

Steady-State and Transient Motor Vehicle Exhaust System Temperatures

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ABSTRACT

One of the known causes of motor vehicle fires is hot surface ignition of combustible material that contacts engine exhaust system components. While ignition is a complicated phenomenon, the temperature of the surface is known to be an important parameter. However, little data is available in the literature concerning exhaust system temperatures, and much of this data is confounded by thermocouple attachment techniques and undocumented variations in driving conditions. In the present study, engine exhaust system temperature measurements were conducted using six test vehicles on a level, 2-mile oval test track at constant vehicle speeds ranging from 0 (idle) to 70 mph. By normalizing transient temperature curves with these steady-state temperatures along with ambient temperature, the rates at which the exhaust system components warm up and cool down are also compared. The effect of thermocouple mounting technique was evaluated by conducting identical testing with the thermocouples located at identical locations on the exhaust system but with two different mounting techniques, namely hose clamps and welding.

INTRODUCTION

Over the past 35 years, there have been several studies conducted to evaluate if, and under what conditions, exhaust system components on motor vehicles could ignite combustible materials. As part of a study funded by the Department of Agriculture Forestry Service, Harrison [1, 2] conducted tests on 1974-1975 vehicles to evaluate the risk posed by catalytic converters, which had recently been introduced into the vehicle fleet, to cause wildfires. Using a very similar experimental

approach, Fournier [3] conducted a study intended to evaluate the risk of ignition of engine compartment fluids by exhaust system components. Engle *et al.* [4] examined the effect of fuel type, gasoline or E85, on the exhaust system temperatures of several 2006 and 2007 model year vehicles. However, in each of the studies, the thermocouples were mounted to the exhaust system components using hose clamps. Results from the present study show that this mounting configuration not only leads to artificially low temperature measurements, it can also produce artificial transient temperature response, particularly when the vehicle is suddenly brought to rest and allowed to cool. This effect has also been reported by Fournier and Bayne [5] where they described how data published in a previous study by Fournier [3] was erroneous because of this thermocouple mounting technique.

In addition to the measurement error associated with the use of hose clamps, each of these studies [1-4] was also conducted on public streets and highways. Although each study describes changing vehicle speed to negotiate traffic and/or changes in road grade during the tests, these important parameters were not measured or correlated with the measured temperatures in any of these studies. Because exhaust system temperatures are coupled to vehicle speed and road grade, it is unclear what effect changes in vehicle speed or road grade during these tests may have had on the reported temperatures.

While the studies described above used public streets and highways, Spreen *et al.* [6] used a dynamometer to conduct temperature measurements on and within catalytic converters from six 1998 model year vehicles. Because these data were collected on a dynamometer,

the catalytic converters were not subjected to airflow as the vehicle was being driven.

In this paper, we present exhaust system temperature data that were measured using welded thermocouples while the test vehicles were operated on a 2-mile oval test track. Comparisons are made between the steady-state temperatures of the exhaust manifolds and catalytic converters for all test vehicles and to the dynamometer results of Spreen *et al.* [6]. Next, by normalizing transient temperature curves using steady state and ambient temperatures, the rates at which the exhaust system components warm up and cool down are also compared. Finally, the temperature measurement error associated with hose clamp mounted thermocouples is described.

EXPERIMENTAL SET-UP

The six test vehicles used in the present study consisted of two pickups, two sport utility vehicles and two sedans ranging in model years from 1999 to 2001. A summary of each vehicle, including the body style, engine size, orientation of the engine, engine fuel type, and catalytic converter locations, is shown in Table 1. Vehicle #1 was a pickup powered by a large, V-8 engine that was turbo charged and had a single underbody catalytic converter. Vehicle #2 was also a pickup and was powered by a V-6 engine that had two sequential underbody catalytic

converters. Vehicle #3 was an SUV that was powered by a V-6 engine that had a right and left underbody catalytic converter. After these catalytic converters, the two exhaust systems joined together to form a single tail pipe. Vehicle #4 was an SUV made by the same manufacturer as Vehicle #2 and had a similar, if not identical, engine and exhaust system. Vehicle #5 was a front-wheel-drive, 4-door sedan with a transverse mounted V-6 engine (front of engine on the passenger side). Downstream of the left (forward) exhaust manifold, the exhaust system was routed behind the engine and then tied into the right exhaust manifold. From here, the exhaust from both manifolds flowed into a single pipe to the underside of the vehicle and then through a single underbody catalytic converter. Vehicle #6 was also a front-wheel-drive, 4-door sedan with a transverse mounted engine (front of engine on the passenger side). It was powered by a V-6 engine and had close-coupled catalytic converters just downstream of the exhaust manifolds. The left side manifold and close-coupled catalytic converter were towards the front of the vehicle. The right side close-coupled catalytic converter was positioned just below the right manifold, but was under the body of the vehicle. Downstream of the point where the left and right exhaust systems merged together, there was a single underbody catalytic converter. Each of the test vehicles was in normal operating condition with no check engine or warning lights illuminated.

Table 1. Test Vehicle Summary

Vehicle	Year	Body	Engine Type	Engine Mount	Fuel	Catalytic Converter(s)
1	1999	Pickup	7.3L, V-8 ¹	Longitudinal	Diesel	Underbody
2	2001	Pickup	4.3L, V-6	Longitudinal	Gasoline	Two Underbody
3	1999	Sport Utility	3.2L, V-6	Longitudinal	Gasoline	Left and Right Underbody
4	2000	Sport Utility	4.3L, V-6	Longitudinal	Gasoline	Two Underbody
5	2000	4-dr Sedan	3.4L, V-6	Transverse	Gasoline	Underbody
6	2001	4-dr Sedan	3.0L, V-6	Transverse	Gasoline	Two Close-Coupled ² and One Underbody

1 Turbo
2 The right close-coupled catalytic converter is located on the underside of the vehicle and is referred to as "Right Close-Coupled/Underbody" catalytic converter in all plots.

For each test vehicle, a single thermocouple was welded to each exhaust manifold and catalytic converter. However, the right manifolds of the front-wheel-drive vehicles (Vehicle #5 and Vehicle #6) were in confined spaces between the engine and the bulkhead, which precluded welding thermocouples to these manifolds. Each exhaust manifold thermocouple was welded 1-3 in. (2.5 – 7.6 cm) downstream of where the last (most downstream) cylinder exhaust port tied into the exhaust manifold. Tests with a handheld infrared thermometer indicated that this location was generally one of the hottest locations on the exhaust manifold. The selected measurement locations on both the exhaust manifolds and catalytic converters are not necessarily the hottest points on either component.

Each catalytic converter thermocouple was mounted to the converter surface at the mid-point between the entrance and exit. In some cases, shields for either the exhaust manifolds or catalytic converters were removed so that the thermocouples could be installed. Once installed, the shields were placed back into their original positions. On Vehicle #1, additional thermocouples were mounted on the turbo inlet, housing and exit, along with the surface of the muffler near the inlet location. The engine coolant temperature was also recorded on this vehicle.

At each exhaust system measurement location, the oxide layer on the surface was sanded away and a Type-K thermocouple was welded in place. The temperature of each thermocouple was then captured

with a data acquisition system sampling at a rate of 2 Hz. The vehicle speed was measured with a MicroSAT GPS velocity sensor or a Corrsys-Datron optical fifth wheel and was also sampled at a rate of 2 Hz.

Testing was conducted on a 2-mile oval test track with banked turns. Although the track appears to be level, the measured grade of the track was -0.67% (-6.7 ft. per 1000 ft.) on the slightly downhill straightaway and 0.78% ($+7.8$ ft. per 1000 ft.) on the slightly uphill straightaway, with the banks having sufficient elevation change to make up the difference in elevation. The ambient temperature for all the tests conducted ranged from 26°C to 42°C .

TEST PROCEDURE AND DATA REDUCTION

Using the experimental set-up described above, exhaust system temperatures for each vehicle were recorded as functions of time at constant vehicle speed and during engine warm-up and cool-down. The following sections describe the procedures used to collect and process these data as well as the reproducibility of the reported values.

CONSTANT VEHICLE SPEED TESTING

Typical temperature and speed data as functions of time during the constant speed testing are shown in Figure 1. In these test types, the vehicle is brought up to test speeds ranging from 20 mph to 70 mph in 10 mph increments. At each of these test speeds, the speed is held nominally constant while the vehicle is driven around the track 5-10 laps or 10-20 miles. Although vehicle speed is constant for each speed condition, the slight grade of the track resulted in changes to the exhaust system temperatures. The measured temperatures increased on the slight uphill straightaway until reaching a maximum and then decreased as the vehicle drove along the slight downhill straightaway.

To facilitate comparison of the temperature data as functions of vehicle speed, the temperatures at each measurement location and the vehicle speed were averaged. This averaging was performed over the last three to six laps of each constant speed segment, with the first several laps (two or more) excluded due to possible transient effects. These average temperature values were then plotted as a function of the average vehicle speed as shown in Figure 2. This averaging of measured temperature also compensates, to some extent, for the slight variation in track grade. Also shown in Figure 2 are the exhaust system temperatures at idle. In these tests, the exhaust system temperatures were monitored as the engine warmed up from a cold condition. Once the temperatures had reached nominally constant values, the temperature at each location was averaged over the last several minutes to give the average idle temperature data shown in Figure 2. Although the test results will be described in more detail in the following sections, the left and right manifold

were among the hottest locations along the exhaust system, as was the turbo housing. The turbo inlet and exit were cooler than the manifolds, with the catalytic converter and muffler being the lowest temperature locations measured.

The temperature variations at each location as the vehicle is driven around the track, shown in Figure 1, depended on the measurement location and the vehicle speed. Generally, components closest to the engine, such as the exhaust manifolds, experienced the greatest temperature variation, while the underbody catalytic converters experienced the least. The maximum temperature variations were approximately $\pm 15^{\circ}\text{C}$ relative to the average at the 20 mph test speed and then decreased to less than $\pm 10^{\circ}\text{C}$ at higher speeds.

The speed variation over the three to six laps used to determine the averages was also largest at 20 mph, as the vehicle cruise control could not be used at this speed. For all vehicles tested, the maximum speed variation was approximately ± 5.0 mph relative to the average at the 20 mph test speed and then decreased to less than ± 1 mph at higher test speeds.

To assess the reproducibility of the average temperature versus speed data, tests involving the exhaust manifolds on Vehicle #1 were repeated. The temperature differences between tests, conducted several weeks apart, were less than 6°C at all speeds with the exception of 14°C when at the 70 mph test speed.

TRANSIENT ENGINE WARM-UP AND COOL-DOWN TESTING

A typical vehicle warm-up and cool-down test used to quantify transient effects is shown in Figure 3. For this type of test, the vehicle was started cold and then immediately accelerated up to the test speed, 70 mph in this case. Once the temperatures stabilized, the vehicle was then stopped as quickly as possible and the engine shut off while continuing to monitor the exhaust system temperatures.

While the raw temperature versus time data presented in Figure 3 is useful, the data from different locations along the exhaust system and from different vehicles can more readily be compared by defining a normalized temperature, θ .

$$\theta = \frac{T - T_{\infty}}{T_{ss} - T_{\infty}} \quad (1)$$

where

T = temperature as a function of time

T_{∞} = ambient temperature

T_{ss} = steady-state temperature at the test speed

This normalized temperature is also useful for comparing transient warm-up and cool-down data associated with different vehicle test speeds. Values of θ in equation (1) are those shown in Figure 4 and Figure 5 while the ambient temperature ranged from 26°C to 42°C .

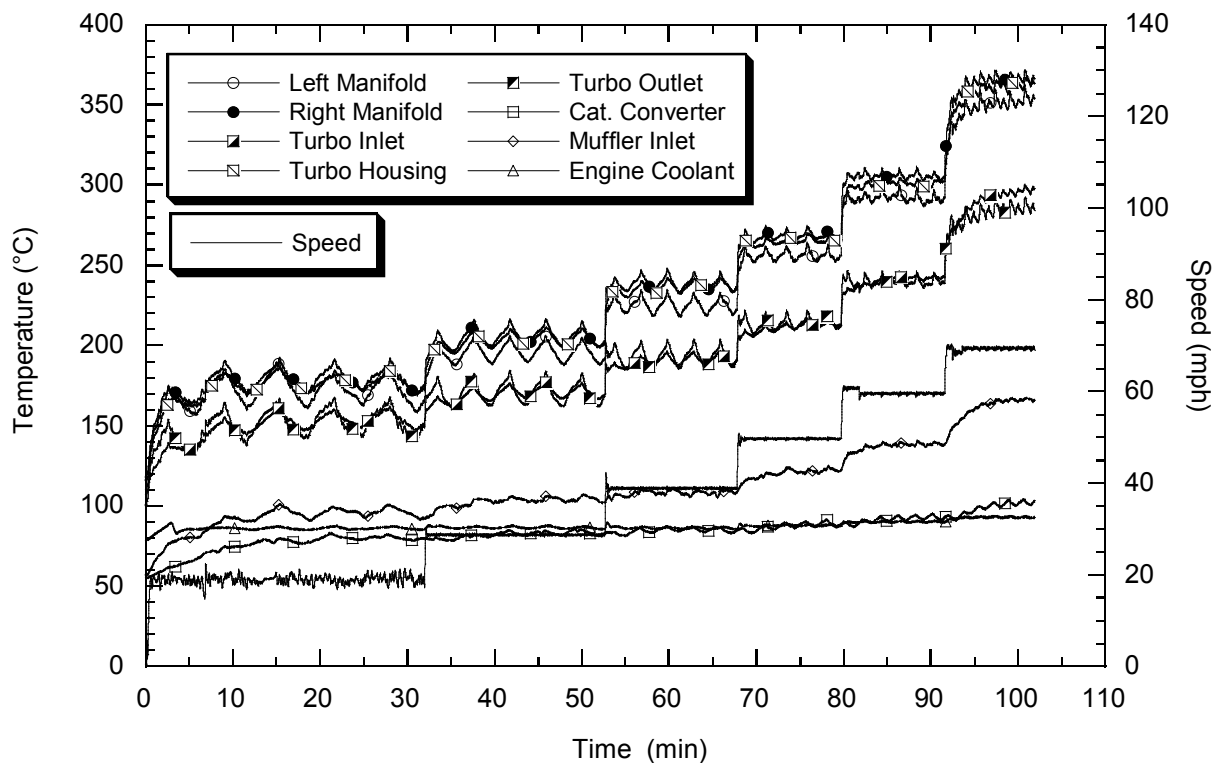


Figure 1. Typical temperature and speed versus time data for Vehicle #1.

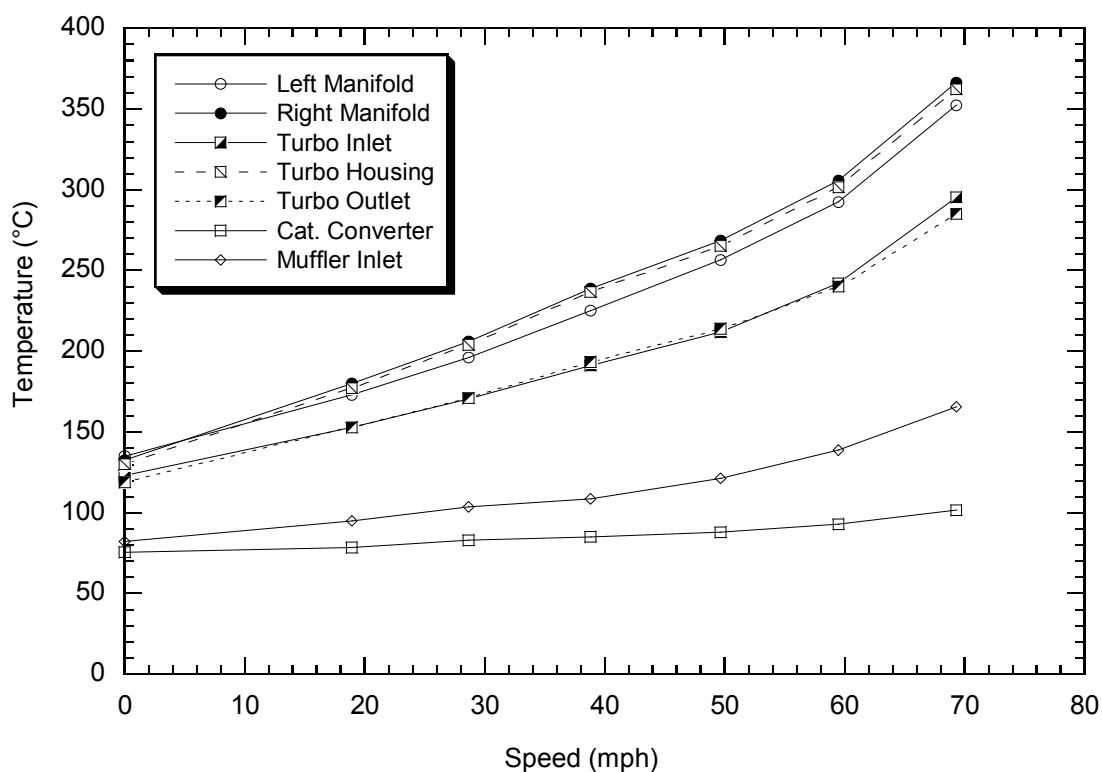


Figure 2. Average temperatures at each measurement location as functions of the average test speed for Vehicle #1.