

Multi-Vehicle Evaluation of Gasoline Additive Packages: A Fourth Generation Protocol for the Assessment of Intake System Deposit Removal

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ABSTRACT

Building on two decades of expertise, a fourth generation fleet test protocol is presented for assessing the response of engine performance to gasoline additive treatment. In this case, the ability of additives to remove pre-existing deposit from the intake systems of port fuel injected vehicles has been examined. The protocol is capable of identifying real benefits under realistic market conditions, isolating fuel performance from other effects thereby allowing a direct comparison between different fuels. It is cost efficient and robust to unplanned incidents.

The new protocol has been applied to the development of a candidate fuel additive package for the North American market. A vehicle fleet of 5 quadruplets (5 sets of 4 matched vehicles, each set of a different model) was tested twice, assessing the intake valve clean-up performance of 3 test fuels relative to a control fuel.

In this trial, the test protocol successfully identified real benefits provided by the experimental additive relative to the control fuel. This was achieved with fewer vehicles than might have been previously required for the same statistical robustness. The output was an additive dose response for the experimental additive package. Several learning points emerged that will be included in future work using this successful test protocol.

INTRODUCTION

The successful development of a new fuel treatment, e.g. a new fuel component or additive package, requires the quantification of real fuel performance benefits, isolated from other effects and measured under realistic market conditions. While this can often be accomplished through the use of established tests, the generation of statistically significant fuel performance data within the constraints of 'real life' usage sometimes requires a vehicle fleet test. However, the inherent variability of vehicle performance, especially over extended mileages, makes it difficult to discriminate benefits arising from the optimization of package formulation or treat rate. To meet this challenge, Shell Global Solutions¹ (Shell GS) have developed, over many years, a fleet test protocol incorporating key structural features as shown in Figure 1. The protocol aims to facilitate optimum test design, rigorous execution and reliable data analysis so that, when a vehicle fleet test is judged to be necessary, it yields results that are robust, cost effective and discriminating.

Early versions of the protocol used a 'paired fleet' design to compare the performance of a candidate fuel with that

¹ Shell Global Solutions is a network of independent technology companies in the Shell Group. In this publication the expression 'Shell Global Solutions' or 'Shell GS' is sometimes used for convenience where reference is made to these companies in general, or where no useful purpose is served by identifying a particular company.

of a control fuel using two matched fleets of vehicles that are operated in an identical fashion. This isolates the long-term fuel benefit from other influencing factors changing over time. Acceptance criteria for vehicle matching and performance measurement were pre-defined in the test-commissioning step. Paired fleet tests, conducted in 1991 (first generation protocol) and 2001 (second generation protocol), successfully demonstrated and quantified statistically significant benefits in fuel economy (FE), exhaust emissions and intake system cleanliness through long-term use of additive-treated gasoline [1, 2]. For example, with 30 vehicles (15 matched pairs), statistically significant fleet-average FE benefits in the range from 1 to 2% were identified.

In 2006, we published an enhanced version of the test protocol employing quadruplets ("quads") of matched vehicles and improved vehicle matching procedures [3]. In effect, this third generation protocol uses four matched fleets of vehicles operated in an identical fashion to compare the performance of a candidate fuel with that of a control fuel. By running two fleets on each of the two fuels, the test program is more robust to unexpected behavior in (or the loss of) a vehicle and provides more information on how fuel benefits vary with vehicle type. Using this updated protocol, a 20-vehicle (5-quad) fleet test was able to discriminate a fleet-average FE difference of less than 0.6%.

The existing protocol is designed primarily for programs in which fuel performance is measured over a period of mileage accumulation without disturbance to the vehicle. Often, however, it is necessary to measure fuel performance in a test in which vehicles have to be partly dismantled. A prime example of this type of test are clean-up tests in which, after running vehicles on one fuel, engine cylinder heads are removed ("stripped") to allow internal deposits to be measured on intake valves, cylinder heads, etc. After rebuilding, the vehicles are switched to a second fuel to complete mileage accumulation. The engines are then stripped again to measure deposits once more and calculate the 'clean-up' performance of the second fuel. Tests of this type pose additional challenges as dismantling and reassembling engines can alter their condition and performance, and thereby introduce extra experimental 'noise' that reduces test discrimination.

A further limitation of the existing protocol is that even the use of quads only provides repeat data on two fuels; a single candidate fuel and a single control fuel. Four different fuels could be tested simultaneously but without the ability to generate repeat data.

To overcome these restrictions, Shell GS has enhanced the fleet test protocol further by strengthening the test design, preparation and execution steps. The resultant fourth generation test protocol can now cope with 'clean-up' test programs that require an engine strip and rebuild, and tests in which the performances of more

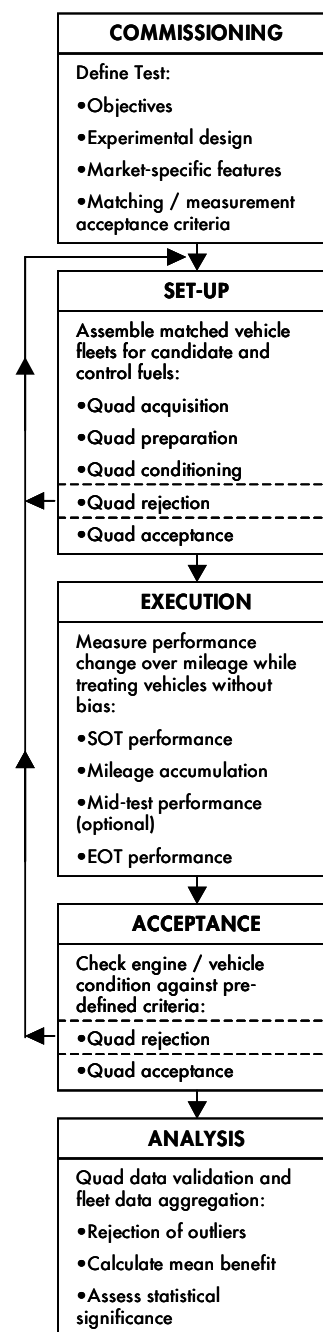


Figure 1: Key features of existing protocol (first and second generation protocols used vehicle pairs rather than quads)

than two fuels are compared. This paper describes the enhancements that we have made and presents an example application of the protocol to the measurement of the ability of gasoline additives to remove pre-existing intake valve deposits in port fuel injected vehicles. In this application, Shell GS has been assisted by staff at Southwest Research Institute who developed detailed engineering procedures to conduct the fleet test according to the new protocol and executed the test.

FOURTH GENERATION TEST PROTOCOL

STRUCTURE

Inherited Features

The latest protocol, illustrated in Figure 2, builds on the previous versions. It retains the key features that earlier work has shown to facilitate the identification of statistically significant fuel benefits, isolated from other influencing factors, under market-realistic conditions. In particular, it retains the innovations introduced during the third revision of the protocol [3]:

- The use of vehicle quads to provide more information on how fuel benefits vary with vehicle type and to reduce vulnerability to the loss of a vehicle from the test through accident, breakdown or rejection because of anomalous behavior.
- The use of improved procedures to ensure that vehicles within a quad are as well matched as possible, both initially and during the course of the test, with the aim of improving test discrimination.

New Features

The latest protocol contains two new features that extend its capability to clean-up test programs and to tests in which the performances of more than two fuels are compared:

First, the test Execution segment has been split into two steps, Dirty-up followed by Clean-up. These are separated by activities in which the engine is stripped and deposits measured, the engine rebuilt and the fuel changed. Extra quad acceptance steps have been introduced to ensure that the vehicles remain well matched after engine rebuild and fuel switch but before the start of the clean-up step.

Second, an option to repeat the complete test Execution segment (Dirty-up step plus Clean-up step) has been included. This is a way to generate repeat data within vehicle models while comparing the performances of up to 4 fuels in quads. This is equivalent to testing an octet of matched vehicles, with pairs running on each of 4 fuels, but only requires the matching of 4 vehicles in each set of models rather than 8. This makes vehicle acquisition and matching much less challenging and more cost-effective.

The key features of the latest protocol are shown in Figure 2 and described below.

COMMISSIONING

As in previous versions of the protocol, the purpose of this element is to define test design, market-specific features, and acceptance criteria for vehicle matching and performance measurement.

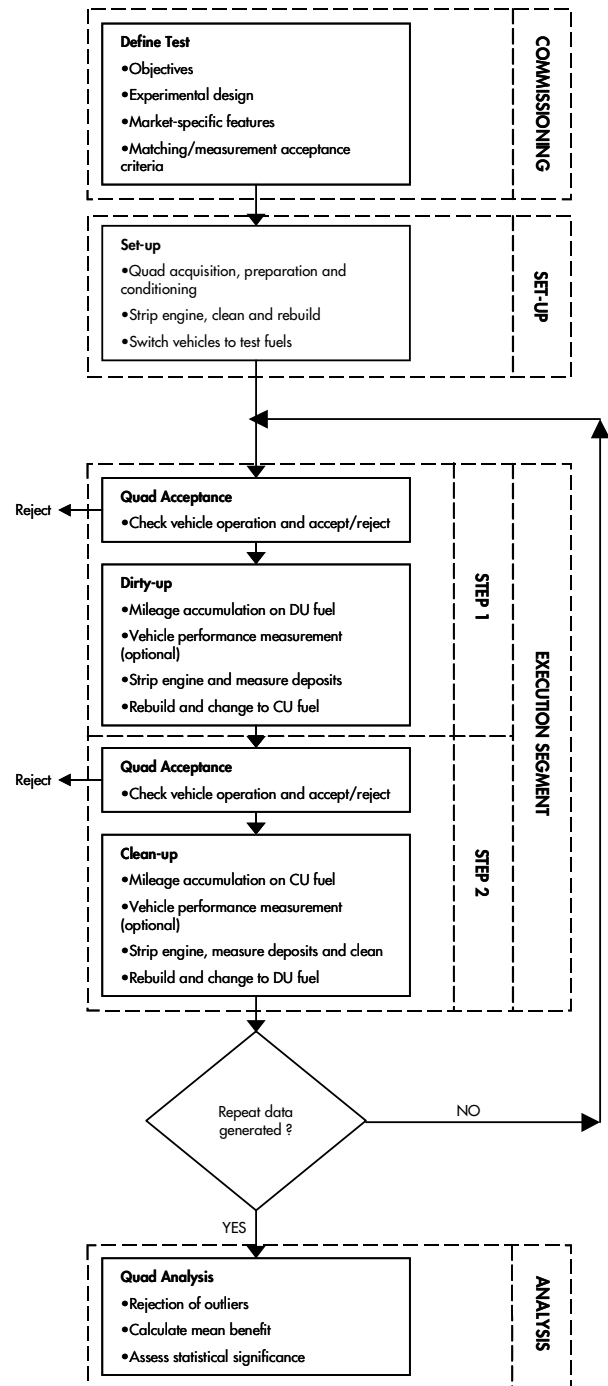


Figure 2: Key features of enhanced protocol

Test Design

The test is designed to isolate fuel effects from other influencing factors by comparing the performance of a candidate fuel with that of a control fuel, using matched vehicle fleets assigned to the fuels randomly and operated in an identical fashion. As in the previous version, the enhanced protocol employs quads of nominally identical vehicles to create 4 matched fleets

which allow multiple test vs. control fuel comparisons to be made without exceeding the capacity of typical vehicle handling and measurement facilities. Even if only one candidate fuel is to be compared with one control fuel, the use of quads (i.e. double pairs) of matched vehicles is recommended as it provides security in the event that a single vehicle is lost from the test through accident or breakdown, or is rejected because of anomalous behavior. Also, for the same total number of cars tested, quads should produce a smaller test standard error and better test discrimination than pairs [3].

To generate repeat data within vehicle models while comparing the performances of up to 4 fuels in the 4 matched fleets, an option has been included to repeat the complete Execution segment (Dirty-up plus Clean-up) using the vehicles for a second time but allocated to fuels in a different random order. This is equivalent to testing an octet of matched vehicles, with pairs running on each of 4 fuels, but only requires the matching of 4 vehicles rather than 8.

The minimum number of quads needed to create the 4 vehicle fleets is determined from previous knowledge of measurement variability and the likely size of the fuel benefit being sought. Fuels are allocated in a statistically unbiased manner to vehicles within each quad; normally the allocated vehicle-fuel pairing varies across the test steps and must vary across test segments.

Market-specific Features

The scope of the test is guided by the selection of market-related boundary conditions. These include the choice of candidate and control fuels, lubricants and oil drain interval, vehicle models and driving pattern, and mileage accumulation distance.

Acceptance Criteria

On the basis of statistical and engineering experience gained in previous fleet tests, quantitative acceptance criteria are defined for the outcome of the vehicle matching and performance measurement activities. These criteria are applied during set-up and at later Quad Acceptance stages to ensure that vehicles within a quad are and remain well matched, and to help identify unusually variable performance measurements. To avoid bias, the criteria are defined before the fleet test gets underway.

SET-UP

The set-up element retains the key function to create 4 fleets of vehicles based on quads that are as well matched as possible in terms of build, physical condition and performance at Start of Test (SoT). The enhanced protocol employs the refined procedures introduced in the previous version to optimize vehicle matching. For completeness, these are described in outline here but full details are presented in [3].

Quad Acquisition

Vehicles are sourced that conform to the model's target specification; model year, build and equipment specification (including engine code and control module calibration, emissions certification group and evaporative emissions designations). To increase the likelihood that engine performance has stabilized to a common level across the quad, while avoiding vehicles that are excessively worn, vehicles are required to have mileages between 5,000 and 20,000 miles, and within $\pm 25\%$ of the average for the quad, and to be no more than 3 years old.

Vehicle performance matching within quads is assessed via coastdown times and power measurements. For all four vehicles, coastdown times from 70 to 30 mph, and static and dynamic power measurements, should fall within $\pm 5\%$ of the mean for the quad.

A vehicle can only progress to the preparation stage of the test if it is one of a matching quad. If the matching criteria are not met, the source of variability is investigated and, if possible, corrective action is taken. If the acceptance criteria cannot be satisfied, the affected vehicle must be returned to the market and a new vehicle sought. To speed up the quad-matching process, it is recommended that 5 vehicles of each model be acquired initially and the best-matched quad selected from these.

Quad Preparation

New fuel injectors are purchased and flow-tested to check that they match. Those that give a flow rate that falls outside the acceptance range (typically $\pm 3\%$ of the mean for the quad) are replaced. Accepted injectors are ranked by flow rate and allocated round the quad, car-by-car, and cylinder-by-cylinder, in a manner that avoids bias.

The vehicles undergo the manufacturer's major service, OEM specification checks and on-board diagnostic (OBD) checks. Simple tailpipe emissions checks (e.g. AFR at idle) are also conducted.

If the quad is still matched at this stage, the as-received cylinder heads are removed and replaced with new, clean cylinder heads that satisfy production specifications and are fitted with new clean valves.

The vehicle fuel tanks are drained and refilled with the appropriate test fuels, as pre-allocated for Test Execution Step 1. Following the fuel change, the engines are flushed with flushing lubricant and test lubricant to remove all traces of the previous motor oils. The vehicles are then charged with the test lubricant, the mass of oil that each vehicle receives being controlled within $\pm 1.5\%$ for all vehicles in a quad.