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ABSTRACT

In previous SAE papers, the initial development and testing of a vacuum-insulated catalytic converter was presented. This paper provides an update of the converter development and an analysis of potential off-cycle emissions savings. Hot vibration, cool-down, and 1975 Federal Test Procedure (FTP-75) emissions test results are provided to demonstrate the effectiveness of design improvements in greatly increasing durability while retaining performance. Using standard drive cycles and "real-world" driving statistics with a vehicle simulator (ADVISOR©), catalyst temperature and vehicle exhaust emissions of a sport utility vehicle (SUV) were predicted for 16 days of driving (107 trips, 770 total miles). Compared to the baseline vehicle with a conventional catalytic converter, the SUV with a vacuum-insulated converter produced 66% less non-methane hydrocarbon (NMHC), 65% less carbon monoxide (CO), and 60% less oxides of nitrogen (NO_x).

INTRODUCTION

In a series of previous SAE papers [1,2,3], the initial design, development, thermal performance, and FTP-75 emissions performance of a vacuum-insulated catalytic converter (VICC) was reported. This converter, now named BENCHMARC®, was originally developed at the National Renewable Energy Laboratory (NREL), a U.S. Department of Energy (DOE) national laboratory, and is currently being commercialized by Benteler Automotive Corporation. It features a thermal management system to maintain the catalyst monolith at or above its lightoff temperature between trips so that most of a vehicle's "cold-start" emissions are avoided. For new vehicles with conventional converters, 60% to 80% of all NMHC and CO emissions occur in the first few minutes of FTP-75 while the converter is warming up [4]. Decreasing these "cold-start" emissions is seen as key to meeting future regulations.

The VICC thermal management system uses vacuum insulation around the monoliths with metal bellows and thin sections of uncoated monolith at the ends to block heat loss by conduction and radiation (see Figure 1). To further boost its heat retention capability, a metal or salt phase-change material (PCM) can be packaged between the monoliths and vacuum insulation. To prevent overheating of the converter during periods of long, heavy engine use, a few grams of metal hydride charged with hydrogen are attached to the hot side of the vacuum insulation. When a critical temperature is reached, the hydride releases about 1/40th of an atmosphere of hydrogen into the vacuum space. Although the resulting pressure is well below that necessary for combustion, this hydrogen increases the effective thermal conductivity of the insulation by more than 100 times, allowing heat to flow out of the converter. As the converter cools below its critical temperature, the hydride reabsorbs the hydrogen. The hydride also acts as an irreversible getter to absorb non-hydrogen gases, maintaining the quality of the vacuum over time. References 5 and 6 provide further details of this variable-conductance vacuum insulation technology.

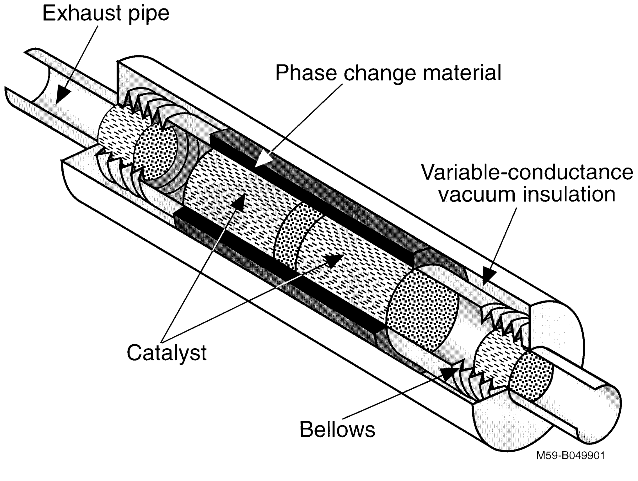


Figure 1. Major features of the vacuum-insulated catalytic converter

Early converter prototypes demonstrated the excellent heat retention capability of this approach, requiring 18 to 24 hours to cool from 600°C to 250°C versus 20 to 30 minutes for conventional converters. FTP-75 cycle testing of a Ford Taurus at Southwest Research Institute (SwRI) showed emission benefits in the range of 80% to 90% for NMHC and CO, and 50% reduction in NO_x for a converter with fully-melted PCM following a 24-hour soak [1].

Although these preliminary results were very encouraging, a number of issues were identified for further development. Two of the primary issues are addressed in this paper: durability and comparison of FTP-75 cycle results with off-cycle or real-world emission benefits.

DURABILITY

BACKGROUND – Automotive catalytic converters are exposed to severe heat, shock, and vibration. At the same time, because of their critical role in emissions control, they have some of the longest warranty periods of any vehicle components. Previous federal regulations specified performance at 50,000 (50K) miles. New standards are increasing that to 100K and 120K miles. As a result, automakers expect converters to pass extreme accelerated durability tests. One of the most severe (especially for the vacuum-insulated converter) is the hot vibration test. Table 1 summarizes the range of test conditions obtained from a number of automakers. Based on this information, a representative set of test conditions was chosen for VICC durability development.

Table 1. Converter Hot Vibration Test Parameters

	Min.	Max.	Selected
Ex. gas temperature (°C)	100	950	800
Ex. gas flow rate (g/s)	20	130	40
Vibration load (g's)	28	60	30
Vibration frequency (Hz)	50	2500	100

INTERNAL SUPPORT OPTIMIZATION – Retaining heat in the converter relies on thermally isolating the interior mass (monolith, inlet/outlet cones, and PCM) from the exterior. Use of thin metal bellows at each end of the interior is critical to reducing heat loss by conduction. Unfortunately, the bellows provide virtually no support of the interior mass. The converter needs structural supports within the vacuum insulation. These supports must be strong enough to withstand the g-forces of the hot vibration test, yet not significantly diminish the system's overall resistance to heat flow. The original supports were simply a set of three wires (2.4 mm in diameter) at each end of the converter running from the interior to the outer shell. This approach had minimal impact on heat flow (<10% increase at 400° C), but exhibited very poor hot vibration durability.

Significant design work was undertaken to develop and optimize a new internal support. Finite-element analysis (FEA) was used extensively to sort through a large number of conceptual designs. This analysis included the temperature distribution along the internal support and the corresponding variation in material properties. The thermal expansion of the inner converter geometry with respect to the outer cylinder was also considered. If not properly addressed, this expansion could contribute more to the overall stress in the internal supports than the vibration load. Through a combination of geometry and materials optimization, an internal support design was developed that has increased hot vibration durability (30 g's at 800°C and 100 Hz) from less than 1 hour to 50 hours, representing approximately 100K miles of typical driving.

IMPACT OF DURABILITY DESIGN CHANGES ON THERMAL AND EMISSIONS PERFORMANCE – Several on-vehicle tests were run to assess the impact of the internal support design changes on the converter thermal and emissions performance. These tests consisted of FTP-75 tests run on a vehicle dynamometer at SwRI as part of a Manufacturers of Emission Controls Assoc. (MECA) study. After testing a stock 1997 Buick LeSabre (3.8 l engine, EPA Tier 1-certified), several changes were made to the vehicle. Most significantly, the standard converter was replaced with a durable VICC. Table 2 shows some of the characteristics of the converter. Also, secondary air injection was added and the stock exhaust manifold was replaced with air-gap-insulated manifolds. The engine also was re-tuned. Full details of this MECA study are available in reference [7].

Table 2. Design Characteristics of VICC

Converter Monolith (each of 2)	
Material	Stainless Steel
Diameter	118 mm
Length	115 mm
Cell Density	78 cells/cm^2
Precious Metal Loading	
Density	5.4 g/l
Overall Dimensions	
Length	580 mm
Diameter	180 mm

To fully melt the PCM, an extended FTP prep cycle consisting of approximately 10 minutes at 65 mph followed by an FTP-75 cycle was used. Figure 2 shows one of the resulting on-car cool-downs. Cool-down time from 600°C to 250°C is 18.8 hours. This is nearly the same as the 19.3 hours achieved with the non-durable prototype reported previously [1]. FTP-75 emission benefits of the new durable converter are also similar to those reported previously for the non-durable prototype, except that even greater NO_x reductions were observed in the most recent study.

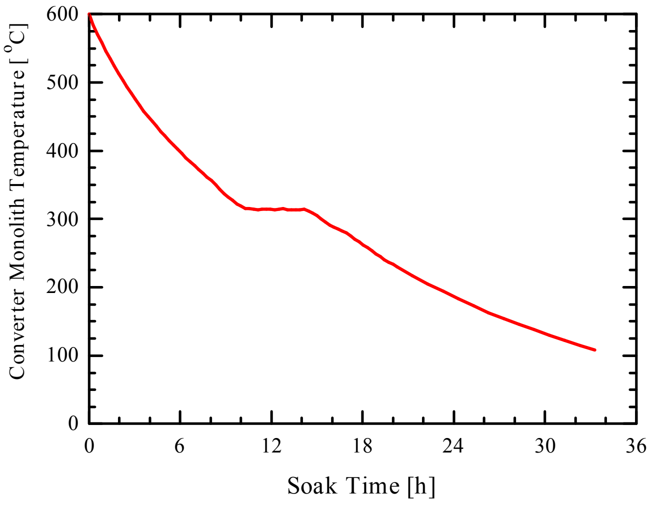


Figure 2. On-vehicle cooldown of VICC

Table 3 shows the NMHC, CO, and NO_x achieved by using the modified vehicle versus the stock. Several tests with the modified vehicle were run using different cold soak periods (6, 16, and 24 hours) and prior to and after full catalyst aging (100 hours, exhaust-in of 820°C). Also included in the table is the weighted average of the different cold-soak cases based on the distribution of cold soaks in real-world driving (see the next section, "Real-World Emission Benefits", and Figure 4). These weighted average emission values approach the recently proposed CARB LEV-II SULEV (Super Low Emission Vehicle) standard, even with the fully-aged catalyst.

Table 3. FTP emission results in g/mi

	NMHC	CO	NOx
Fresh (4000-mi) Catalyst			
Stock vehicle	0.060	0.93	0.138
Modified vehicle			
6-hour soak	0.002	0.083	0.021
16-hour soak	0.022	0.113	0.017
24-hour soak	0.033	0.33	0.027
Weighted average	*0.007*	*0.10*	*0.021*
Fully-aged (100-h) Catalyst			
Modified vehicle			
6-hour soak	0.004	0.17	0.05
16-hour soak	0.039	0.39	0.037
24-hour soak	0.063	0.96	0.048
Weighted average	*0.013*	*0.25*	*0.048*
ULEV Standard (120K miles)	0.055*	2.10	0.070
SULEV standard (120 K mi.)	0.010*	1.00	0.020

*ULEV and SULEV standard use NMOG rather than NMHC

"REAL-WORLD" EMISSIONS BENEFITS

BACKGROUND – From 1990 to 1996, the U.S. EPA conducted a review of the FTP-75 used to evaluate light-duty vehicle emissions and fuel economy [8]. This review included a study of in-use driving habits to compare real-world driving to that represented in the FTP. Some of the differences found, such as higher speeds and accelerations, were incorporated into a supplemental FTP (SFTP) that will be phased into emissions testing over the next several years. Other findings of the study were not incorporated into the SFTP but may be included in the Tier II standards/test procedures due to take effect after 2002. One of these additional findings was that 70% of trips begin with a cold catalytic converter (>1 hour soak), compared to 43% assumed in the FTP-75. Furthermore, the FTP has only two soak periods representedæthe initial soak (prior to Bag 1) of between 12 and 36 hours, and a second soak (prior to Bag 3) of 10 minutes. The EPA study indicates that 58% of all trips start with an intermediate soak, between 10 minutes and 12 hours.

In addition to the large percentage of intermediate cold soaks not being included in the FTP, the test procedure typically uses a short prep cycle: a single Urban Dynamometer Driving Schedule (UDDS). This cycle is only 12 km (7.5 miles) long with an average speed of about 32 km/h (20 mph). For vehicles with conventional catalytic converters, this combination of short, low-speed prep and long cold soak does not directly affect their measured FTP emissions. For the VICC, however, these two FTP features have significant negative effects. Table 4 summarizes the initial catalyst temperature (Tci) and FTP emissions reduction of a durable VICC (similar to the design tested at SwRI and discussed in the Durability section) versus a conventional converter. The slight increase in emissions with a standard prep and a 36-hour prep is due to a small delay in the converter warmup when cool due to its larger thermal mass.

Table 4. Reduction in FTP Emissions of VICC vs Conventional Converter

	Soak (h)	Tci (°C)	HC (g/mi)	CO (g/mi)	NOx (g/mi)
Extended Prep Cycle to Fully Melt PCM					
	12	315	-72%	-75%	-70%
	18	285	-65%	-66%	-63%
	24	204	-28%	-25%	-25%
	36	106	-9%	-7%	-9%
Standard (1 UDDS) Prep Cycle					
	12	212	-30%	-27%	-27%
	18	152	-17%	-13%	-16%
	24	110	-10%	-7%	-9%
	36	61	+4%	+6%	+5%

Because the PCM is not fully melted with a single UDDS prep, the resulting emissions benefits are less than half those obtained with an extended prep sufficient to fully melt the PCM. Improvements to the VICC design have resulted in reduced prep requirements. Currently, a prep of about 12 miles (16 minutes at 45 mph) is needed. Alternatively, the UDDS and SFTP (SC03 and US06) cycles (total of 19 miles) can be used. The question then is: are these extended prep cycles appropriate? A recent study of real-world driving conducted by the California Air Resources Board (CARB) concluded that vehicles in the Los Angeles area traveled an average of 46 miles per day at an average speed of 43 mph. Also, less than 1% of all trips started after a cold soak of more than 24 hours (< 8% are >12 hours) [9]. However, these 46 miles per day were spread over an average of 6.7 trips (and intermediate cold soaks) per day. To use this real-world driving behavior to develop an appropriate alternative FTP prep cycle, a simulation of real-world driving was initiated at NREL.

DEFINITION OF REAL-WORLD DRIVING – The first task in simulating real-world vehicle emissions is to define real-world driving behavior. Several studies have been performed in the past 10 years on this topic, including the 1995 National Personal Transportation Survey (NPTS) [10], the 1992 study performed for the EPA FTP review [8], and the 1996 CARB study [9]. The CARB study was selected for the basis of the present study for two reasonsæit was the most recent, and it also provided a more complete set of applicable driving statistics than the NTPS. These driving statistics include distributions of vehicle speed, acceleration, number of trips per day, distance per trip, and time between trips (cold-soak period).

CONSTRUCTION OF AN EQUIVALENT REAL-WORLD DRIVING CYCLE – The next step in the analysis was to construct a "drive cycle" that captured the key real-world driving behavior distributions. Unlike the recent work by CARB and EPA that resulted in new drive cycles (Unified Cycle and Supplemental FTP), the NREL real-world (RW) cycle developed for VICC evaluation needed to be more extensive and comprehensive. In particular, to get a good representation of the cold soak distribution, which would be key to correctly assessing the performance of the VICC, a large number of trips would be needed in the drive cycle. A total of 107 trips were used. Based on the 6.7 trips per day from the CARB study, this meant that a continuous 16 days of driving would be simulated. Using the trips per day distribution from the CARB study [9], the 107 trips were distributed among the 16 days. Trips per day ranged from 0 to 17, as shown in Figure 3. Similarly, the time between trips (cold-soak period) was distributed among the 107 trips to match the distribution reported by CARB, as shown in Figure 4. Next, definition of the second-by-second vehicle speed for each of these 107 trips needed to be defined. Use of established driving cycles was desired. EPA light-duty cycles (such as UDDS, SC03, and US06) were considered, but these did not offer a sufficient range in certain parameters such as distance per trip.

A more varied set of cycles is available from CARB, known collectively as the Unified Correction Cycles (UCC) [11,12]. Because this set of 15 cycles was developed in conjunction with the CARB real-world study, it inherently captures several of the driving parameters such as acceleration, stops per mile, and percent idle. The set also spans a wide range of miles per trip and average vehicle speed. The 15 cycles are designated by their representative speed, from 5 mph to 75 mph, as shown in Table 5.

Figure 5 shows the vehicle speed versus time for one of the cycles (UCC-35). At the time of this analysis, the highest speed cycle (UCC-75) was still being refined by CARB, so this cycle may change slightly prior to being finalized. Using the distribution of trip distance from the CARB study, the number of each of the UCCs to make up the 107 total trips was determined, as shown in Figure 6. This selection of UCCs also determines the distribution of average trip speed, as shown in Figure 7. Finally, by filling the 107 trip "slots" of the 16-day drive cycle with the selected set of UCCs, the NREL real-world drive cycle (RW cycle) was fully defined.

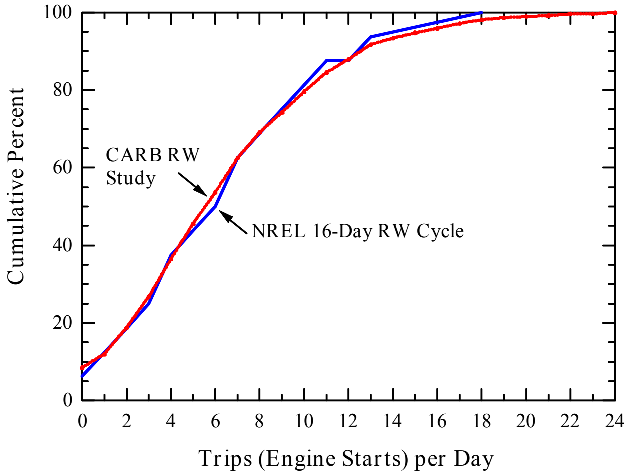


Figure 3. Distribution of trips per day

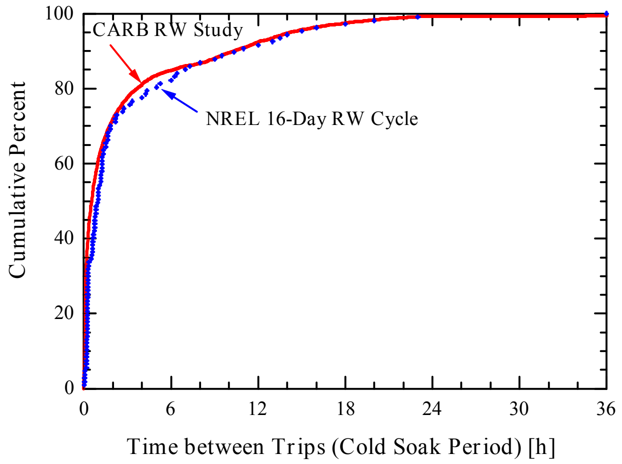


Figure 4. Distribution of soak periods

Table 5. Summary of CARB Unified Correction Cycles

	Mean Speed (mph)	Max Speed (mph)	Max Accel (mph/s)	PKE* (ft/s^2)	Dis-tance (miles)	Stops/ Mile	Idle (%)	Accel (%)
UCC5	2.4	12.9	2.8	1.86	0.1	31.2	60.8	18.0
UCC10	8.0	28.0	4.1	1.74	0.8	8.5	44.5	27.2
UCC15	13.3	36.5	4.6	2.20	1.5	3.84	27.7	40.5
UCC20	17.7	43.8	5.7	1.92	4.1	3.16	16.1	42.3
UCC25	22.9	49.8	5.8	1.72	5.4	2.02	13.2	43.8
UCC30	26.8	59.1	5.4	1.41	7.3	1.36	8.8	45.5
UCC35	31.9	68.7	5.6	1.27	11.9	1.00	7.9	45.7
UCC40	35.6	72.3	5.5	1.11	13.1	0.68	5.6	47.1
UCC45	44.6	71.4	5.7	1.06	16.1	0.43	3.7	45.7
UCC50	43.2	71.6	5.8	0.73	26.1	0.31	6.6	47.5
UCC55	47.4	71.1	5.6	0.66	30.3	0.23	4.7	44.8
UCC60	53.8	70.7	5.9	0.74	41.7	0.19	3.7	43.4
UCC65	57.3	81.4	5.8	0.58	61.2	0.13	3.5	44.9
UCC70	59.1	83.0	6.1	0.71	59.7	0.10	2.0	46.5
UCC75	67.65	88.7	5.9	0.67	91.1	0.07	2.0	49.9

*PKE = Positive kinetic energy

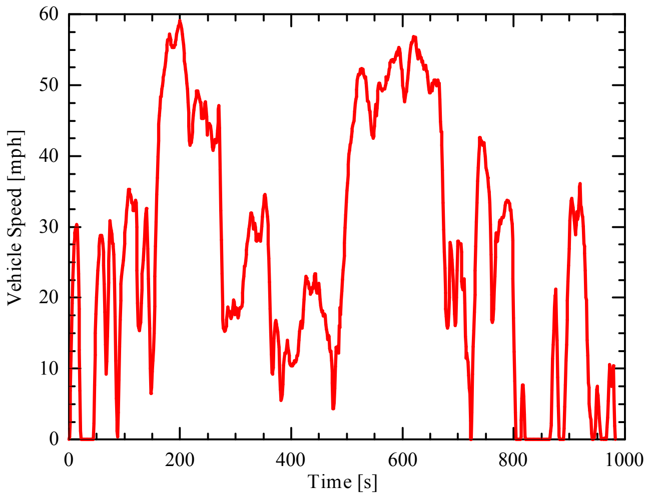


Figure 5. Speed trace for UCC-35

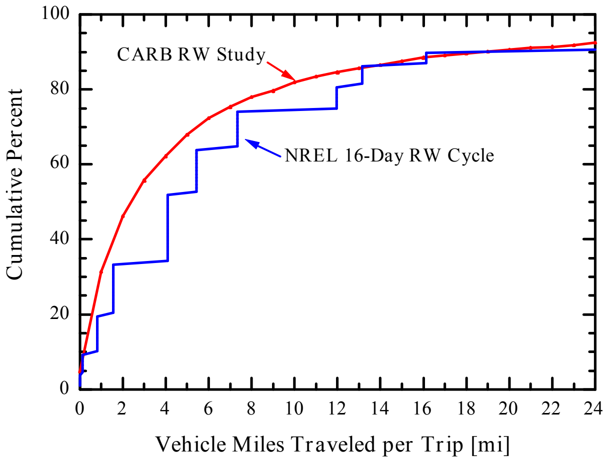


Figure 6. Distribution of trip distance

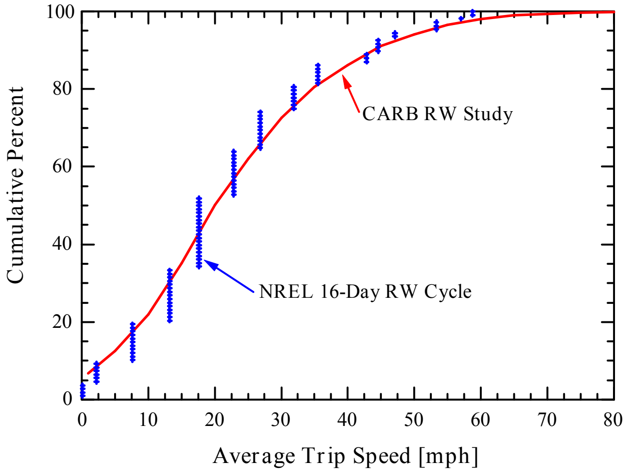
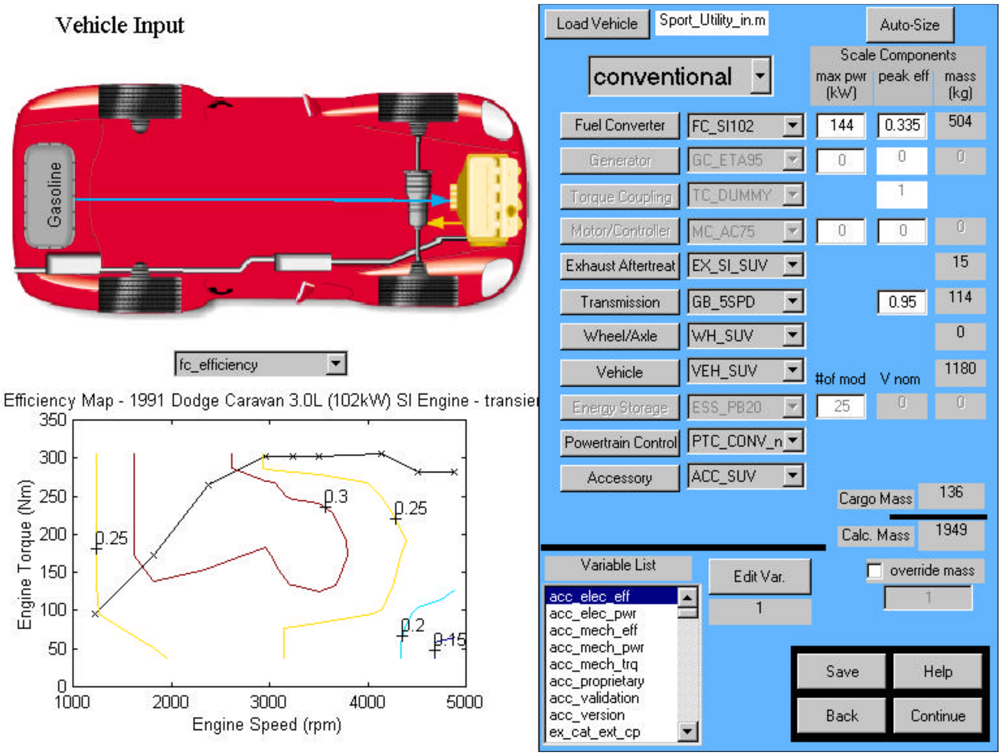


Figure 7. Distribution of average trip speed

VEHICLE SIMULATION VIA ADVISOR© – After the RW cycle was defined, an appropriate tool was selected to simulate the emissions of a vehicle driven on this cycle. Several vehicle emissions simulation tools have been developed. A tool developed at NREL was selected for its familiarity and ease in modification. This tool, known as ADVISOR© (Advanced Vehicle Simulator) was developed for the DOE in 1994 primarily for evaluation of hybrid electric vehicles. However, conventional vehicles as well as pure electric vehicles can also be simulated. A user defines the vehicle from a set of input files that include the mass, aerodynamic drag and frontal area, rolling resistance, engine type, transmission type, and catalytic converter type (see Figure 8).



Sport_Utility_in.m

conventional

		max pwr (kW)	peak eff	mass (kg)
Fuel Converter	FC_SI102	144	0.335	504
Generator	GC_ETA95	0	0	0
Torque Coupling	TC_DUMMY		1	
Motor/Controller	MC_AC75	0	0	0
Exhaust Aftertreat	EX_SI_SUV			15
Transmission	GB_5SPD		0.95	114
Wheel/Axle	WH_SUV			0
Vehicle	VEH_SUV			1180
Energy Storage	ESS_PB20	#of mod 25	V nom 0	0
Powertrain Control	PTC_CONV_n			
Accessory	ACC_SUV			

Cargo Mass 136

Calc. Mass 1949

Edit Var. 1

override mass 1

acc_elec_eff
acc_elec_pwr
acc_mech_eff
acc_mech_pwr
acc_mech_trq
acc_proprietary
acc_validation
acc_version
ex_cat_ext_cp

Figure 8. Sample vehicle-definition screen from ADVISOR©

The model uses measured performance maps for characterizing the major components. For the engine, hot-stabilized engine performance maps (fuel use and emissions versus torque and speed) are used, with empirical correction factors applied during the engine warm-up period. Since modern gasoline spark-ignited (SI) engines are controlled to operate very near their stoichiometric air/fuel ratio, the catalyst performance is primarily a function of catalyst temperature, with an upper "breakthrough" limit in g/s for each pollutant.

After specifying the vehicle characteristics, ADVISOR© requires second-by-second definition of vehicle speed. In this analysis, the 16-day, 107-trip RW cycle was used. Simulation outputs include second-by-second and cumulative fuel use and emissions. ADVISOR© was built using MATLAB/Simulink©, a dynamic system modeling environment. In addition to being used by the DOE, ADVISOR© is used or being evaluated by more than 60 companies, universities, and other organizations. It is freely distributed by NREL and can be downloaded from the Web site provided in the CONTACT section of this paper. Further details including general model validation are available in references [13,14].

Because of their rising popularity and a concern for their contribution to air pollution, a sport utility vehicle (SUV) was selected as the vehicle type for this analysis. A "typical" mid-sized SUV was defined by taking the average characteristics of three U.S.-produced 1998 SUVs (Ford Explorer, Jeep Grand Cherokee, and Chevy Blazer). The following are some of the characteristics obtained from published data of these three representative SUVs [15]:

Weight: 1817 kg curb weight + 136 kg cargo
Wheelbase: 2.75 m, % weight on front axle: 56%
$C_D = 0.44$, Frontal Area = 2.5 m^2
Engine: 144 kW (193 hp) gasoline SI
EPA fuel economy: 17 mpg combined city/highway

EXHAUST SYSTEM ENHANCEMENT AND VALIDATION OF ADVISOR© – The thermal modeling of the exhaust system in ADVISOR© was enhanced for this analysis. Instead of being a simple function of time, the catalyst temperature was predicted via a lumped-capacitance approach. Based on second-by-second fuel use during the drive cycle, the exhaust gas flow rate and engine-out temperature were calculated. The exhaust gas then lost heat to the exhaust manifold and downpipe prior to reaching the converter. The converter was modeled via a four-node lumped capacitance model: (1) monoliths, (2) inner steel shell (and PCM for VICC), (3) outer shell, (4) inlet/outlet pipes. Heat exchange from the gas to the converter nodes, between converter nodes, and from the converter to the ambient was modeled via appropriate conduction, convection, and radiation equations. Within the converter, the heat of catalysis is estimated based on the g/s of each emission component (HC, CO, and NO_x) being catalyzed [16]. This heat adds to the rate of converter warmup. Within the inner steel shell (converter node #2), the model included the capability to specify the amount and type (melting point and transformation enthalpy) of phase change heat storage material. By varying these PCM and thermal conduction parameters, both conventional and vacuum-insulated converters could be modeled.

Figures 9 and 10 show a comparison of data with the modified ADVISOR© model predictions of a conventional converter and VICC monolith temperature versus time during a 20°C ambient cold-soak period. Similarly, Figure 11 shows the exhaust gas, monolith, and PCM temperatures of a VICC during a step change in engine load, and Figure 12 shows the inlet exhaust gas temperature in the conventional converter during a standard FTP. These enhancements have been added to ADVISOR©, starting with version 2.02.

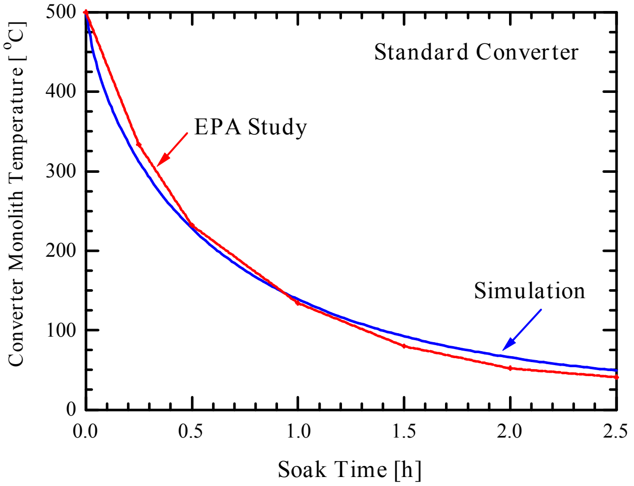


Figure 9. Cooldown of standard converter

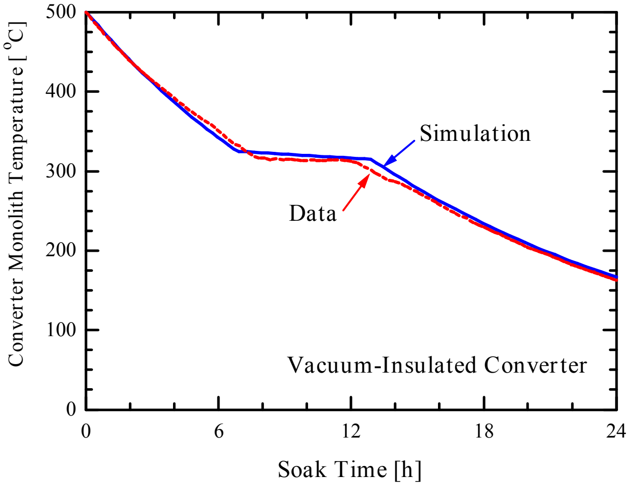


Figure 10. Cooldown of vacuum-insulated converter

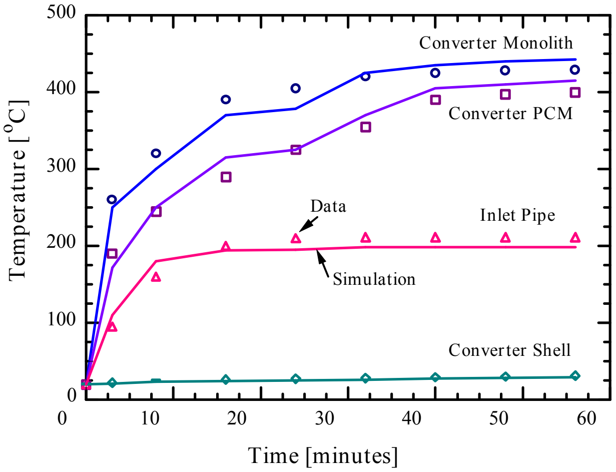


Figure 11. Converter warmup (model vs. data)

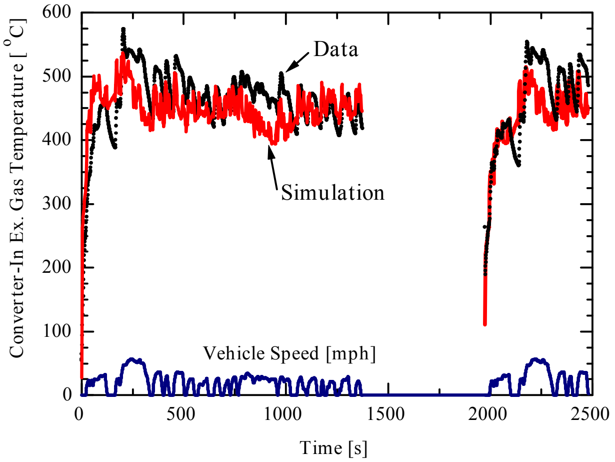


Figure 12. FTP inlet gas temperature (model vs data)

SIMULATION RESULTS – After the ADVISOR© model was enhanced and validated, a series of simulations was run. On a PC (300 MHz Pentium II®, 128MB RAM), each simulation of an SUV driving the 16-day, 107-trip RW cycle took approximately 1 hour. Figures 13 and 14 show the standard converter and VICC monolith temperatures versus time for the entire RW cycle. As one would expect, the VICC stays much warmer. There are also fewer rapid changes in temperature, which may lead to enhanced converter durability.

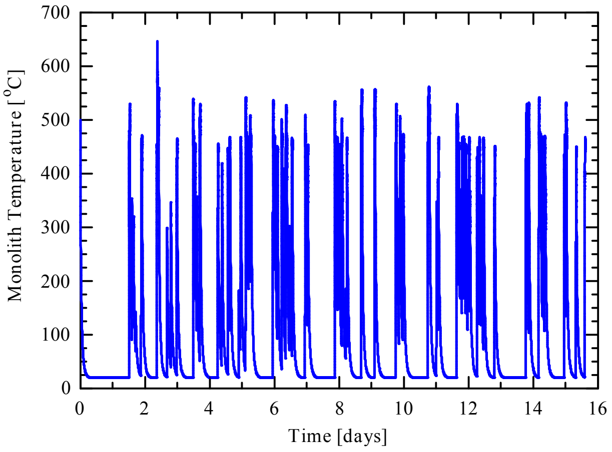


Figure 13. Standard converter temperature

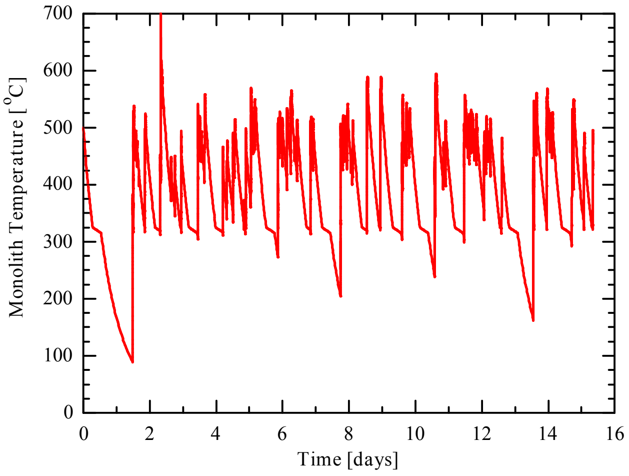


Figure 14. VICC converter temperature

Most important to emissions is the catalyst temperature at the beginning of each trip. Figure 15 is a plot showing this initial temperature for the conventional converter and VICC for each of the 107 trips. Note that even the conventional converter has a fair number of hot or warm starts due to the occurrence of short cold soaks in real-world driving. However, the average initial VICC temperature is 407°C, versus 151°C for the conventional converter.

By considering the FTP a two-trip cycle and weighting the converter temperature at the start of Bag 1 versus Bag 3 by the 0.43/0.57 factor adopted by EPA, an average trip-start converter temperature of 188°C can be estimated for this vehicle on the FTP with a conventional converter. This value is independent of the cold soak chosen (12 to 36 hours), and would also not be affected by an extended prep cycle. In a similar manner, the average trip start temperature can be calculated for the vehicle running the FTP with a VICC. In this case, however, both the cold-soak length and the prep cycle affect this temperature. As Table 6 shows, the conventional converter RW-cycle trip start average temperature is slightly lower than the FTP cycle average trip temperature. However, the average trip start temperature for the VICC is significantly higher than the FTP temperature with a standard prep even for the minimum 12-hour cold soak. With the extended soak, the trip start temperature is between the 12- and 18-hour soak.

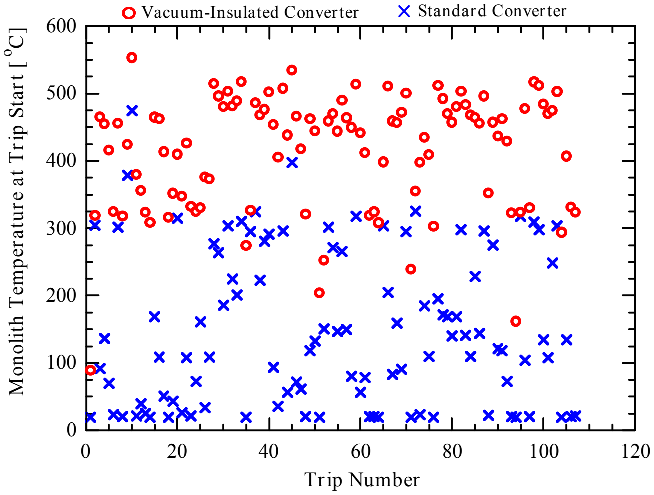


Figure 15. Converter temperatures at trip starts

Table 6. Ave. Converter Temperature at Start of Trip

Standard Converter	
"Real-World" drive cycle	151°C
FTP with std. or ext. prep, 12 to 36-h soak	188°C
VICC converter	
"Real-World" drive cycle	407°C
FTP with *standard* prep -- 12-h soak	351°C
18-h soak	325°C
24-h soak	304°C
36-h soak	283°C
FTP with *extended* prep -- 12-h soak	411°C
18-h soak	390°C
24-h soak	348°C
36-h soak	302°C

Another way of evaluating the appropriate FTP prep cycle for VICC is to compare the percent emission reduction of the converter on the RW cycle versus the FTP cycle. Figures 16 through 18 show the grams of NMHC, CO, and NO_x emissions for the two converters for each of the RW cycle trips.

Over the entire RW cycle, the VICC converter reduced emissions by: 66% for NMHC, 65% for CO, and 60% for NOx. Comparing these values with the percent reductions for the FTP cycle (Table 4), it can again be seen that the FTP with the current single UDDS prep cycle greatly underestimates the real-world emissions reduction potential of the VICC. The percent reductions from the RW cycle are comparable to the FTP with an extended prep cycle and a cold soak near 18 hours. Alternatively, a shorter prep (but longer than a single UDDS) could be used in conjunction with a cold soak around 12 hours and yield comparable representative emissions reductions.

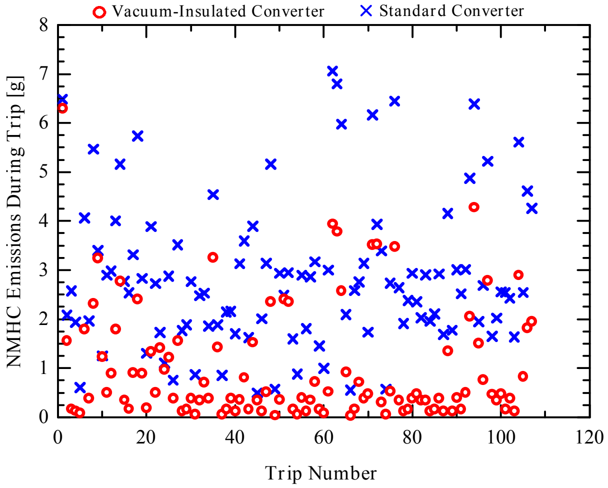


Figure 16. NMHC emissions for each trip

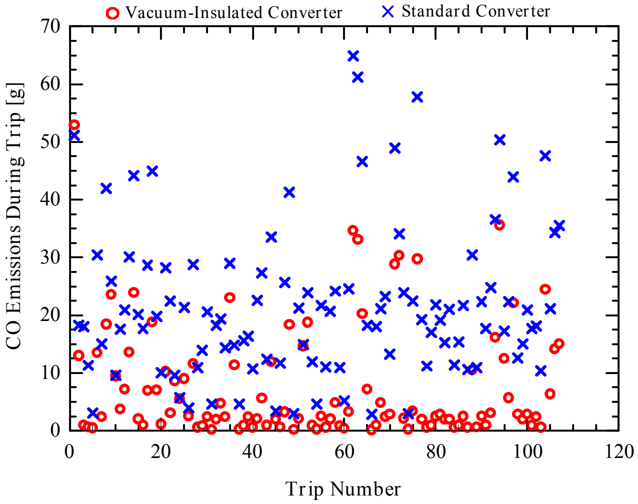


Figure 17. CO emissions for each trip

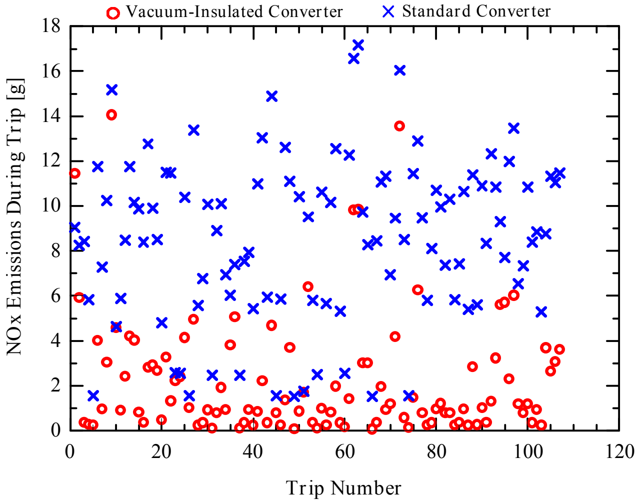


Figure 18. NOx emissions for each trip

CONCLUSION

Since the publication of the last SAE paper in 1996, significant progress has been made in the development and optimization of the BENCHMARC® vacuum-insulated catalytic converter (VICC). Changes to the internal supports have resulted in converters that can endure 50+ hours of hot vibration testing at 850°C. Furthermore, these durability improvements have been made while retaining the excellent thermal and emissions-reduction performance achieved in previous non-durable prototypes. One example of this is the achievement of emissions that approached the SULEV standard on a Buick LeSabre recently tested at SwRI.

To represent the full emissions reduction potential of this technology, the FTP prep cycle must be extended to be more representative of real-world driving. To demonstrate this, a 16-day, 107-trip drive cycle was created that represented many driving characteristics from a recent CARB real-world driving study. Using an enhanced version of NREL's ADVISOR© vehicle simulation model, the VICC was shown to provide a significantly higher average converter temperature at the start of trips (407°C vs 151°C) and a resulting significant decrease in emissions (66% lower NMHC, 65% lower CO, and 60% lower NO_x). This would indicate that changes to the prep cycle and/or cold-soak period would be applicable for FTP and future emission test procedures when testing a vehicle with this type of a catalytic converter thermal management system.

Additional optimization of the converter will lead to further reductions in the time required to fully melt the phase change heat storage material. Fleet studies are also planned to demonstrate the on-car durability on the converter. Further simulation is planned to investigate a variety of effects such as close-coupling VICC to the engine manifold, influence of ambient temperature, and comparison of real-world cycle results to new test standards/procedures (SFTP, Tier II, and LEV II).

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