

Experimentally Compared Fuel Consumption Modelling of Refuse Collecting Vehicles for Energy Optimization Purposes

Francisco Soriano
Ros Roca Group

Jesus Alvarez-Florez and Manuel Moreno-Eguilaz
UPC

ABSTRACT

This paper presents a novel methodology to develop and validate fuel consumption models of Refuse Collecting Vehicles (RCVs). The model development is based on the improvement of the classic approach. The validation methodology is based on recording vehicle drive cycles by the use of a low cost data acquisition system and post processing them by the use of GPS and map data. The corrected data are used to feed the mathematical energy models and the fuel consumption is estimated.

In order to validate the proposed system, the fuel consumption estimated from these models is compared with real filling station refueling records. This comparison shows that these models are accurate to within 5%.

Index Terms: Refuse Collecting Vehicles, Power System Modelling, Duty Cycle, Energy Management, Energy Coastdown

CITATION: Soriano, F., Alvarez-Florez, J., and Moreno-Eguilaz, M., "Experimentally Compared Fuel Consumption Modelling of Refuse Collecting Vehicles for Energy Optimization Purposes," *SAE Int. J. Commer. Veh.* 7(1):2014, doi:10.4271/2014-01-9023.

I. INTRODUCTION

Due to the increasing public interest in environmental issues in general and fuel consumption reduction in particular, a variety of transport related strategies and technologies are currently under development to reduce the energy consumption of road traffic.

High accuracy fuel consumption models are necessary to perform energy optimization studies with reasonable quality. Working with these models, fuel consumption optimization can be carried out analyzing different vehicle architectures as well as alternative powertrains or power split control strategies in case of different power sources on board.

Until now little work has been done in power management or fuel consumption estimation of Refuse Collecting Vehicles (RCVs) [2, 3], which have a very specific drive cycle.

To develop and test management algorithms, most authors have used statistical methods to generate drive cycles [1, 2, 4]. Others only register part of a route and repeat this part in time [3].

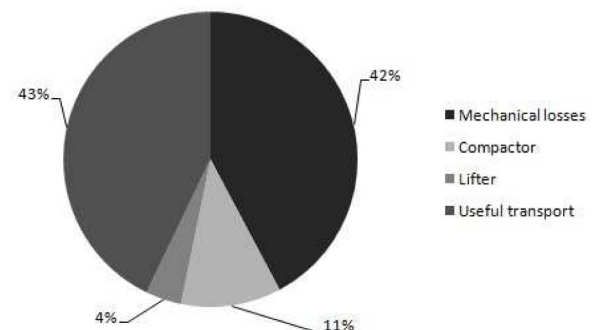


Figure 1. Energetic coastdown of a RCV.

These methodologies are suitable to design vehicles which could work with appropriate results in a wide spectrum of driving cycles. However, when all the possible cycles are similar, better results may be obtained registering the real drive cycles using an on board data acquisition system, capable of recording real time data while the vehicle is running. The main problem of this approach is that before validating the data acquisition system, it must be contrasted against a reference route to define the accuracy of the data acquisition system, because minor errors in an inclinometer installation, or changes in the effective radius of a wheel due to a load change

in a truck, can generate wrong data. This is usually done in laboratory rigs or test tracks [5, 6] which are not always available and are usually expensive.

In this work, a novel methodology for drive cycle data acquisition is proposed. With this methodology, vehicles are run in real drive cycles, and experimental data is corrected using maps and GPS data instead of reference routes.

One of the main goals of this study is to validate this novel high accuracy and low cost acquisition system, and use it to feed fuel consumption models applied to RCVs. One of the main advantages is that the system is easy to move from one vehicle to another and it is capable of recording any physical data.

The models developed in this paper will be useful, for example, to predict the instantaneous fuel consumption of a vehicle in a drive cycle with high precision.

This tool is useful to optimize a vehicle or fleet route, to develop powertrain energetic studies, and could also be used to study the local pollutant emissions of a vehicle during its drive cycle.

The paper is organized as follows. The first part presents the RCV's model and the system to acquire and correct experimental data to feed this model. In the second part different tests are performed to measure the accuracy of this data acquisition system. In the third and last part the model developed is used to estimate the fuel consumption and CO₂ emissions of different powertrains in the same route.

To perform the experimental tests presented in this paper two different RCVs have been used. The first one is a rear loader (Ros Roca Olympus on a Renault Premium 330DXI). The second is a side loader (Farid FMO on an Iveco Stralis CNG 270).

II. VEHICLE ENERGETIC CONSUMPTION MODEL

Using the classical approach found in literature [7, 8, 9], the vehicle power and energy breakdown (see Figure 1) has been done as follows:

A. Aerodynamic Resistance

$$R_a = \frac{1}{2} \rho (S C_x) v^2 \quad (1)$$

where:

1. ρ $\equiv$ air density [kg/m³].
2. S $\equiv$ vehicle frontal surface [m²].

3. C_x $\equiv$ aerodynamic drag coefficient [dimensionless].

4. v $\equiv$ speed of the car [m/s].

B. Rolling Resistance

$$R_{rr} = C_{rr}(m + l)g \quad (2)$$

where:

1. m $\equiv$ mass of the vehicle [kg].
2. l $\equiv$ load of the vehicle [kg].
3. C_{rr} $\equiv$ rolling resistance coefficient of the tire [kg/kg].
4. g $\equiv$ gravity constant [m/s²]

C. Road Profile Resistance

The gravity force, as shown in Figure 2, is decomposed as:

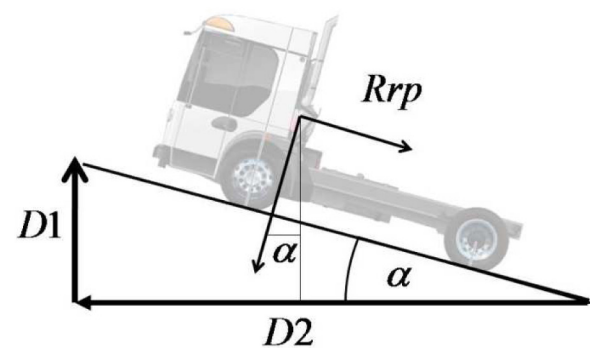


Figure 2. Gravity vector decomposition.

$$i\% = \frac{D_1}{D_2} 100 = 100 \tan \alpha \quad (3)$$

$$R_{rp} = g(m + l) \sin \alpha \quad (4)$$

where:

1. g $\equiv$ gravity acceleration [m/s²].
2. α $\equiv$ angle of the road [radians].
3. i $\equiv$ gradient of the road [%].

D. Inertial Resistance

When the vehicle changes its speed, two types of inertia will resist the acceleration. These inertias are related to the rotating components (engine components, gearbox, wheels, etc.) and to the linear movement of the vehicle mass.

$$R_i = (m_t)a \quad (5)$$

$$m_t = m + \frac{J_w}{r_w^2} + \frac{i_t^2 i_f^2 n_t n_f J_e}{r_w^2} \quad (6)$$

where:

1. $m_t \equiv$ total dynamic vehicle mass [kg].
2. J_w , $J_e \equiv$ inertia of the wheels and engine [$\text{kg} \cdot \text{m}^2$].
3. i_t , $i_f \equiv$ gear and differential ratios [dimensionless]
4. n_t , $n_f \equiv$ efficiencies [dimensionless]
5. $r_w \equiv$ equivalent wheel radius [m]

E. Energy Consumption of the Body

Some special application vehicles also consume energy to operate the body, and this is true of most RCVs.

A typical RCV has a compactor and a lifter, which are powered from the engine through a hydraulic pump. The method to calculate the instantaneous power consumption is:

$$P(kW) = QP \quad (7)$$

where:

1. $Q \equiv$ hydraulic oil flow [m^3/s].
2. $P \equiv$ pressure [Pa].

F. Total Power Consumption

The total power consumption can be expressed as the force that the vehicle has to do to move forward (F_{mf}) multiplied by its speed plus the body power consumption:

$$Power = vF_{mf} + Body_{PC} \quad (8)$$

The resistance to the forward motion can be expressed as the sum of all the resistances (aerodynamic, rolling, road profile and inertia):

$$R = R_a + R_{rr} + R_{rp} + R_i \quad (9)$$

Finally, the power consumed by the vehicle will be expressed as follows (a hydraulic body is assumed, as it is the most common):

$$P(kW) = v \left[\frac{1}{2} \rho(SC_x) v^2 + C_{rr}(m + l)g + \right] + QP \quad (10)$$

$$P(kW) = \left[\frac{1}{2} \rho(SC_x) \right] v^3 + [C_{rr}(m + l)g + mg(\sin\alpha)]v + m_t a v + QP \quad (11)$$

$$P(kW) = \left[\frac{1}{2} \rho(SC_x) \right] v^3 + [C_{rr}(m + l)g + mg(\sin\alpha)]v + m_t \frac{\delta v}{\delta t} v + QP \quad (12)$$

Considering in the discrete domain, the power consumption at a certain instant is:

$$P(kW) = \left[\frac{1}{2} \rho(SC_x) \right] v(t)^3 + g[C_{rr}(m + l) + m(\sin\alpha)]v(t) + m_t \frac{v(t) - v(t - \Delta t)}{\Delta t} v + Q(t)P(t) \quad (13)$$

A summary of the parameters needed to calculate power and energy is shown in [Table 1](#).

Table 1. Parameters needed to characterize a route.

Symbol	Quantity	Units
v	Vehicle speed	m/s
α	Route gradient	radian
l	Vehicle load	kg
Q	Hydraulic oil flow	m^3/s
P	Hydraulic oil pressure	Pa
S	Vehicle frontal surface	m^2
Cx	Aerodynamic drag coefficient	Dimensionless
m	Vehicle mass	kg
m_t	Dynamic Vehicle mass	kg
Crr	Rolling resistance	kg/kg
ρ	Air density	kg/m^3

III. DATA ACQUISITION AND PROCESSING

Once the necessary data has been identified, a methodology to acquire measurements and compensate deviations has to be defined.

An on board kit for real time data acquisition is required. This kit is composed by:

1. CAN Datalogger: CANalyzer CANCase XL with two CAN ports (SN 007130-011289)
2. PLC: IFM CR0505 (SN 024137); Analog channel resolution 12 bits, resolution $\pm 1.0\%$ FS.

3. GPS: RM Michaelides CAN link 2105 (part no. 253004018), fullscale 0.00001° L/L, 0.1m height, CEP 3.5m,
4. Inclinometer: STW YNGS1ST2 with CAN Open port (part no. 080537682003). Range ±6g resolution 0.2 mg.
5. Pressure sensor IFM 9021 (SN 12911 A) Range 0..250 bar, ±0.25 BPSL, ±0.5LS

The port 1 of the CAN datalogger is connected on to one of the CAN J1939 buses of the vehicle.

The second port is connected to a small CANOpen network, consisting of a GPS device, a PLC with CAN ports for mobile applications and an inclinometer. According to the technical specifications of the device manufacturer, the GPS position error is less than 3.5 meters.

The inclinometer is a gravity sensor, which means that its output will be contaminated by any other source of acceleration in the vehicle [5]

The cost of the whole kit remains under 2200 euros, so it fulfills the low cost criteria for the development of the kit.

Once the hardware for data acquisition is defined, the data acquisition process has to be established.

The data shown in [Table 1](#) is divided into three groups.

The first group is the data which can be measured accurately and for which no post processing is needed. It includes pressures, vehicle mass, vehicle load, rolling resistance and aerodynamic drag.

The second group is the data which can be calculated with high precision using information from manufacturers or meteorological stations. It includes vehicle frontal surface, dynamic vehicle mass and air density during the test.

The third group is the data calculated using parameters which have uncertainties and can add errors to the system but which can be corrected through post processing. This includes vehicle distance, vehicle speed, route gradient and hydraulic oil flow. In this paper different correction algorithms are proposed for this data post processing.

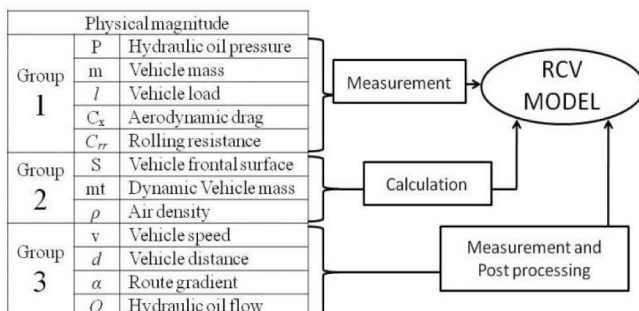


Figure 3. Data flow to feed the mathematical model.

The data from first and second group are taken and not evaluated. However, the data from the third is taken and its precision will be evaluated in this paper in order to get an estimation of the accuracy of the correction algorithms.

A. Vehicle Distance and Speed Correction

The vehicle distance and speed found in the CAN bus of a truck ('wheel based speed' SPN84 and 'trip distance' SPN244, both from J1939 standard) are calculated using the wheel (or propshaft) rotation speed and an estimated effective radius of the wheel.

This technique has an associated error which is due to the variations of the real effective radius versus the estimated one. Several factors can change this real effective radius (vehicle load, tire wearing, pressure drop, etc.) and the vehicle measurement system does not have a mechanism to compensate that value in real time. There is a device (tachograph) which compensates this error using a correction factor (K), whose estimation is based on the measurement of the 'trip distance' parameter and a measurement on a calibrated roll bench. However, the K factor is not corrected in real time (each 2 years correction, according to European regulations).

The proposed method used in this paper for correcting vehicle speed data and measurement errors is to take the 'vehicle distance' value from the J1939 bus (DJ1939), get distances periodically from cartography (DMAP) [11] using geolocation, and calculate a correction factor (from now denominated as K1) in a similar way to that used when correcting the calibration of a tachograph, but in real time.

$$K1 = \frac{D_{MAP}}{D_{J1939}}$$

(14)

This correction factor will be used to correct the vehicle distance and speed.

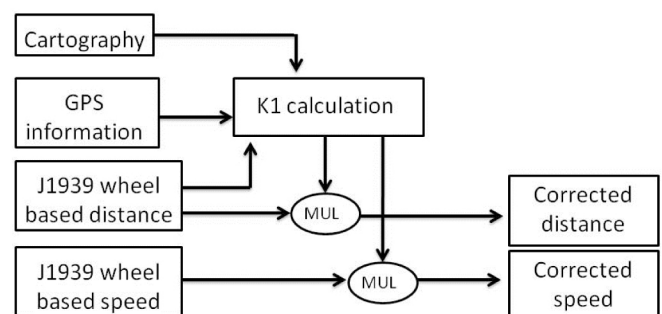


Figure 4. Implemented algorithm to calculate the 'K1' factor and to correct the vehicle speed and displacement.

Using this method, the correction factor can be updated in real time, and the effects of the real effective radius on the error will be minimized. This is important in a RCV whose load is changing constantly in its route. Loaded many times but in very