiatives that have emerged so far is the concept of “eco-driving”, also called “fuel-efficient driving”. It relates to the adoption of driving habits that are environment-friendly due to their lower energy consumption. Sivak and Schoettle (2012) have classified eco-driving decisions in three categories: strategic (choice and maintenance of the vehicle), tactical (efficient loading and routing) and operational (on-road driving habits that influence consumption). Since the driving behavior has a significant impact on global consumption, one of the main goals of eco-driving research is to identify the habits that lead to greater fuel inefficiencies. Typically, events such as idling, harsh-braking, late change of gears, unnecessary acceleration or speeding will be representative of non-efficient driving style, coming along a higher fuel consumption and environmental impact. On the other side, actions such as cruising at low speed, limiting stop-and-go cycles or driving in a non-aggressive fashion can significantly decrease energy use. In general, it is advised to drivers to drive smoothly, to look ahead and anticipate changes in traffic and environment, to optimize the revolution per minute (RPM) range of the engine, and to skip gears as soon as possible (Barkenbus, 2010; Symmons et al., 2009).

Eco-driving is often considered as a low-cost and immediate measure to improve fuel efficiency. It is highly complex to assess the real effects of fuel-efficient practices on the road network global level, in relation to traffic flow and external conditions. However, eco-driving individual benefits on fuel consumption have been extensively studied in previous literature, especially in light-duty vehicles (cars), freight transportation (heavy-duty trucks) and passenger public transportation (buses). Surprisingly, its impact on the sector of waste management, and in particular on the waste-collection process, has been little assessed so far. To fully address the potential benefits of its implementation in this context, published literature about the application and impact of eco-driving is reviewed here briefly. The results of a few studies focusing mainly on the improvement of fuel consumption in different categories of vehicles (light-duty, heavy-duty or buses) are presented in Table 1, providing insights about the range of fuel economy decreases that can be expected from eco-driving implementation. Only research carried out in real-world conditions were considered; simulations and theoretical models were excluded. The type of implementation is specified, along with some indicators about the relevance and the statistical significance (number of vehicles/drivers and time of monitoring). The database used to make table 1 were Science Direct and Scopus. In the search, the main key words used were: fuel savings, eco-driving, diesel emissions, CAN-bus interface, fuel efficient, driver behaviour and on-board eco-driving.

Table 1. Literature review: impact of eco-driving practices on fuel consumption

Authors	Year	Implementation type	Number of vehicles/drivers	Monitoring time	Decrease of fuel consumption (%)
			Cars/Light-Duty Vehicles		
Wang and Boggio-Marzet	2018	Training (T+P)	6 (+ 6 CG)	2 months	6.3
Barla et al.	2017	Training	45 (+ 14 CG)	1 year	2.9 (city) - 4.6 (highway)
Jeffreys et al.	2015	Training (T+P)	853 (+ 203 CG)	> 7 months	4.6
Ho et al.	2015	Training	116	1 day (2 trips)	15.72
Rolim et al.	2014	Training (T)	9 (+ 11 CG)	4-6 months	4.8

Dib et al.	2014	Real-time feedback	not specified	1 day (2 trips)	14.1
Caulfield et al.	2014	Real-time feedback	9	8 months (+ 2 months C)	8.85
Larue et al.	2014	Real-time feedback	1 (13 drivers)	1 day (2 trips)	7
Vagg et al.	2013	Real-time feedback	15	2 weeks (+ 2 weeks C)	7.6
Rutty et al.	2013	Training	14 (64 drivers)	~ 6 months (+ 6 months C)	8
Rionda et al.	2012	Real-time feedback	150	6 weeks	10
Andrieu et al.	2012	Training (or simple advices)	39	1 day (2 trips)	11.3 (training) - 12.5 (advices)
Boriboonsomsin	2010	Real-time feedback	20	2 weeks	6
Beusen et al.	2009	Training (T+P)	10	10 months	5.8
Barth et Boriboonsomsin	2009	Real-time feedback*	not specified	not specified	13
Trucks/Heavy-Duty Vehicles					
Goes et al.	2019	Training	11 (22 drivers)	3 months	0.8 - 7.1
Zavalko	2018	Training	10	3 months	13.6 - 4 (after 3 months)
Ayyildiz et al.	2017	Training	15	2 months (+ 2 months C)	5.94
Díaz-Ramirez et al.	2017	Training	18	2 months (+ 2 months C)	6.8
Schall et al.	2016	Training (only T)	91	6 months	no significant effect
Buses/Passenger Transportation Vehicles					
Huertas et al.	2017	Real-time feedback**	1	1 week	9.6
Sullman et al.	2015	Training	29 (+ 18 CG)	1,5 month (+ 1.5 month C)	11.6
Lai	2015	Reward system	116 (+ 105 CG)	6 months (+ 6 months C)	10.1
Strömberg and Karlsson	2013	Training or Real-time feedback	54	6 weeks	6.8
Zarkadoula et al.	2007	Training	2	2 months	10.2 – 4.35 (after 2 months)
af Wahlberg	2007	Training (+ Real-time feedback)	28	12 months	2 (training) - 4 (feedback)

T = Theoretical; P = Practical; C = Control; CG = Control Group

* feedback combined with newly developed eco-routing software, integrating information from external conditions and from other users on the road

** feedback combined with eco-routing, optimized for a single road only, indicating optimal speed and RPM for each km section

Typically, eco-driving will be implemented either though driver training courses or through the installation of an in-vehicle driving assistance system. Training courses are most of time provided as a combination of theoretical and practical lessons, which are mandatory to lead to tangible results. On the other side, driving-assistance devices monitor engine parameters and integrate data from telemetry equipment to provide real-time feedback to the drivers about their driving behavior. It helps them to become aware of their non-efficient driving habits (such as idling, speeding, unnecessary accelerations or late gear changes). The feedback can take many different forms, such as a GPS tablet, a smartphone application, any kind of visual and/or audio signals, or even a vibrating pedal or steering wheel. Ideally, the device should minimize the distraction of the driver while still providing efficient assistance for greener driving habits (Gonder et al., 2012). Interestingly, Table 1 reveals a high variability of results, since each study displays different types of vehicles (i.e. cars, trucks, buses), of roads (i.e. highway, city, rural), of external conditions (i.e.

density of traffic, weather, temperature) and of implementation strategies. In general, fuel consumption decreases range between 5 and 15 % shortly after implementation, even though higher values have already been reported (reviewed in: Huang et al., 2018; Alam and McNabola, 2014). However, many studies assessing driving improvement fail to consider its impact on the long-term. Many trained drivers have been shown to gradually revert to their old driving styles, and to lose their motivation maintaining efficient habits over time (Degraeuwe and Beusen, 2013). As observed in Table 1, the values of fuel savings tend to be significantly lower when the monitoring time is higher, strengthening the idea that eco-driving might lose efficiency over time. Most of high values of fuel decrease (>10 %) were obtained when the monitoring took place on a single day (Ho et al., 2015; Dib et al., 2014; Andrieu et al., 2012; Barth and Boriboonsomsin, 2009). As the methodology is typically to monitor a vehicle on a specific trip performed twice (once before and once after eco-driving training or feedback device is provided), it is likely that drivers are able to achieve such decreases on a single trip through enhanced awareness, but would not maintain them on the long run. An illustration of this tendency is also provided by Zavalko (2018) and by Zarkadoula et al. (2007), who both monitored high fuel saving values (13.6 % and 10.2 %, respectively) straight after training, but whose values fell down to about 4% only two or three months later. The gradual loss of efficiency could be due to factors such as driver´s fatigue, boredom or lack of maintenance through regular courses. In addition to lower values of fuel economy, eco-driving has been reportedly implicated with several other benefits: financial savings, less pollution, better vehicle maintenance, societal gains related to more relaxed driving, diminution of the number of accidents (Gonder et al., 2012). The substantial fuel saving opportunities have attracted the interest of many road transportation actors. Numerous eco-driving initiatives have been promoted in the last few years, and massive campaigns of awareness have been led by official institutions, leading to better general knowledge in the public. New fleet management programs focusing on route optimization and driving behavior improvement have been developed, and many freight operators have invested in training courses for their drivers (Luque-Rodríguez, 2015). Despite this growing interest, the impact of fuel-efficient driving in the waste-collection process is still little-known. This is paradoxical because the amounts of fuel used by refuse trucks are particularly high, and diesel-use during municipal solid waste (MSW) collection represents therefore one of the most important costs associated to waste-management (Larsen et al., 2009). Even though new technologies such as more efficient biofuels, gas-engines or electrical vehicles are gradually being implemented, virtually all the present-day refuse trucks are still powered by diesel engines. Moreover, these trucks operate in particular conditions which could be considered as extreme parameters. They drive at very low average speeds in highly congested urban environment, and perform constant stop-and-go cycles to pick-up the disposal bins, resulting in a high frequency of acceleration, braking and idling events (Giechaskiel et al., 2019). Classic rear or side loaders typically make 400 to 1200 stops a day, and most refuse trucks include in addition a compaction system using the power take-off (PTO) to reduce the volume of the trash collected. These two features explain why the relative fuel consumption of refuse trucks is so elevated (Fontaras et al., 2012). Implementation of fuel-efficient driving would therefore be particularly relevant in this context. However, most research related to sustainable waste-collection has focused only on the development of smart route planning to optimize the collection route according to the localization and filling-level of the disposal bins (Lozano, 2018; Mamun, 2014). Even though eco-driving has been reported multiple times as an efficient way to reduce energy use in various road-transportation sectors, it is still unclear whether its effects could be observed as well under the very specific waste-collection operating conditions.

So far, only a study by Goes et al. (2019) directly addressed the impact of eco-driving in a waste-collection fleet. They observed an average fuel economy decrease ranging from 0.8 % to 7.1 % after 22 drivers were trained in Rio de Janeiro, Brazil (Table 1). Even though such results bring in substantial economic and environmental benefits when considering the mileage of the entire fleet, the fuel decrease values they observed with bin-picking trucks (0.8 %) were below the average of the typical eco-driving range of benefits. Here, our work shows a different approach implementing eco-driving through an in-vehicle feedback device instead of training courses, on a waste-collecting fleet in the city of Valencia, Spain. In addition, a bigger sample of trucks (67 trucks) belonging to different vehicle categories were monitored for over a year. We also performed a short economic and environmental assessment of eco-driving implementation in the fleet. Overall, our results provide additional insights about the relevance of eco-driving to decrease the ecological footprint of the waste-collection process.

2. Materials and Methods

In this study, we analyze the impact of eco-driving practices on fuel consumption in 67 refuse trucks monitored for over a year. These trucks were part of the fleet of the private waste-collection company SAV (Sociedad Anónima Agricultores de la Vega de Valencia), responsible of waste-collection operations in different cities of the region of Valencia and Alicante (Spain). It must be taken into account that the collection routes as well as the staff didn't vary along the period studied. However, if a different person managed the collection truck (due to a time off work or a rest day), we didn't take into account those days to establish the indicators. This is easy to do as the system allows us to turn on or turn off the efficient driving system. If an electro-mechanic failure that could distort the data occurred, the alarms turned on and it allowed us to check the equipment or the trucks.

Eco-driving practices were implemented through the installation of driving-assistance in-board devices, providing real-time feedback about the driving behavior through non-intrusive lights and acoustic signals. This information was obtained through a connection to the CAN-bus system of the vehicle, which integrates a wide range of telemetry signals and driving parameters provided by various engine sensors. No theoretical nor practical training courses were provided to the drivers. However, after the hidden mode, in several training workshops, drivers were informed about their personal driving mistakes and they discussed about the way to avoid them. In the workshops, the *RIBAS* system was explained as well as its optimum operating parameters. Once the *RIBAS* system was implemented, it creates a continuous learning role about efficient driving as the lights and acoustic signals emitted in each non efficient driving event stablishes guidelines that the driver finally assumes. Fuel consumption was monitored before and after installation of the feedback devices in different types of waste-collecting trucks, and the gains in fuel efficiency were related to the improvement of eco-driving behavior.

2.1 Waste-collecting vehicles

To gain representative insights of fuel consumption in a broad range of real-life situations, five different types of waste-collecting vehicles were selected for this study: rear automatic loaders, side automatic loaders, crane-assisted loaders, “Easy-system” bilateral loaders and waste-transfer trucks.

The four first categories are refused trucks designed to collect the waste at multiple points in the city and to haul it to the treatment plant. All these vehicles perform stop-and-go cycles, but they use specific mechanisms to pick up the bins along their route and display distinct operating parameters (such as RPM, bin-picking time, maximum load or PTO-use). The rear loaders and the side loaders (74.62% of the total trucks) represent the majority of the vehicles that were monitored. These are the classic refuse trucks with which a single driver is able to complete a pick-up event in less than one minute of idling. Rear-loaders display an opening at the back of the truck, while side loaders are filled laterally. Both types include a joystick-controlled robotic arm used to automatically empty the containers. Crane-assisted and “Easy-system” trucks are both using cranes to lift the bins, which typically requires a longer time. The “Easy-system” is an automatized bilateral arm while the classic crane has to be hooked manually to the bin by a second operator. Finally, the waste-transfer trucks do not properly collect trash, but only transfer it from a point to another (typically to the landfill or to the disposal plant). Unlike all the other vehicles, they do not perform any stop-and-go driving cycles.

The fleet displays a high heterogeneity regarding to the engines model, age or efficiency. Therefore, substantial differences are to be expected between the relative fuel consumptions of the trucks, even while performing identical tasks on the same itinerary. Moreover, external parameters such as tire pressure are also likely to influence that consumption.

The number of trucks of each category that were equipped with the driving-assistance devices are given in Table 2. In total, 67 vehicles were monitored for 15 months.

Table 2. Quantity, description and theoretical bin-picking time of the different types of trucks monitored

Type	Quantity	Function	Description	Bin-picking time (s)
Rear loaders	20	Collection	Automatic bin-lift on the posterior part	50
Side loaders	30	Collection	Automatic bin-lift on the lateral part	50
Crane-assisted loaders	10	Collection	Manual crane with double hook	250
"Easy-system" bilateral loaders	2	Collection	Automatic crane with bilateral robotic arm	180

Waste-transfer trucks	5	Transfer	Transfer to the treatment/disposal plant	n.a.
Total	67			

2.2 Data monitoring & real-time feedback

Implementation of eco-driving was carried out through the installation of real-time driving-assistance devices in the cabs of the trucks. As many solutions existed on the market, the software *"Fleet Management"* from the company *MiX Telematics* was chosen, because it was emphasizing mostly on driving behavior improvement thanks to the associated feedback device called *RIBAS*. This device integrates information coming from the engine, from various sensors and from telemetry signals (GPS-signaling) to provide indications and suggestions about the driving. It is a small display using color lights with a simple code of symbols and acoustic signals, designed to be non-intrusive and to keep the driver focused on the road. Five LED indicators illustrate different non-efficient driving events: over-**R**evving, excessive **I**dling, harsh **B**raking, harsh **A**cceleration and over-**S**peeding (RIBAS). The lights stay green as long as the driving is optimal. However, it turns to orange if the driver is getting close to the limit of one parameter, and to red with an alert sound when that limit is reached. It helps the driver to adopt a greener behavior featuring less idling, smoother acceleration and braking, and lower speed. The limit value of each variable depends on several factors such as the type of service, the orography, the truck engine or the category of truck (rear, side, crane-assisted and "Easy-system"). Therefore, for each case, a customized combination of values was selected.

RIBAS devices use data provided by a hardware sensor connected to the CAN-bus port of the engine, responsible to monitor a wide range of driving parameters, including fuel consumption, revolutions per minute, odometer, acceleration, torque, fuel levels, PTO time and engine temperature. The CAN-bus interface used in this study was the model *Fm3306 (FM Tracer)*, also from the company *MiX Telematics*. A USB-key was used to identify the drivers associated to each ride and to control access to the vehicles. The software "*Fleet Management*", associated to the *Fm3306*, was used to visualize all the trips performed by each vehicle, along with the associated driving data. The global organization of all the components used to monitor the trucks and to provide driving-assistance are schematized in Figure 1. This experimental set-up was installed in the 67 vehicles described in Table 2.

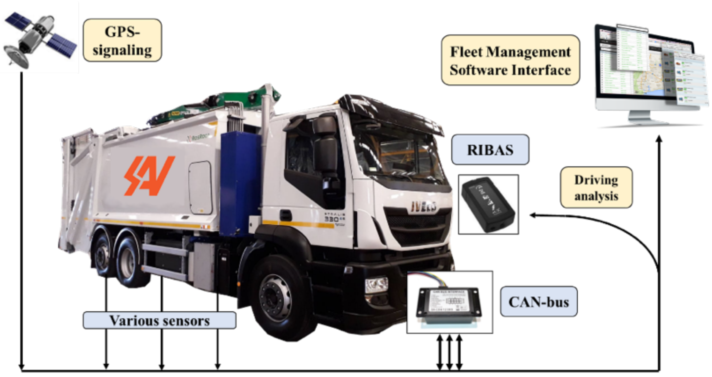

Figure 1. Truck and Fleet Management Software.

2.3 Methodology of the data collection process

The experimental part took place for 15 months in 67 waste-collecting vehicles of the SAV waste-collection fleet. At first, the installation of CAN-bus sensors in the engines was concealed and drivers were not warned that their parameters would be monitored, to avoid any modification of their driving style. This period was referred to as the *hidden mode*, and lasted for about four weeks. This first month allowed to get an accurate estimation of the reference diesel consumption of each vehicle before any eco-driving practice was implemented. The system can provide daily data but due to operational reasons, we decided to log the data monthly. However, some alarms were set in order to register excessive daily values which allowed to detect some electromechanics failures. Therefore, a monthly consumption data for each truck was calculated (in l/100km) taking into account the monthly consumption of fuel and the distance traveled in km.

Next, drivers were informed about the experiment, and *RIBAS* devices were installed in the trucks, divided in the five categories described in Table 2. Driving parameters and fuel consumption were monitored on all trips during 14 additional months while the drivers were using the driving-assistance feedback to acquire fuel-efficient practices. The monthly average diesel use was obtained for all the vehicles, and the global average consumption was then calculated from the 14 months data set. The values were compared to the reference diesel consumption obtained during the hidden mode, and the difference of fuel use was determined in percent from these two results.

Any positive percentage was assumed to be related to the installation of the *RIBAS* device and hence to an improvement of the driving behavior.

Additionally, meetings were organized with the drivers to get constructive feedback and to assess the progress of the fleet. The workshop was and is key to achieve the aims of fuel and emissions reduction. The meetings were held every 3 months but if some incidence was detected (as excessive driving errors or extra fuel consumption), more personal meetings were convened. Drivers were called altogether and they were asked to share their personal driving data with the rest of work colleagues (and it was always accepted). Each case was shown and analyzed and at the end of the meeting a space for discussion was opened where the drivers shared efficient driving experiences. In these spaces the drivers' opinions were taken into account to make possible modifications and incidents were collected in order to assist to maintenance tasks. It was essential to show the drivers their driving historic sheet and their actual data as it motivated them to improve the indicator each three months. Finally, it is important to remark that the 3 best drivers were awarded with a certificate, they had an extra payroll and it was promoted through social networks.

2.4. Data analysis

Statistical tests were carried out to evaluate differences between datasets regarding their central tendencies (means) and variances. The following tests were applied:

- Shapiro-Wilk test. Used to check the normality of a dataset.
- Paired t-test. It is applied when the dataset is not normally distributed.
- Paired Wilconson test. It is applied when the dataset is not normally.

In this case study, it was considered that the data set "Reference fuel consumption" and "Fuel Consumption" are two paired datasets, as they use the same trucks before and after using the RIBAS device.

All the tests were carried out using the program R commander©. A level of significance (α) of 0.05 was considered.

3. Results & Discussion

3.1 Fuel consumption decrease following eco-driving implementation

The average and standard deviation (SD) fuel consumption of the waste-collecting fleet over the course of the fourteen months monitoring are given in Table 3, along with the reference fuel consumption obtained during the 4 weeks-long hidden mode (before installation of the driving-assistance devices). The reference fuel consumption is only a value for each truck. The average percentage of fuel use decrease achieved by each truck is also indicated. Note that some refuse trucks display a negative percentage of fuel consumption decrease (seven of them), meaning that their fuel efficiency was in fact better during the hidden mode than when using eco-driving feedback devices.

The data are divided according to the type of vehicle (rear loader, side loader, crane-assisted loader, Easy-system and waste-transfer trucks). For each type of truck, the average fuel consumption and its standard deviation were calculated for the hidden mode as well as for the consumption over the experimental period.

Overall, a fuel consumption decrease of 7.45 % is obtained when considering the whole fleet (67 vehicles). As a wide range of studies have reported energy consumption decreases ranging from 5 % to 20 % following driver training courses and/or installation of driving assistance devices (see Table 1), this score is highly consistent with previous literature about eco-driving implementation in heavy-duty fleets. The fuel consumption decrease did not seem to be influenced by the reference fuel consumption (the vehicles that were using more diesel during hidden mode did not undergo a stronger consumption decrease). Moreover, no influence of the age or models of the different engines were observed.

Interestingly, a high variability of the reference fuel consumptions is observed between the trucks, even within a same category of vehicles performing an identical task. Before any *RIBAS* device was installed, some vehicles were already using two or three times more diesel than others. For example, the initial fuel economies of rear loaders range from 35.00 to 62.43 L/100 km, while the ones of crane-assisted loaders range from 21.41 to 59.00 L/100 km, a nearly a three-fold difference. This fact is reflected in the high values of SD due to the different type of vehicles. As mentioned in Section 2.1, the variability of the reference fuel consumption is likely to be related to various parameters such as the tire pressure or the age and model of the truck´s engine. This fact highlights the importance of the hidden mode, which allows to compare the real effect of eco-driving implementation on each individual truck, and not on absolute fuel economy values.

Moreover, a high variability can also be observed between the different categories of vehicles. Remarkably, the best values of fuel consumption decrease (11.50 % on average) are obtained by the waste-transfer trucks. Unlike the other vehicles of the fleet, these trucks do not perform stop-and-go cycles to collect the bins, but only carry out basic transportation of the waste to the disposal plant. The four other categories of vehicles (rear, side, crane-assisted and "Easy-system") achieved fuel use decreases of 6.34 %, 8.06 %, 6.97 % and 1.86 %, respectively, which represents a score of 7.13 % on average for the 61 bin-picking vehicles. Despite obtaining substantially higher values, our results are in line with the ones obtained by Goes et al. (2019). In their study over another waste-collecting fleet, they monitored a fuel decrease of 0.8 % for bin-picking vehicles ('P6') performing a stop-and-go cycle, and 7.1 % for transfer trucks ('P9') delivering waste to a single destination (a nearly 10-times fold). Their lower decrease values might indicate that eco-driving implementation through training courses is less efficient than the use of driving-assistance devices such as the *RIBAS* display. However, the same divergence between the economies of waste-transfer trucks and bin-picking trucks was observed in both studies, even though our results suggest a 1.5-fold instead of a 10-fold. It is likely that the inherent nature of stop-and-go waste-collecting vehicles makes the adoption of eco-driving techniques more difficult. Indeed, a green driving behavior is presumably harder to associate with parameters related to the task of refuse trucks, such as the slow speed in a dense urban environment, the traffic congestion or the continuous idling due to frequent stops and extensive use of compaction machinery. On the other side, transfer trucks performing delivery of waste to a single point display an activity analogous to basic freight transportation and are probably less susceptible to urban traffic flow and infrastructure design. Therefore, they might undergo more easily an efficient eco-driving transition, and this could explain why they display the highest improvement. A fuel decrease of 11.50 % is substantial, but consistent with many studies reporting values of the same range in heavy-duty transportation fleets (as illustrated in Table 1).

Table 3. Average fuel consumption decrease following eco-driving implementation

ID number of the vehicle	Reference fuel consumption (L/100 km)	Fuel Consumption (L/100 km)		Fuel consumption decrease (%)
Rear loaders		Average	SD	
108	55.48	49.99	1.07	9.90
109	62.43	59.28	2.21	5.05
110	43.92	39.26	1.10	10.61
121	68.65	66.45	2.96	3.20
139	48.70	37.56	1.90	22.87
140	47.40	42.99	1.82	9.30
141	48.40	44.49	2.52	8.08
142	46.80	46.59	1.54	0.45
143	43.54	38.03	2.03	12.66
144	53.88	42.63	2.31	20.88
147	53.88	53.95	1.29	-0.13
148	50.57	48.45	1.91	4.19
151	60.14	56.17	3.32	6.60
196	38.64	38.48	1.53	0.41
760	45.82	41.32	2.73	9.82
CU51	35.00	37.06	1.38	-5.89
CU52	44.00	45.00	1.08	-2.27
CU53	44.23	43.57	1.51	1.49
CU54	49.00	45.57	1.21	7.00
CU55	47.00	45.78	1.22	2.60
Mean	49.37	46.13		6.34
SD	7.98	7.78		
Side loaders				
152	60.14	59.24	2.65	1.50
153	67.73	66.16	3.14	2.32
155	46.21	46.72	1.43	-1.10
156	46.11	40.76	2.14	11.60
157	62.34	59.74	1.65	4.17
158	64.64	64.65	3.65	-0.02
159	62.29	61.28	2.28	1.62
185	60.59	48.01	2.08	20.76
186	54.44	49.82	1.45	8.49
4	59.50	53.68	1.22	9.78
5	51.50	52.88	1.92	-2.68
729	43.93	39.75	1.54	9.52
730	62.51	59.63	2.28	4.61
731	57.08	55.68	1.43	2.45
732	67.25	61.34	2.18	8.79
733	56.33	52.25	1.56	7.24
734	60.49	55.11	2.54	8.89
735	62.80	54.87	3.34	12.63
736	59.40	52.05	2.16	12.37
737	61.30	50.48	1.72	17.65
738	63.17	52.97	2.58	16.15
739	56.54	53.11	1.91	6.07
740	65.17	56.13	2.56	13.87
741	61.32	54.02	1.38	11.90
742	61.15	52.43	1.63	14.26
743	63.13	57.68	3.54	8.63
744	59.06	54.98	1.93	6.91
745	50.48	47.03	2.50	6.83
746	58.06	53.98	1.77	7.03
747	57.18	51.74	1.45	9.51
Mean	58.73	53.94		8.06
SD	6.00	6.01		
Crane-assisted loaders				
194	59.00	58.51	4.92	0.83
197	42.80	39.08	1.21	8.69
198	45.20	42.24	1.84	6.55
217	24.00	23.26	0.75	3.08
234	32.07	29.01	0.71	9.54
548	33.38	24.98	1.28	25.16
770	28.15	30.46	1.35	-8.21
771	33.00	27.50	0.96	16.67
CU56	48.09	44.58	2.35	7.30
CU60	21.41	21.40	2.69	0.05
Mean	36.71	34.10		6.97
SD	11.79	11.74		
Easy-system loaders				
290	82.37	80.21	6,93	2.62
291	80.84	79.96	4,28	1.09
Mean	81.61	80.09		1.86
Waste transfer trucks				
313	55.59	50.37	2.00	9.39
320	51.64	46.11	5.10	10.71
321	54.49	46.59	4.65	14.50
323	56.11	46.35	0.80	17.39
324	51.38	48.56	0.62	5.49
Mean	53.84	47.60		11.50
SD	2.21	1.83		
Global Average				**7.45**

Reference fuel consumption = monitored during hidden mode (4 weeks), before installation of the RIBAS feedback devices.
Average fuel consumption = average of the monthly fuel consumption, over a monitoring period of 14 months.

Finally, to prove that the RIBAS device improved significantly the driving it was determined whether there are any significant differences between "Reference fuel consumption" and "Fuel Consumption". For this purpose, tests mentioned in section 2.4 were used.

The behavior of the whole fleet was compared before and after using the driving-assistance devices. To this end, the Paired t-test a confidence level of 95% ($\alpha = 0.05$) was used. We decided to employ this parametric test because both datasets follow a Normal distribution. From the results, it can be stated (with 95% confidence) that there are significant differences in the fuel consumption before and after using the RIBAS device, since the p-value obtained is 3.69E-14 (p-value << 0.05). The same calculation was made for each type of vehicle (except for the "Easy-system loader" as it only had two data). In all the cases, the fuel consumption before and after the experience was different. The Paired Wilcoxon test a confidence level of 95% ($\alpha = 0.05$) was used for the "rear loader" and "side loader" trucks. From the results, it can be stated that there are significant differences in the fuel consumption before and after the experience since the p-value obtained are 0.00016 and 4.07E-6 (p-value << 0.05) respectively.

For "crane-assisted loader" and "waste-transfer truck" the Paired t-test with a confidence level of 95% ($\alpha = 0.05$) was used. In this case, it can also be stated that there are significant differences in the fuel consumption in both types of trucks, since the p-value obtained are 0.0239 and 0.0063 (p-value < 0.05).

3.2 Evolution of fuel consumption over time

To determine if the benefits of eco-driving practices were stable on the long-term, we studied the evolution of consumption over time by analyzing the behavior of the fuel consumption curves (Figure 2). The graphs display the monthly fuel use from Month 1 to Month 14, providing insights about the general trends of the evolution of consumption over time. The curves of all the vehicles that were monitored are presented in white, while the mean curve is the thick black dashed line. Due to visibility reasons, the relation between each curve and each vehicle is not indicated. The area comprised between the maximum and the minimum of each month has been shaded in blue, to highlight the range of obtained values. Interestingly, the curves of the mean values are remarkably steady, indicating that a majority of the individual curves did not display substantial difference between the beginning and the end of the monitoring (this is verified by the low values of SD of each truck over the experimental period). Moreover, values seem to be confined in a relatively thin interval (shaded area), except for a single truck in the crane-assisted category that biases the graph by worsening its driving behavior (***C**, top curve*). The curves of all the individual trucks monitored are shown in white. The mean curve is shown as a dashed black line. The interval between lowest and highest monthly values is colored in light blue. The vehicles used were: A: Rear Loaders; B: Side Loaders, C: Crane-assisted loaders; D: "Easy-system" loaders; E: Waste-transfer trucks.

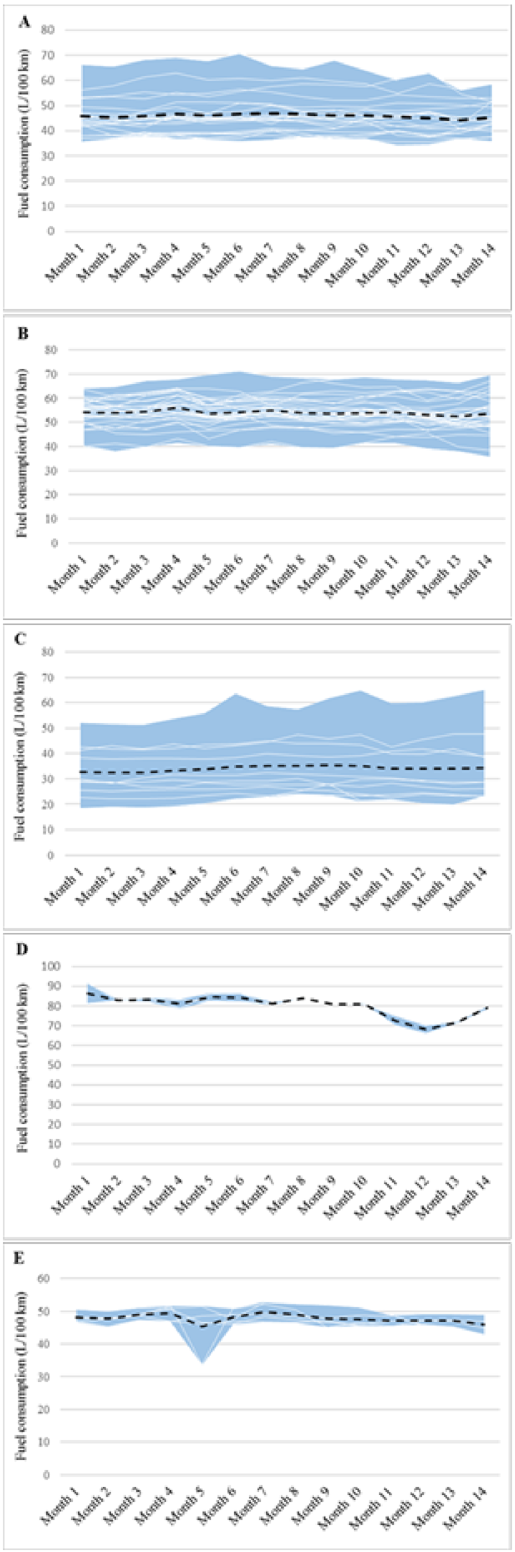

Figure 2. Evolution of fuel consumption over time, according to vehicle category.

To better quantify this trend, we calculated for each truck the difference of fuel consumption between the first month and the last month of the monitoring (Table 4). Any negative value of consumption difference (ΔC) means that the vehicle in fact improved his fuel efficiency over the course of the 14 months. Interestingly, a ΔC of only -0.45 % was found on average, meaning that the vehicles displayed virtually the same fuel consumption at the beginning (just after implementation of eco-driving practices) and at the end of the study. This trend seems to indicate that better fuel economies were associated with the installation of *RIBAS* devices, but also that these economies were persistent over time, on a period longer than a year. Unlike many studies reporting an attenuation of eco-driving effectiveness on the long run, the benefits that we monitored did not tend to fade away as time passed by. The green driving habits obtained through the use of driving-assistance devices might therefore be steadier than theoretical or practical training courses, because the ongoing real-time feedback is less likely to turn into driver´s lassitude or fatigue. Also, it does not tend to be forgotten and does not need maintenance on a regular basis. Overall, our results seem to indicate that real-time feedback provided to drivers might be more suitable than training courses to improve the driving behavior and the fuel consumption in a steadier fashion. Regarding the SD of each type of truck, in the first and last month (1 and 14 respectively), all the values are high due to the differences in fuel consumption.

Table 4. Fuel consumption difference ΔC (%) between the first and the last month of monitoring

ID number of the vehicle	Fuel consumption Month 1 (L/100 km)	Fuel consumption Month 14 (L/100 km)	ΔC (%)
Rear loaders			
108	49.45	49.20	-0.51
109	56.26	58.75	4.43
110	38.18	42.49	11.29
121	66.51	59.91	-9.92
139	37.10	37.63	1.43
140	44.65	39.71	-11.06
141	46.39	51.77	11.60
142	47.02	44.84	-4.64
143	42.68	35.64	-16.49
144	43.19	43.01	-0.42
147	53.15	53.05	-0.19
148	45.72	51.40	12.42
151	53.07	51.68	-2.62
196	38.10	43.14	13.23
760	42.48	40.89	-3.74
CU51	35.38	37.37	5.62
CU52	43.55	44.85	2.99
CU53	41.74	44.41	6.40
CU54	46.00	46.42	0.91
CU55	45.04	43.96	-2.40
Mean	45.78	46.01	0.92
SD	7.3	6.76	
Side loaders			
152	56.97	58.83	3.26
153	64.14	66.88	4.27
155	49.96	48.48	-2.96
156	40.36	38.50	-4.61
157	59.37	61.21	3.10
158	63.62	69.51	9.26
159	60.33	61.74	2.34
185	46.86	45.59	-2.71
186	49.55	48.61	-1.90
4	55.86	52.78	-5.51
5	52.52	56.40	7.39
729	40.04	35.70	-10.84
730	60.42	63.42	4.97
731	57.95	55.54	-4.16
732	59.26	64.76	9.28
733	53.30	52.55	-1.41
734	55.11	52.17	-5.33
735	56.16	54.06	-3.74
736	53.48	48.68	-8.98
737	49.24	49.05	-0.39
738	52.59	48.28	-8.20

739	51.08	51.63	1.08
740	58.16	56.29	-3.22
741	54.74	52.04	-4.93
742	55.02	51.23	-6.89
743	57.54	52.71	-8.39
744	56.76	57.15	0.69
745	46.84	44.48	-5.04
746	55.48	54.99	-0.88
747	52.15	49.93	-4.26
Mean	54.08	53.44	-1.62
SD	5.78	7.62	
Crane-assisted loaders			
194	52.11	65.12	24.97
197	38.44	38.86	1.09
198	42.59	38.57	-9.44
217	22.57	22.94	1.64
234	28.78	28.86	0.28
548	25.46	23.22	-8.80
770	29.81	28.70	-3.72
771	28.98	26.04	-10.14
CU56	41.26	47.63	15.44
CU60	18.35	23.30	26.98
Mean	32.84	34.32	3.83
SD	10.43	13.62	
"Easy-system" loaders			
290	91.62	78.42	-14.41
291	81.25	79.86	-1.71
Mean			-8.06
Waste-transfer trucks			
313	50.55	45.95	-9.10
320	47.83	46.91	-1.92
321	46.68	42.80	-8.31
323	46.92	44.90	-4.31
324	48.32	49.07	1.55
Mean	48.06	45.93	-4.42
SD	1.54	2.33	
Global Average			**-0.45**

Finally, to check that there are not differences between the fuel consumption in months 1 and 14, test mentioned in section 2.4 were also used. They were used for each type of truck (except for the "Easy-system loader") no differences were found. In the "rear loader" and "side loader" trucks, the Paired t-test a confidence level of 95% (α = 0.05) was used. From the results, it can be stated that there are not significant differences between months 1 and 14, since the p-value obtained are 0.787 and 0.233 (p-value > 0.05). For the "crane-assisted loader" and "waste-transfer truck", the Paired Wilcoxon test a confidence level of 95% (α = 0.05) was used. Significant differences were not found between both months, since the p-value obtained is 0.233 and 0.625 (p-value > 0.05).

3.3 Environmental and economic assessment

Our results show that the installation of driving-assistance devices resulted shortly in an average fuel consumption decrease of 7.45% at the fleet scale, coming along consequent economic and environmental benefits. An estimation of the global impact of eco-driving in terms of spared fuel and of exhaust emission reduction was therefore meaningful. Table 5 displays an economic assessment of the implementation of *RIBAS* devices in the SAV fleet. We used data about the mileage and the fuel consumption to estimate how many liters of fuel were saved every year by each truck. As the price of diesel is subject to continuous market fluctuations, we decided to approximate the cost of one liter to 1.2 €, that is the traded prize payed by the company. Moreover, we deduced from the final benefits the price of the installation of the hardware (850 € per truck) and the yearly fee required for the *Fleet Management* software use (252 € per truck, per year). Hence, this assessment covers the first year of use and the whole implementation process. Note that every vehicle displayed its own mileage and a specific fuel economy value. Therefore, the results indicated were calculated from the individual data of each truck, not from the average values of each category.

As shown in Table 5, fuel-efficient driving practices provided substantial economic gains. As nearly 120,000 L of diesel were spared, the total fuel savings of 141,000 € covered by far the price required for the hardware installation and software use during the first year, leading to a net profit of 67,000€ for the 67 vehicles.

Table 5. Economic assessment of the implementation of eco-driving practices in SAV fleet after one year

	Total mileage (km/year)	Fuel savings (L)	Average benefit per vehicle (€)	Total benefits (€)
Rear loaders (20)	797,964	28,850	629	12,579
Side loaders (30)	1,079,293	56,810	1,170	35,112
Crane-assisted loaders (10)	348,096	9,586	48	483
"Easy-system" loaders (2)	52,773	758	-647	-1,294
Waste-transfer trucks (5)	344,833	21,626	4,088	20,440
Total (67)	2,622,959	117,630	1,058	67,322

Negative values in Table 5 highlight the fact that the fuel consumption improvement was not enough to cover the cost of installation and use of the feedback device for the category of the “Easy-system” loaders. Therefore, we realized that the vehicle type mattered when considering the implementation cost of eco-driving. Only the two “Easy-system” trucks revealed not being profitable in just one year, while all other categories yielded positive return. However, the savings achieved with the crane-assisted trucks were small (less than 1 %). The side loaders represented logically half of the total benefits due to the high number of vehicles of this type. Remarkably, 30% of the global benefits were brought in by the waste-transfer category, which encompass only 5 vehicles. When considering the proportional values (average benefit per vehicle), 69 % of the savings would actually come from the waste-transfer category, while the rear loaders and the side loaders would represent 10 % and 20 %, respectively.

Altogether, these results tend to indicate that implementation of eco-driving should be carefully planned ahead according to the vehicle type and the numbers of trucks to be equipped. In this case, it should be focused primarily on the transfer trucks, since they display a saving potential substantially higher than the other categories. However, the rear and side loaders are also to be considered due to the number of vehicles implicated. The two categories of trucks involving the use of a crane were far less profitable, and could be seen as a lower priority. Pilot studies are crucial to provide insights about where fuel-efficient driving would raise the greatest impact. Overall, the implementation of eco-driving in a heavy-duty waste-collection fleet proved to be very profitable. Since the assessment covered only the first year, further economic returns are to be expected as the hardware cost is already absorbed and as the fuel economy should remain steady over time.

Concerning the environmental assessment, a significant diminution of the released atmospheric pollutants is to be expected from fuel savings. Diesel exhaust pollution includes mainly CO_2, NOx, CO, HC and PM (Reşitoğlu et al, 2014). Usually, pollutant emissions are estimated using the maximal standards defined for the engine model, e.g. the Euro standards in European Union. These standards represent the acceptable limits for exhaust emissions of any new vehicle sold in the EU. However, these approval tests are standardized and might not be representative of real-life driving conditions. This is particularly true in the case of refuse trucks, which display very particular operating parameters that are completely different from classic freight transportation. Low-speed, frequent stops and trash compaction could trigger the release of much higher amounts of pollutants than estimated in laboratory testing. It is therefore likely that the limits imposed by current standards are not representative of the actual emissions. We therefore decided to approximate the emission decrease rates related to fuel savings using an estimation from Larsen et al. (2009). Instead of standardized tests, they used a transport simulation software called TEMA2000 to approximate the emission rates of heavy-duty diesel engines performing waste-collection. For the Euro IV, which is the Euro standard followed by the vehicles of the SAV fleet, they estimated that burning one liter of diesel would cause 2.6 $kg \cdot L^{-1}$ of CO_2, 2.2 $g \cdot L^{-1}$ of CO, 1.2 $g \cdot L^{-1}$ of HC, 17 $g \cdot L^{-1}$ of NOx and 0.1 $g \cdot L^{-1}$ of PM to be released. Using these values, the amounts of atmospheric pollutants that were saved over the course of a single year were approximated for the fleet (Table 6).

Table 6. Theoretical quantification of the pollutant emissions reduction in one year

	CO_2 (kg)	CO (g)	HC (g)	NOx (g)	PM (g)
Rear loaders	75,846	63,469	34,619	490,443	2,885
Side loaders	149,354	124,982	68,172	965,771	5,681
Crane-assisted loaders	25,202	21,089	11,503	162,964	959
"Easy-system" loaders	1,994	1,668	910	12,891	76
Waste-transfer trucks	56,854	47,576	25,951	367,637	2,163
Total	309,248	258,785	141,156	1,999,705	11,762

These results might be over-estimated, as the vehicles of the waste-transfer category do not act as typical refuse trucks and could therefore display real-life emissions lower than the ones indicated. Nonetheless, the decrease values of the pollutants released are substantial. In particular, 300,000 kg of CO_2 a year would mean that nearly one thousand tons of GHG would be saved in a little more than three years at the scale of a single private company. International expansion of these practices would reduce considerably the atmospheric pollution and the worldwide ecological footprint of the road transportation sector. Further assessment using a Portable Emissions Measurement System (PEMS) would provide meaningful indications about the exact quantities of pollutants released, and about the true environmental impact of fuel-efficient driving in a waste-collection fleet.

4. Conclusion

This study concludes that the stablishing an efficient driving system supporting the driver in real-time can be useful to reduce the fuel consumption and the emissions associated to the municipal waste collection trucks. It has been shown that this type of system maintains the efficiency over time, which doesn’t happen when the driving efficiency is carried out with training courses.

However, it was clear that the impact of the solution on the savings depends on the vehicle used and the waste collection system. In this way, during the experimental part, an average fuel consumption decrease of 7.45 % was observed following the installation of feedback devices, but the decrease values ranged from 1.86 to 11.50 % according to vehicle category. As the waste-transfer vehicles had significantly higher decrease values, due to they don’t load and unload waste, eco-driving practices implementation should be focused in first place on this category. Finally, an essential aspect to take into account due to its impact in the results is the importance of organizing follow-up meetings with the drivers as these meetings allowed to know the consumption indicators and the individual driving errors which has encouraged an environment of continuous improvement.

From the methodological point of view, this work has presented the efficient driving solutions through assistant systems for driving in the transport and collection of waste as the system has been tested under real conditions during a long period of time and using different types of vehicles. An important achievement of this work is the development of initial reliable indicators in the hidden stage. To achieve this goal, it was crucial that the drivers didn't have indications about their monitoring as it could have an impact changing their behavior and consequently it could have distorted the initial indicators.

The methodology presented is valid and for this reason it can be used in future works taking into account the workshops in the continuous improvement as well as the precautions in the initial indicators stage.

From the environmental point of view, it was proven that the eco-driving practices implementation allowed to reduce the pollutant emissions in the towns. For this reason, municipalities should include these systems in their vehicles as a good policy to reduce emissions. The company where the experimental process was carried out, has already implemented it in its fleet.

As future studies related with the driving efficiency, it should be considered the use of gas or biogas instead of fuel with the aim to reduce the emissions and it could be interesting to study the type of waste unload to reduce the bin unloading time.

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