

# Modal-Based Intermediate Soak-Time Emissions Modeling

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A comprehensive modal emissions model for light-duty cars and trucks is being developed under the sponsorship of NCHRP Project 25-11. Model development has been described previously for vehicles operating under hot-stabilized conditions. A modal emissions model is presented for vehicles operated under *incremental soak-time* conditions. The Federal Test Procedure (FTP) measures vehicle emissions after a 24-h soak time during Bag 1 testing and vehicle emissions after a 10-min soak time during Bag 3 testing. Vehicle incremental soak-time emissions refer to vehicle emissions after intermediate variable soak times of between 10 min and 24 h. Recent research shows that most on-road vehicles experience soak times of between 10 min and 24 h during daily driving; thus, there is strong desire to model vehicle emissions under such circumstances. An intermediate soak emission model has been developed on the basis of second-by-second emissions measurements generated at the College of Engineering Center for Environmental Research and Technology, University of California–Riverside vehicle testing facility by using the FTP Bag 1 and Bag 3 test cycles. The modeling results are based on a composite vehicle concept in which more than 300 tested vehicles are composited into two dozen vehicle technology groups. The modeling approach is a fuel-based physical modal emissions model in which vehicles' fuel use, engine-out emissions, air/fuel equivalence ratio, catalyst efficiencies, and tailpipe emissions are modeled individually as a function of variable soak time. Since the developed model is based on modeled vehicle fuel consumption under any given driving cycle, it not only is capable of predicting vehicle emissions under variable soak time for any given test cycle but also is capable of predicting emissions under different starting test cycles.

The College of Engineering Center for Environmental Research and Technology (CE-CERT) at the University of California–Riverside is developing a comprehensive modal emissions model for light-duty vehicles under sponsorship of NCHRP [NCHRP Project 25-11, (1–5)]. The overall objective of this project is to develop and validate a modal emissions model that accurately reflects the impacts of speed, engine load, and start conditions on exhaust emissions under a comprehensive variety of driving characteristics and vehicle technologies. In this project, approximately 300 in-use vehicles have been recruited and tested on a single-roll 1.22-m (48-in.) dynamometer over three different driving cycles: (a) the Federal Test Procedure [FTP (6)], (b) the high-speed US06 cycle (7), and (c) a specially designed modal emission cycle [MEC01, which is described elsewhere (1)]. For each of these cycles, second-by-second engine-out and tailpipe carbon dioxide (CO<sub>2</sub>), oxygen (O<sub>2</sub>), carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), and hydrocarbon (HC) emissions data are being collected. On the basis of these measured emissions data, a modal emissions model is being developed to estimate vehicle emissions under several operating modes:

(a) The *cold start* period, that is, the first few minutes after the vehicle is started;

(b) *Stoichiometric operation*, the predominant mode of operation when the vehicle's air/fuel ratio is at the proper stoichiometric ratio;

(c) *Enrichment events*, that is, when excessive load conditions are placed on the engine (e.g., during sharp accelerations and steep grades) and the air/fuel ratio is commanded rich; and

(d) *Enleanment events*, which typically occur with sharp deceleration or load reduction events, during which time the air/fuel ratio is lean and incomplete combustion or misfire occurs.

Details of this model development have been described elsewhere (1–5); however, this paper focuses on modeling of emissions under *incremental soak-time* conditions and what impacts different cold-start test cycles have on the catalyst light-off time and overall emissions.

FTP Bag 1 measures vehicle emissions after a 24-h or longer soak time, and FTP Bag 3 measures vehicle emissions after a 10-min soak time. Recent research shows that most on-road vehicles experience soak times of between 10-min and 24-h during daily driving (8–10). The Environmental Protection Agency (EPA) has examined the causes of postsoak emissions with data from the EPA Soak/Start Test program and a preliminary program called the Albany Cooldown Study that gathered real-world engine and catalyst cooldown profiles. The data from these programs indicated that increased emissions following intermediate soaks arise in three ways: rapid catalyst cooldown following key off, slow catalyst thermal recovery following a restart, and manufacturer calibration strategies in response to the start-up condition. In the most updated EMFAC7G model, the California Air Resources Board (CARB) has included vehicle emissions under variable soak time (11). Thus, there is a strong interest from regulatory agencies and environmental groups to fully understand vehicle emissions under variable intermediate soak times.

EPA has also developed a new Soak Control Cycle (SC01) that is to be used to control emissions after intermediate soaks. Initial idles and start driving are addressed in SC01 by incorporating the EPA Start Cycle (ST01) in its entirety. The balance of SC01 is composed of two microtrips of moderate driving selected from the in-use survey database. EPA considers the SC01 cycle preferable because it has speeds and power levels that are more representative of in-use start driving behavior (7). CARB has also introduced a different cold-start cycle, the LA92 Bag 1 cycle, to simulate vehicle cold-start driving under a contemporary California driving environment (12). Whether these new starting cycles can or should be eventually included in legislation is beyond the scope of this paper. Nevertheless, it shows that there is a demand for modeling of vehicle cold-start emissions under variable starting cycles.

In this paper, preliminary analysis and modeling of vehicle emissions under cold-start conditions are presented. In the past, EPA and Systems Applications International have developed a fuel-based cold-start emissions model on the basis of extensive regression analysis (13,14). The present analysis and modeling are based on measured data from CE-CERT's NCHRP testing program. To assist with model development, the emissions traces of composite vehicles are used. The

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composite vehicle emissions traces are constructed on the basis of 24 vehicle technology groups, as defined in a previous paper (1).

This paper first presents a Bag 1-type cold-start model. The Bag 1-type cold-start model calculates vehicle emissions after a complete engine cooldown or a vehicle soak time longer than 24 h. Then the soak time variable  $t_{\text{soak}}$  is introduced to modify the developed Bag 1 cold-start model. The developed model does not make any assumptions about the ambient temperature. The temperature is always assumed to be at FTP temperature to start.

## BAG 1-TYPE COLD-START MODEL

The FTP Bag 1-type cold-start model calculates vehicle emissions after a complete engine cooldown or a vehicle soak time longer than 24 h. As discussed in previous papers, the fuel-rate module serves as a key function for the modal emissions model, since both engine-out emissions and catalyst efficiencies are directly linked to a vehicle's fuel consumption.

### Fuel Rate Module

Modeling of the fuel rate in any driving cycle for any vehicle has been described elsewhere (2,3). With the possibility of a rich mixture, this model can be expressed as follows:

$$FR(t) = \phi(t) \cdot \left[ k(t) \cdot N(t) \cdot V + \frac{P(t)}{\eta} \right] \cdot \frac{1}{44} \quad \text{for } P(t) > 0 \quad (1)$$

where

$FR(t)$  = fuel use rate (g/s),

$P(t)$  = engine power output (kW),

$k(t)$  = engine friction factor [kJ/(rev · liter)],

$N(t)$  = engine speed (revolutions per second),

$V$  = engine displacement,

$\eta \approx 0.4$  and is a measure of indicated efficiency,

44 kJ/g = lower heating value of a typical gasoline, and

$\phi(t)$  = fuel/air equivalence ratio.

For vehicle model years in the 1980s and 1990s, a satisfactory approximation is

$$k(t) \approx k_0 \cdot \left\{ 1 + [N(t) - 33]^2 \cdot 10^{-4} \right\} \quad (2a)$$

$$k_{\text{idle}} \approx 1.5 \cdot k_0 \quad (2b)$$

where  $k_{\text{idle}}$  is the engine friction factor during engine idling, and  $k(t)$  represents the fuel energy used to overcome engine friction per engine revolution and unit of engine displacement. For cars manufactured in the early to mid-1990s,  $k_0$  ranges from 0.20 to 0.25 kJ/(revolutions · liter).

### Fuel/Air Equivalence Ratio Module

Estimation of the fuel/air equivalence ratio is another key component of the model. The estimation under hot-stabilized conditions has been discussed previously (2). During a cold start, the engines of most vehicles operate with a rich fuel mixture. The following equations are introduced to address this phenomenon:

$$\phi(t) = \left[ 1 + (\phi_{\text{cold}} - 1) \cdot \left( \frac{T_{\text{cl}} - T_{\text{su}}(t)}{T_{\text{cl}}} \right) \right] \cdot \phi_{\text{hot}} \quad \text{if } T_{\text{su}}(t) < T_{\text{cl}} \quad (3a)$$

$$\phi(t) = \phi_{\text{hot}} \quad \text{if } T_{\text{su}}(t) \geq T_{\text{cl}} \quad (3b)$$

where

$\phi_{\text{hot}}$  = hot-stabilized fuel/air equivalence ratio,

$\phi_{\text{cold}}$  = maximum value of fuel/air equivalence ratio at the start of a cold start,

$T_{\text{su}}$  = a surrogate temperature defined as

$$T_{\text{su}}(t) = \sum_{j=1}^t FR(j) \quad (4)$$

$T_{\text{cl}}$  = cold-start surrogate threshold temperature when the engine reaches closed-loop control, and

$FR(j)$  = calculated fuel rate at the  $j$ th second.

If it is assumed that the real temperature is proportional to the cumulative fuel consumption, then the surrogate temperature is a good surrogate variable to represent the real temperature. Figure 1 illustrates example modeling results between surrogate temperature  $T_{\text{su}}$  and cold start time  $t$ .

Equations 3 and 4 state that the fuel/air mixture will be richest during the initial second and will gradually decrease to reach closed-loop control after the surrogate closed-loop temperature  $T_{\text{cl}}$  is achieved, as illustrated in Figure 2.

### Engine-Out Emissions Module

Under hot-stabilized operation, CO engine-out emission is a function of both the fuel rate and the fuel/air equivalence ratio. HC and NOx engine-out emissions are approximately linear functions of fuel rate and thus do not directly depend on fuel/air equivalence ratio (since fuel rate depends on fuel/air ratio, their dependence on the fuel/air ratio is secondary).

Under cold-start conditions, the initially excessive engine-out CO emissions can be directly explained by cold-start enriched fuel/air equivalence ratio. HC and NOx emissions, however, are not directly related to the fuel/air ratio and enriched fuel consumption alone is not strong enough to explain the excessive initial emissions; therefore, cold-start engine-out emissions multipliers have been introduced for HC and NOx emissions. The cold-start engine-out HC and NOx emissions multipliers are independent of the degree of enrichment and need to be determined on the basis of vehicle emissions measurements.

On the basis of a detailed analysis of the data, cold-start engine-out emissions are modeled by introducing the following parameters: (a) cold-start fuel/air enrichment equivalence ratio,  $\phi_{\text{cold}}$ ; (b) cold-start surrogate threshold temperature to reach close-loop operation,  $T_{\text{cl}}$ ; (c) cold-start engine-out HC emission index multiplier,  $CS_{\text{HC}}$ ; and (d) cold-start engine-out NOx emission index multiplier,  $CS_{\text{NOx}}$ .

The first two parameters,  $\phi_{\text{cold}}$  and  $T_{\text{cl}}$ , determine the enrichment fuel/air equivalence ratio during cold-start on the basis of Equation 1, and the cold-start engine-out CO emissions have the same form used in modeling of the hot-stabilized operation:

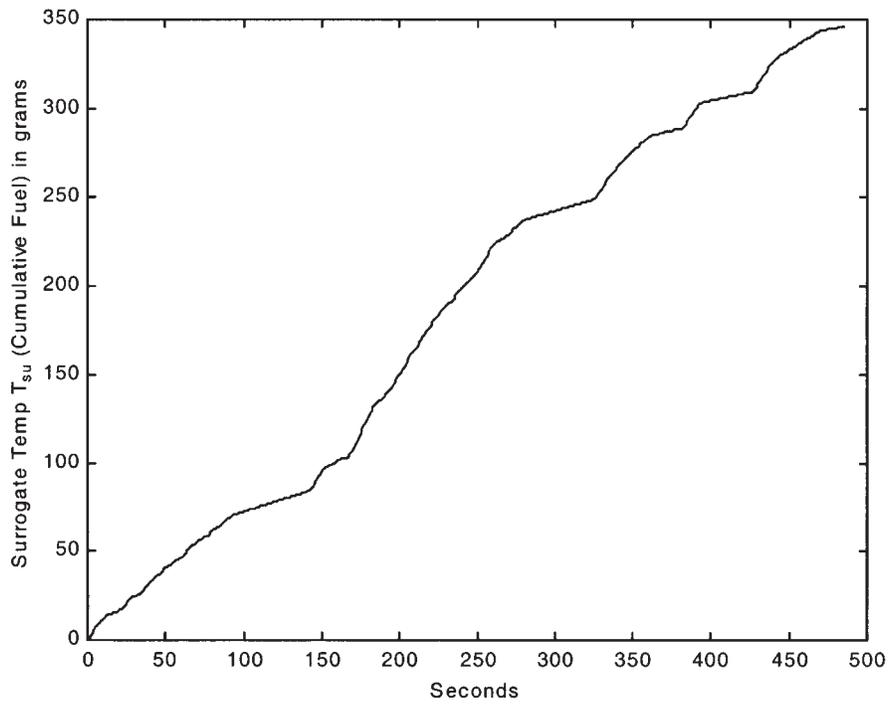
$$ECO_{\text{cold}} = \left[ C_0 \cdot (1 - \phi_{\text{cold}}(t)^{-1}) + a_{\text{CO}} \right] \cdot FR(t) \quad (5)$$

where

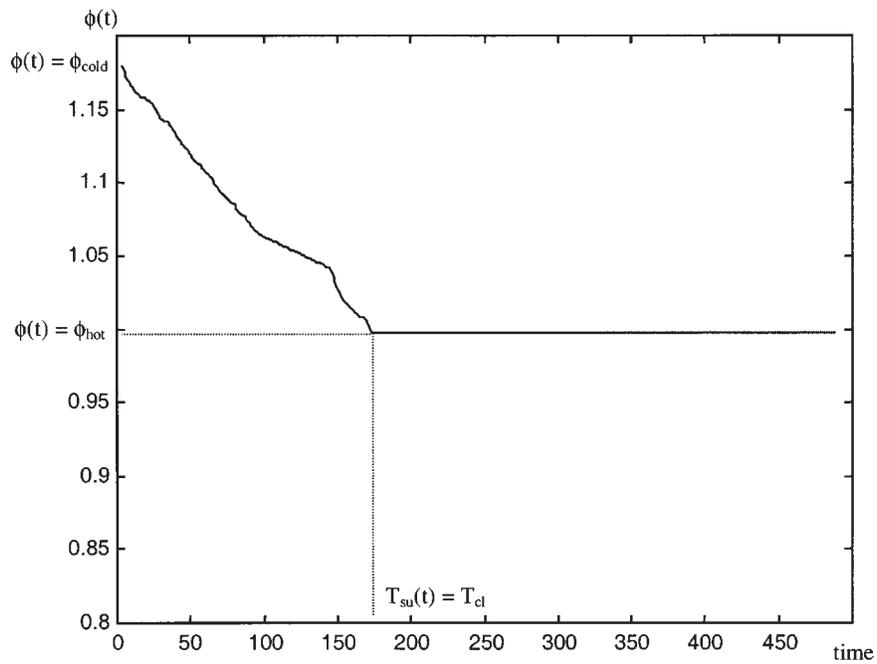
$ECO_{\text{cold}}$  = engine-out emission rate (g/s),

$C_0$  = enrichment coefficient (about 3.6 for most cars), and

$a_{\text{CO}}$  = CO emission index coefficient [emissions (g/s) divided by fuel use (g/s)].



**FIGURE 1** Example modeling results illustrating relationship between surrogate temperature  $T_{su}$  and cold-start time  $t$ .



**FIGURE 2** Example modeling results illustrating relationship between fuel/air equivalence ratio  $\phi$  and cold-start time  $t$ .

The first term of in Equation 5 represents enrichment-related processes. The second term represents a stoichiometric combustion process.

The cold-start engine-out HC and NOx emissions ( $EHC_{cold}$  and  $ENOX_{cold}$ ) are estimated as follows:

$$EHC_{cold}(t) = \left[ 1 + (CS_{HC} - 1) \cdot \frac{T_{cl} - T_{su}(t)}{T_{cl}} \right] \cdot EHC(t) \quad \text{if } T_{su}(t) < T_{cl}$$

$$ENOX_{cold}(t) = \left[ 1 + (CS_{NOx} - 1) \cdot \frac{T_{cl} - T_{su}(t)}{T_{cl}} \right] \cdot ENOX(t) \quad \text{if } T_{su}(t) < T_{cl} \quad (6)$$

$$EHC_{cold}(t) = EHC(t), ENOX_{cold}(t) = ENOX(t) \quad \text{if } T_{su}(t) \geq T_{cl}$$

where

- $T_{su}(t)$  = surrogate temperature defined by Equation 6,
- $EHC$  and  $ENOX$  = hot-stabilized engine-out HC and NOx emissions, respectively, and
- $T_{cl}$  = definition given for Equation 3.

Example modeling results based on Equation 6 are illustrated in Figure 3.

### Catalyst Efficiency Module

Under the hot-stabilized operation, catalyst efficiency is modeled only as a function of fuel rate and fuel/air equivalence ratio. During cold start, catalyst efficiency is also a function of time. It increases gradually as the catalyst warms up. In the following, surrogate temperature is used to approximate the temperature effects of catalyst efficiency during cold start.

The cold-start catalyst efficiency ( $Cat\_Eff$ ) can be estimated as a function of the vehicle's cumulative fuel use:

$$Cat\_Eff_i(t) = \frac{\Gamma_i}{1 + 20 \cdot e^{-T_{su}(t)/\beta_i}} \quad (7)$$

where

- $i$  = CO, HC, and NOx;
- $\Gamma_i$  = maximum hot-stabilized catalyst efficiency;
- $T_{su}$  = surrogate temperature based on cumulative fuel consumption (defined by Equation 2); and
- $\beta_i$  = a cold-start catalyst coefficient for each pollutant.

The number 20 in the equation is just an empirical number that is not sensitive to the final results, as long as it is larger than 10. The modeled cold-start catalyst efficiency increases with cumulative fuel use as an S curve, matching the measured cold-start catalyst profile fairly well. Equation 5 does not rely on any specific cold-start cycle and requires only one parameter ( $\beta_i$ ) for each pollutant, which can be determined via a calibration process based on measurement data. Example modeling results based on Equation 7 are illustrated in Figure 4.

### Modeling Results

In summary, the Bag 1-type cold-start emission model relies on the following cold-start parameters:  $\phi_{cold}$  [cold start maximum fuel/air equivalence ratio (Equation 1)],  $T_{cl}$  [surrogate temperature or accumulative fuel use to reach engine stoichiometric operation (Equation 3)],  $CS_{HC}$  (cold-start engine-out HC emission multiplier (Equation 6)),  $CS_{NO}$  [cold-start engine-out NOx emission multiplier (Equation 6)],

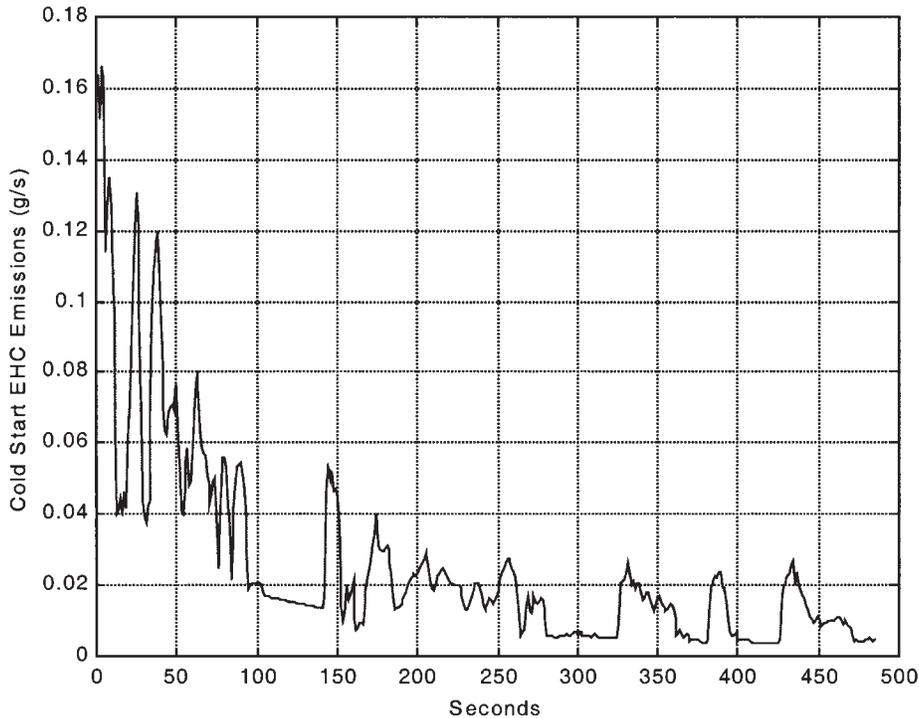


FIGURE 3 Example modeling results illustrating the relationship between engine-out HC emissions and cold-start time.

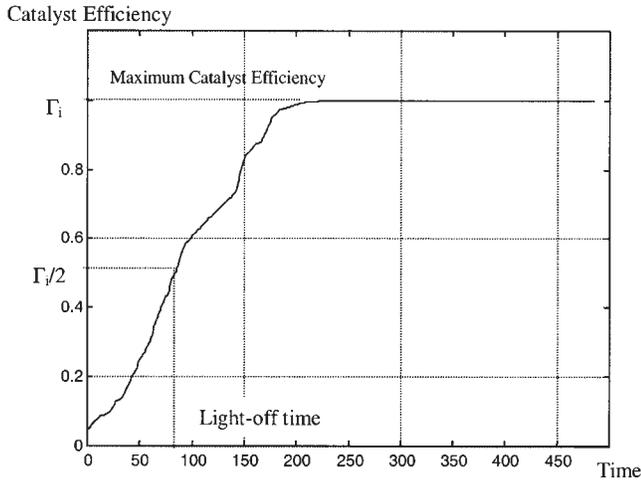


FIGURE 4 Example modeling results illustrating the relationship between catalyst efficiency and cold-start time.

and  $\beta_{CO}$ ,  $\beta_{HC}$ , and  $\beta_{NOx}$  [cold-start catalyst coefficients for CO, HC, and NOx, respectively (Equation 7)].

As an example, Figures 5(a), 5(b), 5(c), and 5(d) show a comparison of the modeled and measured results for a composite vehicle for the FTP Bag 1 cycle [this is category 10, a particular Tier 1 composite car (J)]. In each plot, the solid line represents the modeled results and the dashed line represents the measurement results. Numbers to the right of the plot give average gram-per-mile values for the measured and modeled emissions. Figure 5(a) presents the cold-start catalyst CO, HC, and NOx efficiencies versus time in the FTP Bag 1 cycle for the composite vehicle. Figure 5(b) presents the cold-start engine-out and tailpipe CO emissions versus time in the FTP Bag 1 cycle. Figure 5(c) presents the cold-start engine-out and tailpipe HC emissions versus time in the FTP Bag 1 cycle. Figure 5(d) presents the cold-start engine-out and tailpipe NOx emissions versus time in the FTP Bag 1 cycle.

## INTERMEDIATE SOAK-TIME EMISSIONS MODEL

The previous discussion of cold-start emissions modeling is based only on the FTP Bag 1-type test conditions. To handle variable soak times, it was found to be useful to introduce adjusted surrogate temperature  $\Delta T_i$  for each pollutant as a function of soak time:

$$T_{su_j}(t_{soak}, t) = T_{su}(\infty, t) + \Delta T_i(t_{soak}) \quad (8)$$

$$\Delta T_i(t_{soak}) = e^{-t_{soak}/C_{soak_j}} \cdot T_{cl} \quad (9)$$

where

$i$  = CO, HC, and NOx, respectively;

$t_{soak}$  = soak time for modeled vehicles,

$C_{soak_j}$  = calibrated soak-time coefficient for each pollutant,

$T_{su}(\infty, t)$  = surrogate temperature during Bag 1-type cold start defined by Equation 4, and

$\infty$  = soak time equal to or larger than 24 hrs.

The relationship between  $\Delta T_i$  and soak time  $t_{soak}$  is illustrated in Figure 6.

Thus, when  $t_{soak}$  goes to 0, corresponding to hot-stabilized operation,  $\Delta T_i$  tends to  $T_{cl}$ , meaning that the surrogate temperature  $T_{su}$  starts with the threshold warm-up temperature  $T_{cl}$ . When  $t_{soak}$  becomes very large, say,  $t_{soak}$  is equal to 24 h,  $\Delta T_i$  tends to 0. When  $t_{soak}$  is between 0 and 24 h,  $\Delta T_i$  is between  $T_{cl}$  and 0; this is the case for the FTP Bag 3 operational condition, in which  $t_{soak}$  is equal to 10/60, which is equal to 0.167 h.

Thus, in the soak-time emission module,  $T_{su}(t_{soak}, t)$  defined by Equation 8 is used to replace  $T_{su}(t)$  defined by Equation 4 to model soak-time fuel/air equivalence ratio and engine-out emissions. The soak-time catalyst efficiencies need to be treated slightly differently and will be introduced later.

## Intermediate-Soak-Time Fuel/Air Equivalence Ratio

The intermediate-soak-time cold-start fuel/air equivalence ratio can be modified by  $T_{su}(t_{soak}, t)$  on the basis of Equation 1, as follows:

$$\phi(t, t_{soak}) = \left[ 1 + (\phi_{cold} - 1) \cdot \left( \frac{T_{cl} - T_{su}(t_{soak}, t)}{T_{cl}} \right) \right] \cdot \phi_{hot} \quad (10)$$

Thus, the severity of the cold-start fuel/air equivalence ratio  $\phi$  is a function of soak time  $t_{soak}$ . The shorter the  $t_{soak}$ , the less rich the fuel/air equivalence ratio at the initial seconds.

## Intermediate-Soak-Time-Cold-Start Engine-Out Emissions

Intermediate-soak-time-cold-start engine-out emissions can be modified on the basis of  $T_{su}(t_{soak}, t)$  and Equation 6, as follows:

$$EHC_{cold}(t_{soak}, t) = \left[ 1 + (CS_{HC} - 1) \cdot \frac{T_{cl} - T_{su}(t_{soak}, t)}{T_{cl}} \right] \cdot EHC(t) \quad (11)$$

$$ENO_{cold}(t_{soak}, t) = \left[ 1 + (CS_{NO} - 1) \cdot \frac{T_{cl} - T_{su}(t_{soak}, t)}{T_{cl}} \right] \cdot ENO(t) \quad (12)$$

These equations establish a relationship in which engine-out emissions are functions of soak time as well. The shorter the  $t_{soak}$ , the lower the engine-out emissions during the initial seconds.

## Intermediate-Soak-Time-Cold-Start Catalyst Efficiency

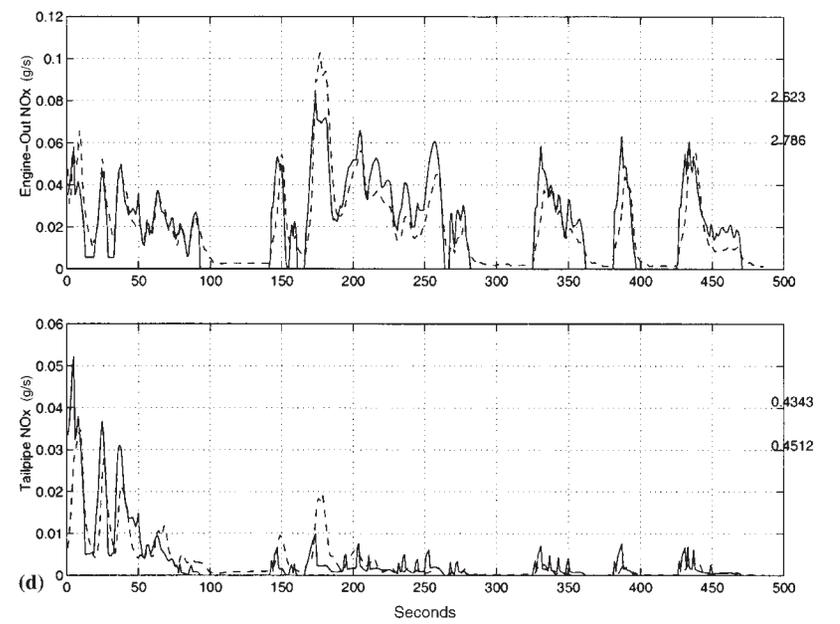
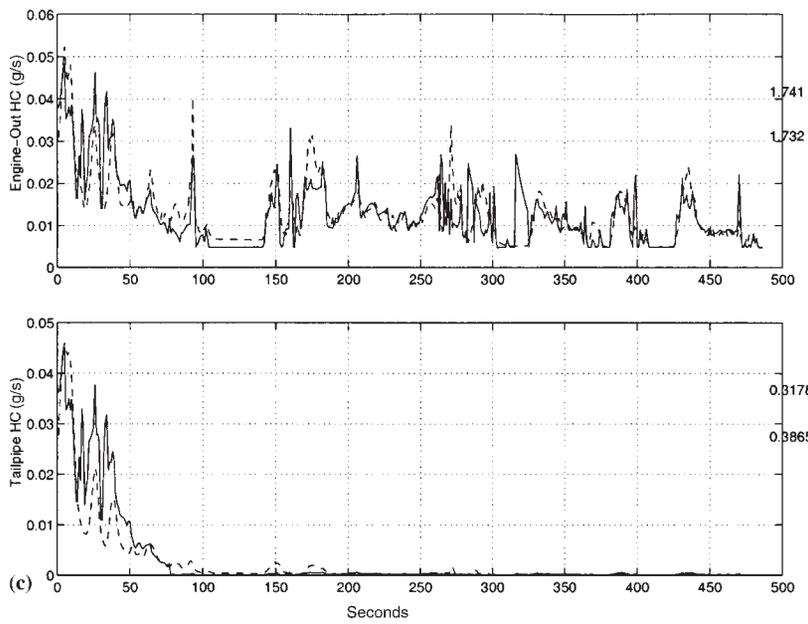
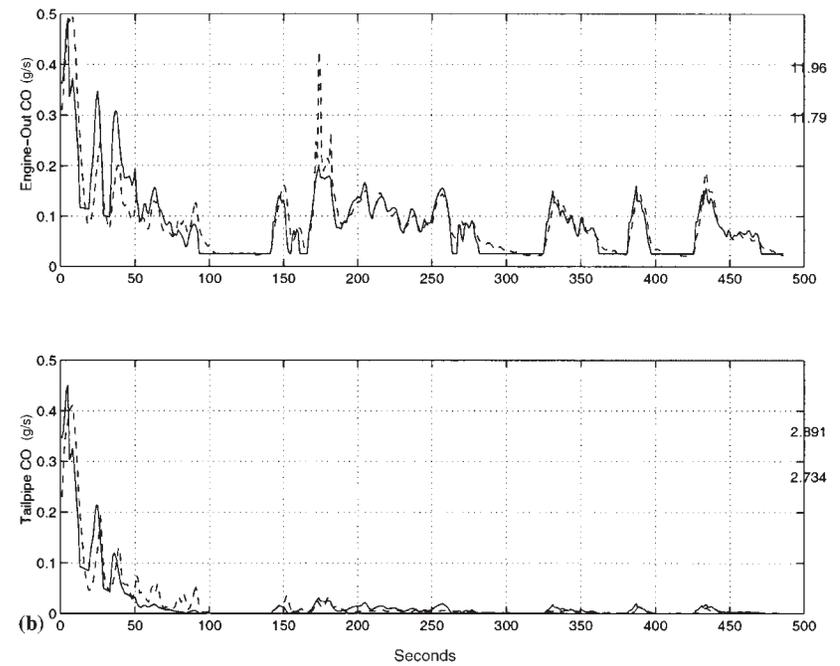
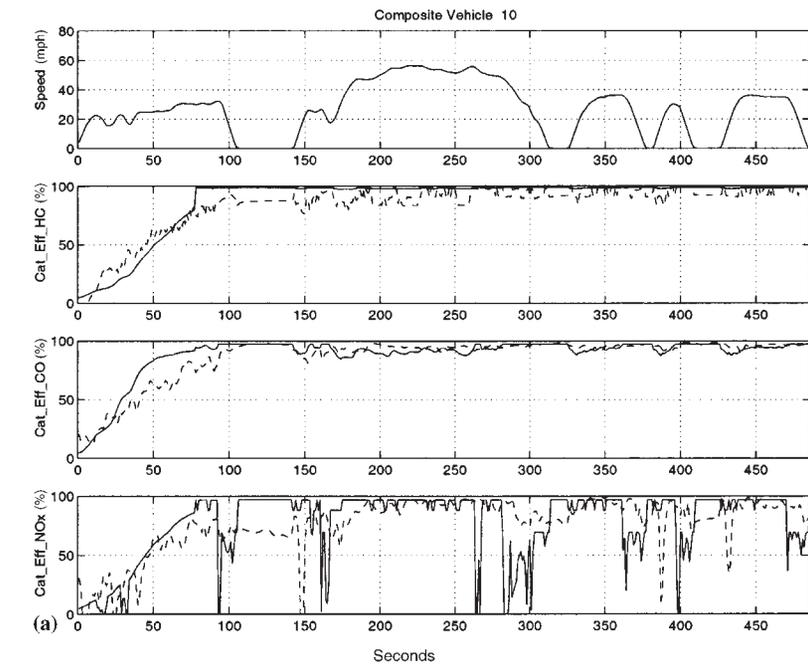
The intermediate-soak-time catalyst efficiencies need to be modified differently. The reason is that the catalyst cooldown rate differs from the engine's cooldown rate and thus needs to be adjusted differently. Here an adjustment for catalyst surrogate temperature is introduced as follows:

$$\Delta T_{cat}(t_{soak}) = e^{-t_{soak}/\alpha_{soak_j}} \cdot T_{cl} \quad (13)$$

where  $\alpha_{soak_j}$  is a calibrated soak-time coefficient for a catalyst (CO, HC, or NOx). Equation 13 has behavior similar to that of Equation 9.

Thus, the intermediate-soak-time catalyst efficiencies can be modeled on the basis of Equations 7 and 13 as follows:

$$Cat\_Eff_i(t_{soak}, t) = \frac{\Gamma_i}{1 + 20 \cdot e^{-[T_{su}(t) + \Delta T_{cat}(t_{soak})]/\beta_i}} \quad (14)$$



**FIGURE 5** (a) Cold-start catalyst efficiency versus time in FTP Bag 1 cycle, Composite Vehicle 10. (b) Cold-start engine-out and tailpipe CO emissions versus time in FTP Bag 1 cycle, Composite Vehicle 10. (c) Cold-start engine-out and tailpipe HC emissions versus time in FTP Bag 1 cycle, Composite Vehicle 10. (d) Cold-start engine-out and tailpipe NOx emissions versus time in FTP Bag 1 cycle, Composite Vehicle 10.

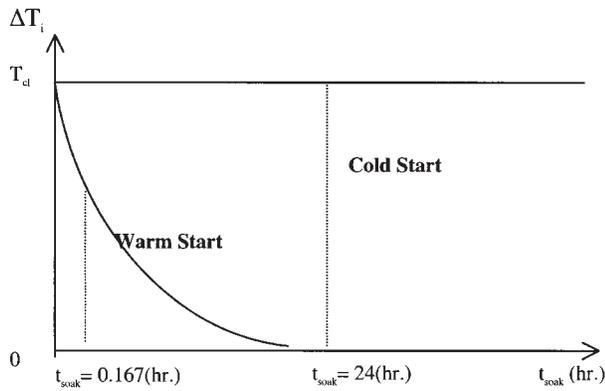


FIGURE 6 Relationship between incremental soak time factor  $R_{soak}$  and soak time  $t_{soak}$ .

where  $\Gamma_i$  is the maximum hot-stabilized catalyst efficiency for each pollutant. This equation says that the initial catalyst efficiency (when  $T_{su}$  is equal to 0) is a function of  $t_{soak}$ . For example, when  $t_{soak}$  approaches 0,  $Cat\_Eff(t_{soak}, 0)$  approaches  $\Gamma_i$ , which corresponds to a fully warmed up situation. When  $t_{soak}$  approaches  $\infty$ ,  $Cat\_Eff(t_{soak}, 0)$  approaches 0, which corresponds to an FTP Bag 1 cold-start condi-

tion. When  $t_{soak}$  is between 0 and  $\infty$ ,  $Cat\_Eff(t_{soak}, 0)$  is equal to  $\Gamma_i / (1 + 20 \cdot e^{-\Delta T_{cat}(t_{soak})/\beta_i}) > 0$ .

**Calibration Procedure to Determine  $C_{soak}$**

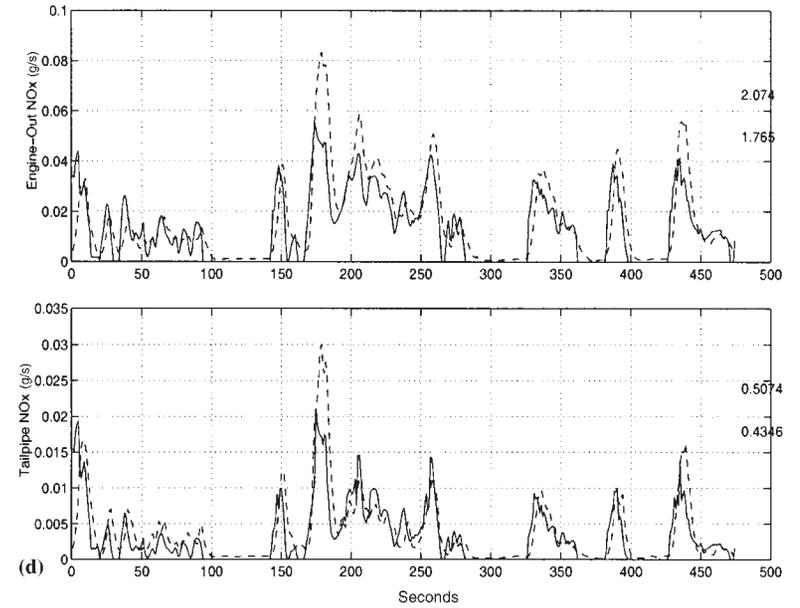
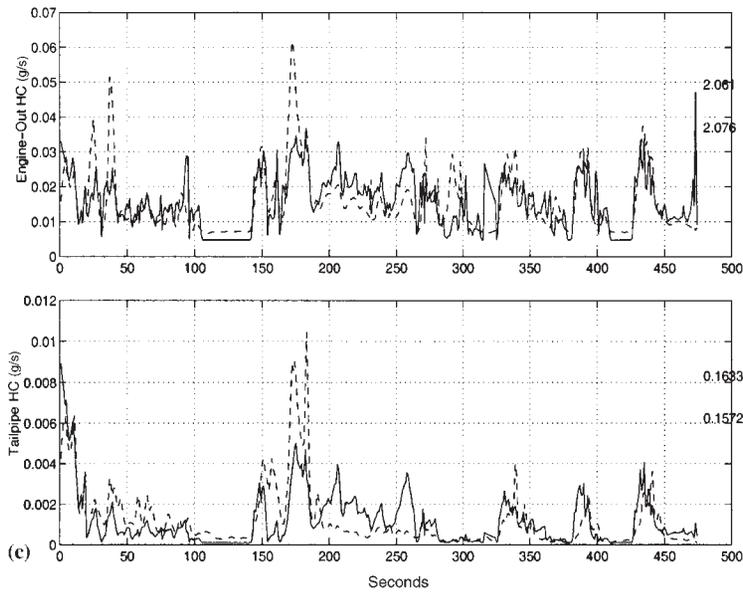
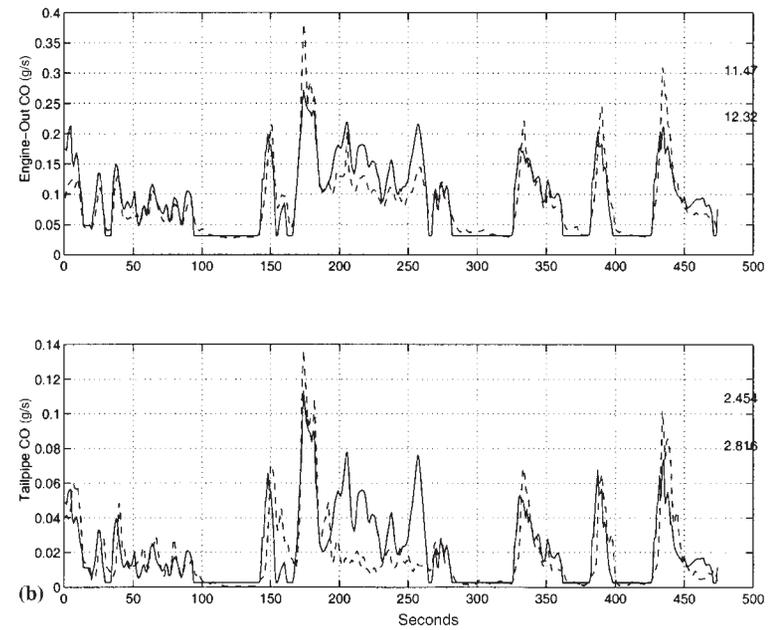
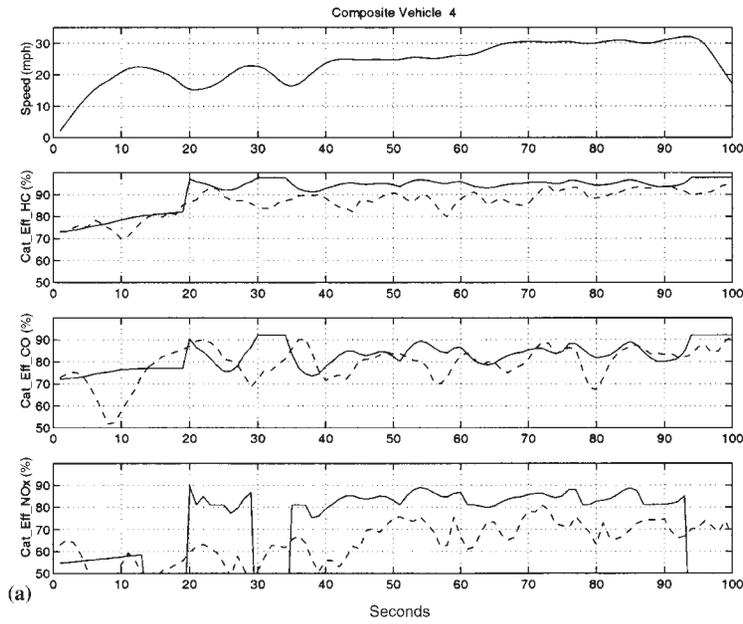
$C_{soak_j}$  of Equation 9 can be calibrated by matching measured and modeled FTP Bag 3 engine-out emissions for each pollutant, in which  $T_{soak}$  equal to 10/60, which is equal to 0.167 h, is used.  $\alpha_{soak_j}$  of Equation 13 can be calibrated by matching measured and modeled tailpipe CO, HC, and NOx emissions, respectively. Thus, to incorporate the intermediate-soak-time emissions into the model, six additional parameters,  $C_{soak\_co}$ ,  $C_{soak\_hc}$ , and  $C_{soak\_no}$  and  $\alpha_{soak\_co}$ ,  $\alpha_{soak\_hc}$ , and  $\alpha_{soak\_no}$ , are introduced to model soak-time impacts on CO, HC, and NOx emissions, respectively.

**Modeling Results**

Table 1 lists the cold-start and-soak time modeling parameters for the 24 vehicle-technology groups. As an example, Figures 7(a), 7(b), 7(c), and 7(d) show the modeled and measurement results for Composite Vehicle 4 [(a particular Tier 0 composite car (1)) under the FTP Bag 3 cycle. Figure 7(a) presents the warm-start catalyst

TABLE 1 Cold-Start and Soak-Time Parameters for 24 Composite Vehicles

	$\phi_{cold}$	$T_{cl}$ grams	$CS_{HC}$	$CS_{NO}$	$\beta_{CO}$ grams	$\beta_{HC}$ grams	$\beta_{NOx}$ grams	$C_{soak\_CO}$ min.	$C_{soak\_HC}$ min.	$C_{soak\_NO}$ min.	$\alpha_{soak\_CO}$ min.	$\alpha_{soak\_HC}$ min.	$\alpha_{soak\_NO}$ min.
1	1.26	263	3.5	1.7	50	200	200	61.3	18.1	600.0	200.0	200.0	200.0
2	1.21	500	3.0	1.8	50	60	105	128.2	40.6	600.0	11.9	14.9	6.5
3	1.21	110	3.3	0.1	41	26	0	74.9	17.2	2.8	200.0	200.0	9.6
4	1.18	54	5.2	4.8	50	200	4	525.8	0.3	77.6	1.0	200.0	1.0
5	1.21	77	4.9	3.0	15	34	14	28.8	29.9	600.0	12.2	200.0	24.4
6	1.17	32	4.3	5.0	50	200	4	40.1	17.6	374.2	200.0	200.0	1.0
7	1.19	94	2.3	0.5	13	46	200	45.5	8.8	0.0	28.6	200.0	200.0
8	1.11	97	1.9	0.8	9	27	30	33.5	6.7	8.3	11.5	200.0	200.0
9	1.14	138	2.1	0.5	7	22	22	36.3	12.0	24.4	166.7	37.0	20.0
10	1.15	32	4.6	4.0	7	200	9	554.2	13.4	314.2	28.6	200.0	1.0
11	1.19	53	5.8	3.1	16	11	4	54.3	49.6	465.8	200.0	52.6	6.1
12	1.25	167	6.6	3.7	50	0	200	600.0	0.0	600.0	200.0	9.6	200.0
13	1.29	273	4.8	0.9	50	1	200	600.0	0.0	6.9	1.0	1.0	1.0
14	1.12	230	2.4	1.9	36	34	40	54.0	10.0	600.0	200.0	18.5	15.4
15	1.14	101	2.2	1.3	28	43	22	69.1	16.7	599.9	1.0	200.0	200.0
16	1.12	180	1.9	1.8	50	200	77	69.9	31.6	599.9	10.8	200.0	200.0
17	1.11	75	4.3	2.5	22	17	19	328.3	0.6	525.8	1.0	66.7	1.0
18	1.11	119	3.7	1.0	24	25	200	101.0	21.4	585.8	6.5	21.3	200.0
19	1.37	150	6.1	1.5	25	24	200	1.1	0.9	10.0	1.6	0.4	200.0
20	1.26	156	4.0	3.5	50	22	24	2.8	0.2	10.0	0.0	0.2	0.0
21	1.14	178	2.8	2.1	38	16	24	10.0	0.1	0.3	0.0	0.1	0.0
22	1.23	454	2.7	1.6	50	97	186	10.0	0.0	0.2	0.0	0.0	0.0
23	1.13	178	2.4	1.2	50	200	73	2.5	0.0	10.0	0.0	0.0	200.0
24	1.07	188	2.3	2.2	1	14	0	0.8	0.4	10.0	0.3	200.0	0.3
Mean	1.18	162	3.6	2.1	33	72	77	143.0	12.3	276.1	61.8	100.9	78.6
Max.	1.37	500	6.6	5.0	50	200	200	600.0	49.6	600.0	200.0	200.0	200.0
Min.	1.07	32	1.9	0.1	1	0	0	0.8	0.0	0.0	0.0	0.0	0.0



**FIGURE 7** (a) Catalyst efficiency versus time in the first 100 s of FTP Bag 3 cycle with a 10-min soak, Composite Vehicle 4. Solid lines are modeled results; dashed lines represent measurement results. (b) Engine-out and tailpipe CO emissions versus time in the FTP Bag 3 cycle with a 10-min soak, Composite Vehicle 4. (c) Engine-out and tailpipe HC emissions versus time in FTP Bag 3 cycle with a 10-min soak, Composite Vehicle 4. (d) Engine-out and tailpipe NOx emissions versus time in FTP Bag 3 Cycle with a 10-min soak, Composite Vehicle 4.

**TABLE 2 Catalyst Light-Off Time (in Seconds) by Cycle for Composite Vehicle 10**

Soak time (hrs.)	Catalyst (CO)	Catalyst (HC)	Catalyst (NOx)
0.5	0	0	28
1	15	44	40
2	30	59	40
5	39	62	40
24	40	62	40

CO, HC, and NOx efficiencies versus time in the first 100 s of the FTP Bag 3 cycle for the composite vehicle. In each plot, the solid line represents the modeled results and the dashed line represents the measurement results. Numbers to the right of the plot give average grams-per-mile values for the measured and modeled emissions. Figure 7(b) presents the warm-start engine-out and tailpipe CO emissions versus time in the FTP Bag 3 cycle. Figure 7(c) presents the warm-start engine-out and tailpipe HC emissions versus time in the FTP Bag 3 cycle. Figure 7(d) presents the warm-start engine-out and tailpipe NOx emissions versus time in the FTP Bag 3 cycle.

### LIGHT-OFF TIME, SOAK TIME, AND DRIVING CYCLES

So far a fuel-based incremental soak-time emissions model has been established. Using the established model, one can predict vehicle incremental soak-time emissions under the following conditions:

1. Vehicle incremental soak-time emissions and catalyst light-off times under different soak times;
2. Vehicle incremental soak-time emissions and catalyst light-off times under different starting cycles.

Here the catalyst light-off time is defined as the time to reach 50 percent of its fully warmed up maximum catalyst efficiency.

Table 2 shows the catalyst light-off times for modeled Composite Vehicle 10 under five different starting cycles, assuming that a 24-h soak time is applied for each test cycle. Table 2 shows that the catalyst of the composite vehicle has the longest light-off time under the NYC cycle: 56 s for catalyst CO, 82 s for catalyst HC, and 55 s for catalyst NOx. The catalyst of the composite vehicle has the shortest light-off time for CO and NOx emissions under the US06 cycle: 20 s for catalyst CO and 19 s for catalyst NOx. For catalyst HC efficiency, the FTP HWY cycle offers the shortest light-off time (42 s). It appears that the more aggressive starting cycles result in shorter light-off times for catalyst. This is intuitive, since more aggressive cycles cause a more rapid increase in the catalyst temperature, resulting in a shorter light-off time.

Table 3 shows the different catalyst light-off times for Composite Vehicle 10 under the FTP Bag 1 cycle with different soak times of 0.5, 1, 2, 5, and 24 h.

Table 3 shows that for this particular composite vehicle, the catalyst light-off time for CO and HC emissions increases rapidly as vehicle soak time increases. For example, when a vehicle's soak time is under 0.5 h, the CO and HC catalyst efficiencies never fall below 50 percent; thus, the catalyst light-off times are zero for these two pollutants. When the soak time increases to 1 h, the catalyst light-off times increase to 15 s for CO and 44 s for HC. When a vehicle's soak time reaches 5 h, the catalyst light-off times are almost the same as those at the 24-h soak time: 39 s for CO and 62 s for HC. In contrast, for the catalyst NOx efficiency, its light-off time is relatively independent of soak time after soak time is equal to 1 hour, and it is always equal to 40 s.

### CONCLUSIONS

A modal model that simulates emissions as they depend on driving mode has been extended to account for soak time. The modal model applies to CO, NOx, and HCs and to 24 composite vehicles, each of which represents an average light-duty vehicle of a particular group. The results describe the time dependence of emissions as the engine and catalyst warm up in a reasonably satisfactory manner.

The extension made here is preliminary because it is based only on measurements with two soak times, 10 min and 24 hours, which occur in the FTP. It cannot yet be verified whether the interpolation between these two times, which the authors formulated, is reliable. Measurements at other soak times are essential.

Moreover, the measurements that were used to make this extension involve the driving pattern at the beginning of the FTP, and so the accuracy of the extension to other driving modes cannot be verified. However, the authors are confident that the fuel use-based formalism is a sound way to represent emissions dependence on driving mode.

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**TABLE 3 Composite Vehicle 10 Catalyst Light-Off Time (in Seconds) under Different Soak Times for FTP Bag 1 Cycle**

Cycle:	Catalyst (CO)	Catalyst (HC)	Catalyst (NOx)
FTP HWY	22	42	21
FTP Bag 1	40	62	40
LA92	46	78	45
NYCC	56	82	55
US06	20	48	19

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