

Development of a Fuel Consumption Test Procedure for Refrigeration Units

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FPINNOVATIONS

ABSTRACT

This project's objective was the development of a test procedure to evaluate the impact of the refrigerated van box on the fuel consumption of the refrigeration unit. The scope of the project included a review of the test procedures, the development of a testing methodology for measuring the fuel consumption of the refrigeration unit on a specific duty cycle, and testing with a view to validating the methodology.

Road and track tests are subject to variations in conditions, and controlling or accounting for these variables as much as possible is an important part of ensuring accurate results. However, when testing a refrigerated van on the track or on the road, it is very difficult to eliminate variable external influences and to isolate the particular influence of the refrigerated van on the refrigeration unit's fuel consumption. For this reason, tests were conducted in an environmental chamber in controlled temperature and humidity conditions.

Validation tests took place in an environmental chamber at an ambient temperature of +32°C. The refrigerated box had an interior temperature of -10°C. The tests aimed to compare the fuel consumption of the same refrigeration unit installed on the same test vehicle, but with two different refrigerated van boxes. The first refrigerated box had a classic design, with aluminum and steel joints and insulated with spray-on urethane foam, whereas the second unit had a newer design, using high-density polyurethane sandwich panels, and without any internal or external metal joints, which eliminate thermal bridges promoting heat transfer.

The tests showed that it is feasible to conduct fuel consumption tests in an environmental chamber to evaluate the fuel consumption of a refrigeration unit, and the repeatability of the tests can be ensured. The tests resulted in $9.6\% \pm 1.8\%$ fuel savings with the newer design refrigerated box, when compared with the classic design refrigerated box.

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INTRODUCTION

The California Air Resources Board (CARB) estimates that there are 40,200 transport refrigeration units operating in California at any given time, with an annual diesel consumption of more than 20 million gallons [1]. A study conducted for the National Renewable Energy Laboratory [1] presents a novel in situ method for measuring emissions and fuel consumption of transport refrigeration units, powered by dedicated diesel engine. Fuel consumption was measured using a gravimetric fuel measurement system integrated with a data acquisition system, on a chassis dynamometer. The tests conducted on a 48-ft semi-trailer, with ultra-low sulfur diesel and gas-to-liquid (GTL) diesel, and with two exhaust configurations (a stock original equipment manufacturer muffler and a Thermo King pDPF diesel particulate filter) showed an average fuel consumption of 4.9 L/h at engine high speed. Differences in measured fuel consumption were

observed across the test configurations. However, these differences were likely within the measurement error of the experimental equipment.

Road transport refrigeration equipment is required to operate reliably in much harsher environments than stationary refrigeration equipment. Due to the wide range of operating conditions and constraints imposed by available space and weight, transport refrigeration equipment have lower efficiencies than stationary systems. This, coupled to rapidly increasing use of refrigerated transport arising from the much wider range of transported goods, home delivery and greater quality expectations, is placing considerable pressures on the food industry to reduce the energy consumption of refrigerated transport. According to a study conducted by Brunel University in England, the fuel consumption of auxiliary diesel of the refrigeration unit engine for a dual compartment 13.6 m (44.6-ft) semi-trailer in 30°C ambient is

approximately 2 L/hour (8% of vehicle main engine consumption) [2].

The measurement method should be based on standard operating conditions of refrigeration units and exclude the influence of all random effects such as particular truck and engine types, different test roads and driving styles, the real load (capacity) of the unit, etc. [3]. Reference [3] applies to the measuring of fuel consumption for refrigeration units powered by vehicle's engine and proposes the concept of a standard engine to separate the fuel consumption of the refrigeration unit from the fuel consumption of the vehicle. The test procedure presented in this paper is used for measuring the fuel consumption of refrigeration units powered by their own engine, in order to evaluate the impact of the refrigerated van box on the fuel consumption of the refrigeration unit.

Road and track tests are subject to variations in conditions between tests, and controlling or accounting for these variables as much as possible is an important part of ensuring accurate results. However, when testing a refrigerated van on the track or on the road, it is very difficult to eliminate variable external influences and to isolate the particular influence of the refrigerated van on the refrigeration unit's fuel consumption. For this reason, the tests were conducted in an environmental chamber in controlled temperature and humidity conditions.

METHODOLOGY

Test Site

The tests were conducted in an environmental chamber under controlled conditions (temperature and humidity). Table 1 gives the chamber's specifications. The chamber is 16.5 m long and 6.10 m wide. Its access door is 3.35 m wide and 4.14 m high.

Table 1. Specifications of the environmental chamber

Temperature range	-55°C to +80°C
Humidity range	8% to 95%
Cooling capacity	130 kW at -40°C; 444 000 BTU/h
Cooling rate	20°C/h
Heating rate	15°C/h
Air evacuation rate	56 m ³ /min
Air intake	90.6 m ³ /min

Test Procedure

Fuel consumption tests were conducted to compare the fuel consumption of the same refrigeration unit installed on the same test vehicle in two different conditions:

- The vehicle equipped with the control van box (base segment);
- The vehicle equipped with the test van box under evaluation (final segment).

Validation tests took place in an environmental chamber at an ambient temperature of +32°C. The refrigerated box had an interior temperature of -10°C. Ambient (chamber) and interior temperatures in the refrigerated box were also recorded.

For the two segments, the van boxes were empty since a refrigeration unit consumes more fuel to keep the temperature of an empty box cool compared with a van that contains products (which are always already cold when loaded into the van and act as a thermal mass). Thus, the test situation represented an extreme case of cooling and therefore of energy use.

The fuel consumption of the refrigeration unit was measured with precision, by comparing the weight of a portable fuel tank before and after each test. The vehicle and the refrigeration unit were in good working order.

Each segment, base and final, was structured the same way:

- The conditioning of the vehicle to reach test temperatures:
 - The vehicle was put into the chamber that had an ambient temperature of +32°C and humidity of 10%, for nine hours, with the rear doors of the van box open;
 - The van box doors were then closed and the refrigeration unit was turned on for the van to reach an interior temperature of -10°C, with the portable tank providing the source of fuel;
 - When the interior of the van box reached -10°C, the refrigeration unit was turned off, the rear doors of the van were opened for 10 minutes (to simulate a delivery operation), the portable tank was weighed and its weight recorded as the initial weight for the first test.
- The test segment, consisting of three tests for measuring fuel consumption to keep the van's interior temperature at -10°C:
 - For each test, the refrigeration unit was programmed to reach and keep the interior temperature of the van at -10°C;
 - Each test lasted three hours;
 - Tests were separated by 10-minute stops, during which the refrigeration unit was turned off and the rear doors of the van opened (to simulate a delivery operation). During the stops, the portable tank was weighed and the weights recorded.

The ratio of the consumption of the refrigeration unit at the base segment and the final segment (B/F) was calculated for the pairs of tests corresponding to the two segments, to ensure that the results are repetitive, similar to [4] and [5].

For each pair of tests, the fuel saved (E_{Ci}) was expressed as the variation in percentage between the quantities of fuel consumed in the respective run of baseline segment (B_i) and final segment (F_i), using the equation:



$$E_{Ci} = 100 \times \frac{B_i - F_i}{B_i} \quad (1)$$

The representative result of the test is the fuel saved expressed as average of the variations in percentage between the quantities of fuel consumed for each pair of tests, E_C , at the 95% confidence interval according to SAE J1321 Type II fuel consumption tests [4]. The confidence interval is shown as a $\pm$ value about the nominal value. The confidence interval (CI) is determined from the variation in fuel saved relative to the nominal value, based on the critical value of the t distribution for 95% confidence interval (t), standard deviation (σ) and the number of data values obtained (n), with the equation:

$$CI = \frac{t \times \sigma}{\sqrt{n}} \quad (2)$$

Refrigeration Unit

The test vehicle was a Kenworth T-370 2011, with a refrigerated van box and a Paccar PX-6 engine. The vehicle was equipped with a Carrier Supra 850 refrigeration unit with a Kubota CT3-44 TriVortex diesel engine. Table 2 gives the unit's specifications.

Table 2. Specifications of the refrigeration unit

Parameter	Description
VIN	NFC 91217151
Make and model	Carrier Supra 850
Year	2010
Engine	Kubota CT3-44 TriVortex
Number of cylinders	3
Displacement	0.719 L (43.88 in ³)
Rated power	14.9 kW (20 HP)
Couple maximum	46 Nm (34 lb-ft)
Compressor	05K24, 4 cylinders
Refrigerant	R-404A
Cooling capacity	At 2°C: 6740 W (23,000 BTU)
	At -18°C: 4745 W (15,500 BTU)
	At -29°C: 2930 W (10,000 BTU)

Refrigerated Boxes

Table 3 presents the characteristics of the two refrigerated boxes used for the tests. The control refrigerated box had a classic design, with aluminum and steel joints and insulated with spray-on urethane foam, whereas the test unit had a newer design, using high-density polyurethane sandwich panels, and without any internal or external metal joints, which eliminate thermal bridges promoting heat transfer. Figures 1 and 2 present the test vehicle in the environmental chamber.



Figure 1. Test vehicle equipped with the control refrigerated box in the environmental chamber (rear view)



Figure 2. Test vehicle equipped with the test refrigerated box in the environmental chamber (side view)