

Establishment of a New Research Center for the Study of Extremely Low Emission Vehicles (SELEV)

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ABSTRACT

要 旨

Vehicles such as the new Honda Accord PZEV (Partial Zero Emission Vehicle) can help California and other regions achieve their air quality objectives. However, the potential impact of this technology upon air quality is not fully understood by regulators or by the general public, and it has not been accurately quantified. For this reason, Honda has initiated a research center at the University of California, Riverside, for the "Study of Extremely Low Emission Vehicles" (SELEV). There are three interrelated objectives for this center: (1) Measure the emissions of advanced-technology vehicles under real-world conditions; (2) Build a database of vehicle population and activity; and (3) Use these data to develop air quality models that can accurately assess the impact of near-zero-emission vehicles.

This paper will detail the development and validation of an on-board system capable of determining mass-based emissions, and the use of this system to prove that advanced-technology vehicles maintain their emission performance under real-world driving conditions. It will also be shown that data collected during this program can be used to improve the accuracy of emission inventory predictions. The preliminary, encouraging results of this program have been recognized by the California Air Resources Board (CARB), and some of the recent changes in the ZEV regulation reflect the real-world near-zero emission vehicle performance being confirmed in this research program. This program has also received the attention of the national media.

Honda Accord PZEV(Partial Zero Emission Vehicle)のような新しい車は、カリフォルニア州や他地域の大気質改善の目的達成に貢献している。しかしながら、このテクノロジーが大気質に及ぼす潜在的な影響は、政策立案者や一般人から十分には理解されていない。また、これまで正確な定量分析も実施されたことはなかった。これらの理由から、Hondaはカリフォルニア大学リバーサイド校に「Study of Extremely Low Emission Vehicles(以下、SELEV)」を行うためのリサーチセンタを設立した。当センタには、3つの目的がある。(1)先進技術を用いた自動車の排ガスをリアルワールドの状況で測定、(2)自動車台数とその走行実態のデータベースを構築、(3)このデータベースを使い、Near Zero Emission Vehicle(以下、NZEV)のもたらす影響を正確に評価できる大気質モデルを開発。

この論文は、排ガス排出量が測定可能な車載システムの開発とその確認に関する詳細について述べるとともに、先進技術を適応した自動車がリアルワールドの運転状況でも排ガス性能を維持できることを証明するものである。さらに、当プログラムから収集したデータは、排出量推計の精度を上げるために使われる。当プログラムのこれまでの良好な結果は、California Air Resources Board(以下、CARB)によって認知されており、最近のZEV規制見なおしの一部はこのプログラムで確認されたリアルワールドのNZEV性能を反映している。また、当プログラムは全国メディアからも注目されている。

1. Introduction

1.1. Background

In the 1980's, it became clear in the US that vehicle emission standards would require additional tightening. As a result, the Clean Air Act was amended in 1990, thereby producing the federal "Tier 1" standards. In the

same year, the California Air Resources Board initiated the Low Emission Vehicle (LEV) program, a key component of which was the Zero Emission Vehicle (ZEV) regulation. Several additional states subsequently adopted the California program. The concept behind the ZEV regulation was that Battery EV technology looked promising, and in 1990, CARB considered gasoline-

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powered vehicles to have limited emissions reduction potential such that air quality goals could not be achieved.

However, at the dawn of the 21st century, a technological breakthrough occurred that could not have been foreseen a decade earlier. Gasoline-powered vehicles began entering the market with emissions at near-zero levels. For example, most Honda Accords sold in California in 2003 had emissions essentially equivalent to that of an electric vehicle, when the powerplant emissions associated with the latter are considered. Current air quality predictions do not account for the impact of this technology, because it has not been quantified. Therefore, the government agencies could not accurately account for these “Extremely Low Emission Vehicles” (ELEV) vehicles in their regulatory framework. Environmentalists and the general public remained skeptical that a vehicle powered by gasoline could be so clean.

It was against this backdrop that the CARB, US EPA, and Honda initiated the SELEV Center at the University of California, Riverside. The purpose for establishing this center was to establish an independent, credible entity with the ability to objectively measure and assess the effect of ELEV technology upon air quality. The University’s College of Engineering Center for Emission Research and Technology (CE-CERT) group was uniquely suited for this role, due to their extensive experience with emission measurement and air quality modeling.

1.2. SELEV strategy

The key components of the SELEV Center are shown in Fig. 1. A cornerstone of the program is the collection of real-world data. It was known that ELEV’s perform well under laboratory conditions, but laboratory measurements alone cannot confirm the performance of these vehicles under actual-use situations. Therefore, tailpipe emissions were measured while the vehicles were being driven on the road, using an on-board

analyzer. Another group of CE-CERT researchers collected data regarding the current vehicle activity and fleet distribution in Los Angeles; i.e., driving patterns and a breakdown of the various vehicles classes. These data were then used to improve California’s existing emission inventory, using modeling tools such as CMEM (Comprehensive Modal Emissions Model) and modifications to current inventory models. CMEM is described later in this paper. Traditional laboratory measurements were used to provide some of the data used to calibrate CMEM, and also to validate the accuracy of the on-board measurement system. For the final step, the inventory data were prepared for use in air quality models, thereby permitting the assessment of ELEV impact upon the air basin of an entire city.

2. Experimental

2.1. On-board emission measurement

2.1.1. Background

The importance of measuring the emissions on board a vehicle under real-world conditions is well understood. For example, the US EPA is seriously considering the implementation of “on-vehicle” compliance standards, and perhaps even on-vehicle certification. The reason for this is that the EPA has discovered that some low-emission technology emits two to three times the standard under real-world conditions, despite the fact that the standards were met in the laboratory. The National Academy of Sciences is also pushing the EPA to use on-board measurement to assess the effect of federal emission regulations ^{(1),(2)}.

Within the SELEV Center, the measurement of on-road emissions serves two purposes: (1) It determines the real-world performance of ELEV technology, and confirms that the near-zero emission levels measured under laboratory conditions are realized in actual on-road driving; (2) It provides emission calibration data for modeling tools such as CMEM.

2.1.2. Hardware

The on-board analyzer assembled by CE-CERT was based upon technology developed by Honda R&D, Los Angeles ^{(3),(4)}. The accuracy of Honda’s FTIR-based system compared favorably to traditional laboratory techniques, based upon an independent assessment performed by CE-CERT ⁽⁵⁾. The Honda system was dedicated to a single vehicle, and was designed to simultaneously measure ambient air quality and tailpipe emissions. In contrast, the CE-CERT system was designed to be easily transferred between vehicles in less than two hours, and required only a single FTIR (Fourier Transform Infrared Spectroscopy) analyzer. Most of the system hardware was contained within two modular components: a sample conditioning module and an analytic module; Fig. 2. The conditioning system consisted of two Nafion (Nafion is registered trademark of E.I. du Pont de Nemours and Company.) driers, one fitted with a piezoelectric cooler to increase efficiency. Sample water content was maintained at a constant low level through the use of dewpoint feedback control. The

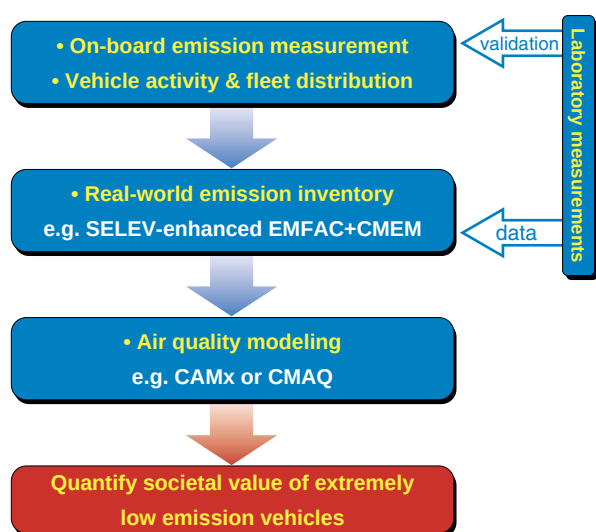


Fig. 1 Overview of SELEV Center strategy

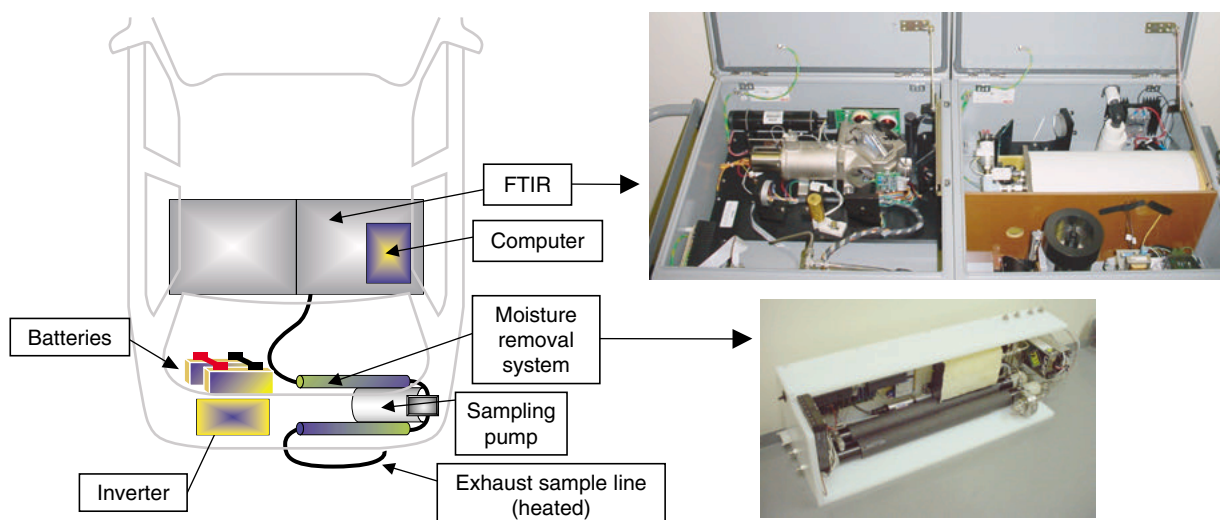


Fig. 2 Modular on-board analyzer system developed by CE-CERT

analytic module consisted of a modified FTIR with an 8.3 meter cell. The CE-CERT system also included instrumentation to record vehicle speed, location, and various engine operating parameters. This permitted an accurate measurement of tailpipe emission on a mass basis. Also, emission performance could be correlated to specific events, such as acceleration on a freeway on-ramp.

2.1.3. System validation

The validation of this system was a two-step process. The first step was to confirm that the on-board analyzer could match the accuracy and precision of a traditional dynamometer system; i.e., a CVS (Constant Volume Sampler) and bench analyzers. A variety of low-emission vehicles were tested in a dynamometer laboratory, while the on-board system measured emissions concurrently with the dyno bench analyzers. No information was shared between the two analytic systems; i.e., the mass-based emissions were calculated for the on-board analyzer using only the data acquired from the vehicle's ECU. The second validation step involved driving the vehicles over a test cycle (e.g. FTP-75) on the road, while the on-board analyzer collected data. Because this procedure was very challenging for

the driver, it was conducted at the Honda Proving Center in California (HPCC). These tests were critical, because the analyzer system must retain its accuracy and precision in on-road conditions to produce credible real-world data.

The on-board analyzer passed both validation steps, as can be seen in Fig. 3. In this example, the first two columns in each set represent the laboratory testing with results collected concurrently from the dyno bench and on-board analyzer, and the third column represents the separate on-road testing.

2.2. Laboratory testing

In addition to validating the on-board analyzer, laboratory testing fulfilled other requirements of the SELEV Center research. For example, data collected during laboratory testing, such as catalyst efficiency, was used to calibrate the CMEM emissions inventory model.

All testing of SULEV-technology vehicles was performed at the California Air Resources Board laboratory in El Monte, because the CE-CERT laboratory was not certified to test SULEVs. In one interesting example of this work, the on-board analyzer identified a contamination problem in the CARB's laboratory

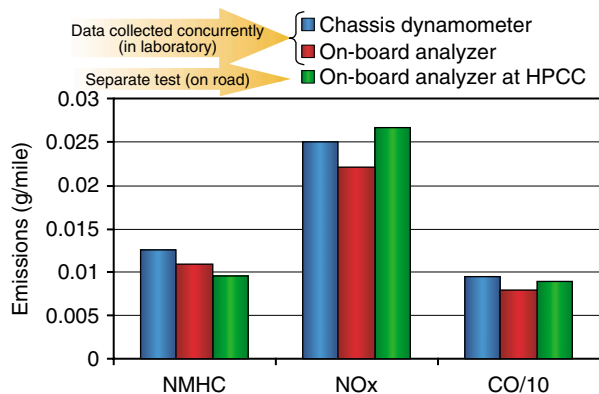


Fig. 3 Validation of CE-CERT on-board analyzer. Test vehicle = 2001 Honda ULEV Accord.

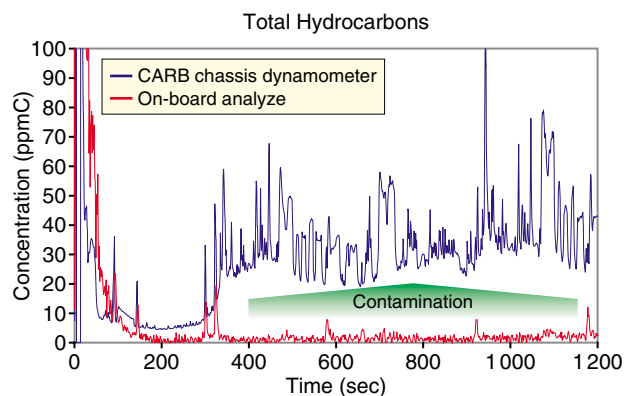


Fig. 4 Contamination of CARB laboratory system discovered by on-board analyzer

system during US06-cycle testing; see Fig. 4. Similar contamination was discovered at the CE-CERT laboratory. In both cases, it was due to the out-gassing of emission sampling hardware during periods of high temperatures. These problems were subsequently corrected.

2.3. Vehicle activity patterns and fleet distribution

In order to determine mobile source emission inventories using models such as CMEM, it is necessary to have a good understanding of vehicle activity patterns and fleet distributions for the target area. In the SELEV program, vehicle activity was measured in three cities within the South Coast Air Basin. Within each city, three types of roadways were studied: Freeway, arterial (major non-freeway highways), and residential. Equipment used for this study:

- A. Digital video camera, with automated data analysis; "Autoscope". This equipment provided data such as average speed, vehicle type, and traffic volume.
- B. High-resolution digital video camera. This camera captured the license plates of passing vehicles. The Vehicle Identification Number (VIN) could be determined by cross-reference with the license data, thereby providing information such as vehicle make, model, catalyst type, etc.
- C. Instrumented vehicle. This vehicle was driven along the targeted roadways during monitoring periods, providing speed, acceleration, road grade, and position data on a second-by-second basis.

Equipment configuration "A" is shown in Fig. 5, together was an example of the data. This Fig.

demonstrates how the Autoscope placed "virtual detectors" on the video image during post-processing. Vehicles passing through these detection areas were automatically counted and classified as to speed and vehicle class. This data example indicates average speed over the various roadways monitored in the city of Yorba Linda.

2.4. Emission inventory models

An accurate inventory of emissions is a prerequisite to the understanding the factors that affect air quality. The on-road mobile source emissions models used today for inventory and regulatory purposes are MOBILE, which was developed by the USEPA⁽⁶⁾, and EMFAC, which was developed specifically for California⁽⁷⁾. These two models are structured similarly and they calculate mass emissions by multiplying the vehicle activity data by the emissions factors. Both models have built-in assumptions for emission rates, deterioration rates, and other factors. Unfortunately, these assumptions are generally not appropriate for ELEV technology, and can lead to an over-prediction of the emissions for these vehicles. The data being collected in the SELEV program will allow appropriate adjustments to be made to these default assumptions.

CE-CERT has developed CMEM, which takes a different approach to vehicle emissions modeling. The CMEM framework computes a vehicle's emissions based upon operating mode. For example, the number of stops, acceleration events, the traffic conditions, and other factors are accounted for in the CMEM framework. Specifically, CMEM uses a power-demand modal

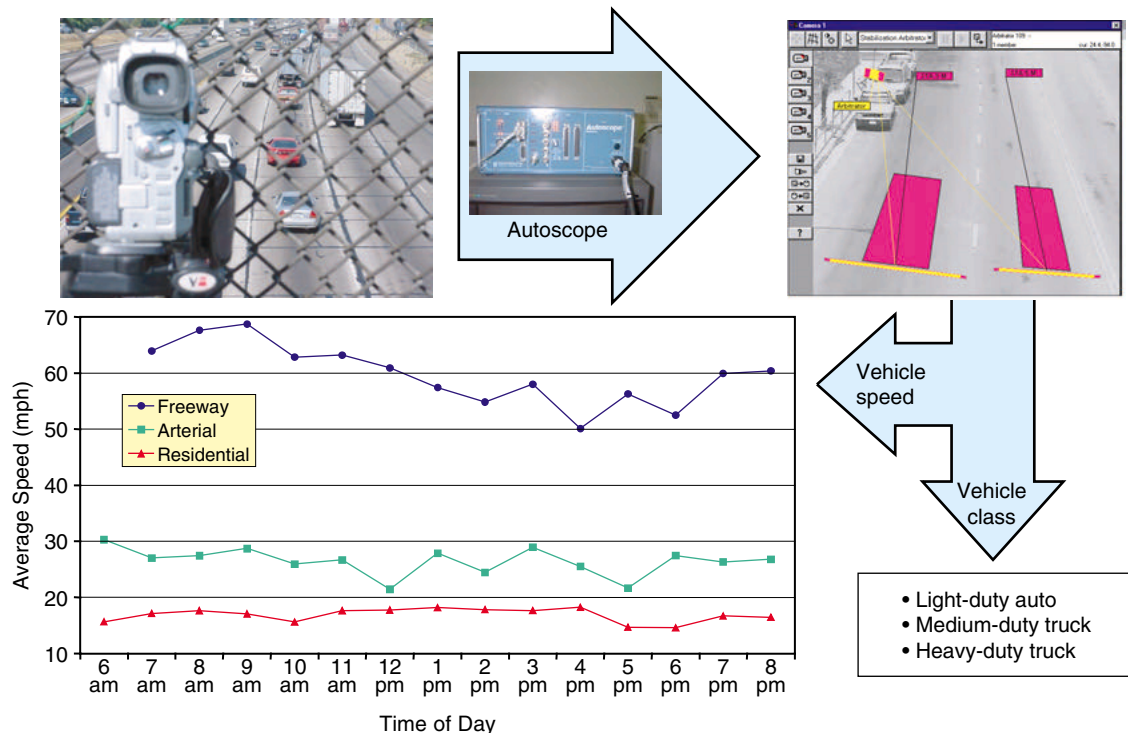


Fig. 5 Measurement of vehicle activity patterns and fleet distribution. Equipment configuration "A". Data from city of Yorba Linda.

modeling approach based on a parameterized analytical representation of emissions production. In such a model, the entire emissions process is broken down into different components that correspond to physical phenomena associated with vehicle operation and emission production⁽⁸⁾. Each component is then modeled as an analytic representation consisting of various parameters. The architecture of the model is shown in Fig. 6. Over 400 extensive dynamometer tests were used in the development of the CMEM model. Laboratory and on-road data collection during the SELEV program have enabled the development of CMEM modules for vehicles with emission categories of ULEV and below. This aspect of the program is still in progress; the elements currently being modified to accommodate ELEV technology are highlighted in Fig. 6. This enhanced version of CMEM can then be used as a supplement to the SELEV-modified EMFAC, resulting in an emission inventory that will reflect the introduction of ELEV technology.

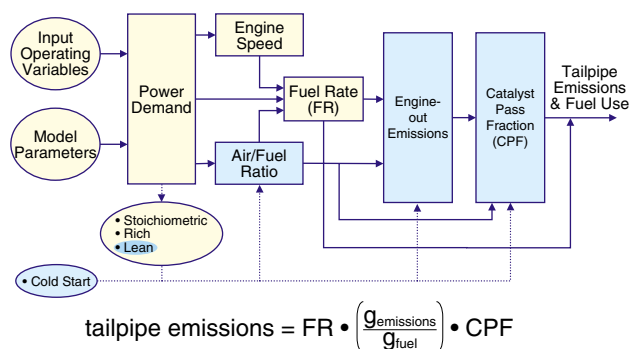


Fig. 6 Basic architecture of CMEM modal emission model. Blue areas are being modified to accommodate ELEV technology.

2.5. Air quality modeling

Emission inventories are the major component of air quality models. Other key components are meteorological data and photochemical reaction mechanisms. These sophisticated air quality models can predict the concentration of ambient air pollutants. An example of the output of one such model, CAMx (Comprehensive Air Quality Model with extensions), is shown in Fig. 7.

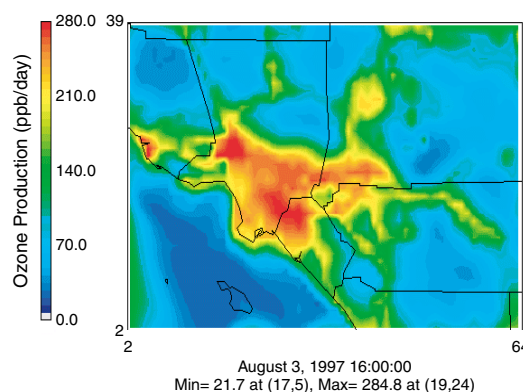


Fig. 7 Example of CAMx air quality model prediction of ozone production for Southern California. (August 3, 1997.)

This figure represents the CAMx “prediction” of ozone production for Southern California over a specific timeframe in 1997. In the SELEV program, the 1997 air quality scenario will be compared to a predicted scenario for the year 2010. In this prediction, a high percentage of ELEVs will be assumed. Other emission sources, such as stationary and biomass, will be held constant. In this manner, the impact of ELEV technology upon air quality can be quantified. This work is currently in progress. This far, substantial progress has been made on the integration of emission models and atmospheric models. This has been accomplished through the use of the SMOKE (Sparse Matrix Operator Kernel) emission processing system.

3. Results and Discussion

3.1. Real-world emission measurement

Data from on-road, real-world driving are shown in Fig. 8 for a 2000 SULEV Accord. Emissions are plotted versus time. Vehicle speed is also shown. Three types of roadways are represented, as indicated in the figure. The GPS system which was used to collect the speed data also recorded elevation data, not shown. The latter data are important for the understanding and subsequently modeling of vehicle emission behavior, because the grade of the roadway is an important parameter that affects the vehicle’s power demand.

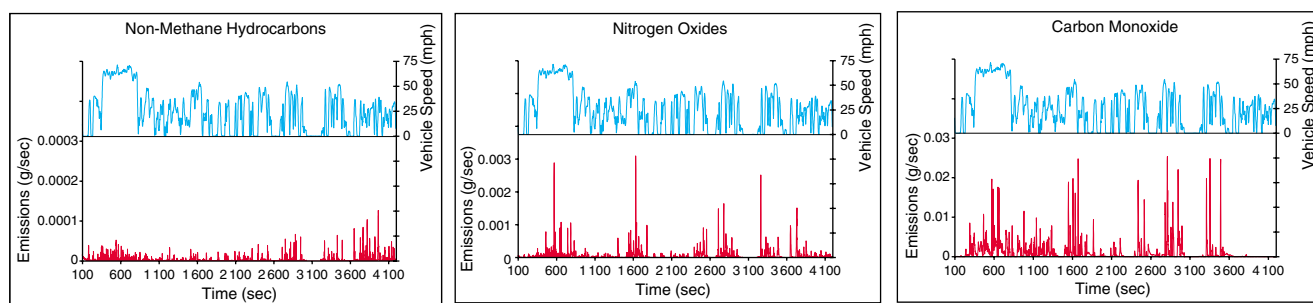


Fig. 8 Emission and speed measurements acquired on road under real-world conditions. 2000 Honda SULEV Accord.

The speed data itself can be used to help validate the CMEM emission inventory model. For example, the cycle's speed data can be used as an input for CMEM, and the emission results calculated by CMEM can be compared to the actual results measured on-road during that cycle. Of course, any on-road data used for the calibration of CMEM cannot be used for this purpose, or the validation would be invalid.

Throughout the various driving conditions encountered during the approximate one-hour period of data collection, tailpipe emissions remained extremely low. Based on previous research performed by Honda^{(3),(4)}, the exhaust species concentrations depicted in Fig. 8 are often below those of ambient air in the Los Angeles area. It's important to note that exhaust emissions remained low even during periods of rapid acceleration that are not encountered during laboratory FTP-75 testing.

3.2. Real-world data compared to EMFAC model

Data acquired from on-board measurements can also be used to check EMFAC model predictions. A comparison of EMFAC-predicted emissions for SULEV technology with actual on-road emissions from a Honda SULEV Accord is shown in Fig. 9. In both cases, data from arterial driving are shown. For further comparison, the second phase of an "on-road" FTP result acquired at HPCC is also shown. Only the second phase was used here in order to produce a valid comparison with an arterial driving situation in which no starts are observed. It can be seen that the emissions predicted by the EMFAC model are significantly higher than the actual emissions produced by the SULEV vehicle. The latest version of EMFAC available at the time of this writing was used for this comparison; (EMFAC 2002 version 2.2).

3.3. Observed vehicle fleet and impact on emission models

The accuracy of emission model estimates is dependent upon the accuracy of the input data. The composition of the on-road fleet is one of the key parameters. The fleet composition data collected during

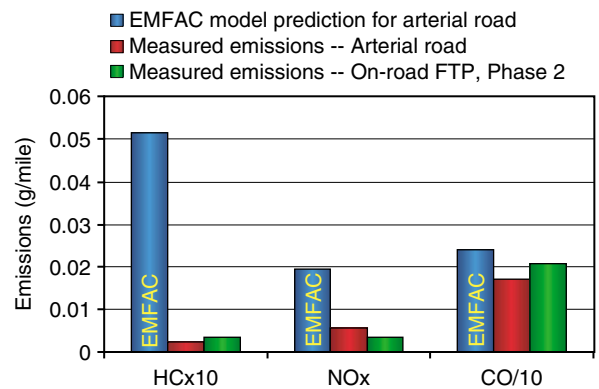


Fig. 9 EMFAC-predicted emissions for SULEV technology compared to actual measurements. 2000 Honda SULEV Accord, warmed-up conditions.

the SELEV program were used as inputs for both the EMFAC and CMEM models. The purpose of this was not to compare the models themselves, but rather to determine the effect of using actual SELEV fleet composition data as inputs compared to using default parameters. In the case of EMFAC, the default settings used for this comparison were those for calendar year 2001, for the counties indicated in Fig.10. The model was then re-run using the SELEV fleet data collected during the summer of 2001. The SELEV data were prorated to keep the total vehicle population constant between the two cases. As can be seen in Fig. 10a, running the EMFAC model with the SELEV data produced emissions that were 22% to 45% lower than those calculated using the default values.

A similar exercise was performed using the CMEM model. In this case, the default input values consisted of a random sampling of vehicles registered with the DMV (Department of Motor Vehicles) within each target city. Running the CMEM model with the SELEV data produced emissions that were 8% to 70% lower than those calculated using the default values; see Fig. 10b.

These two comparisons demonstrate the importance of using actual, observed fleet characterizations as inputs

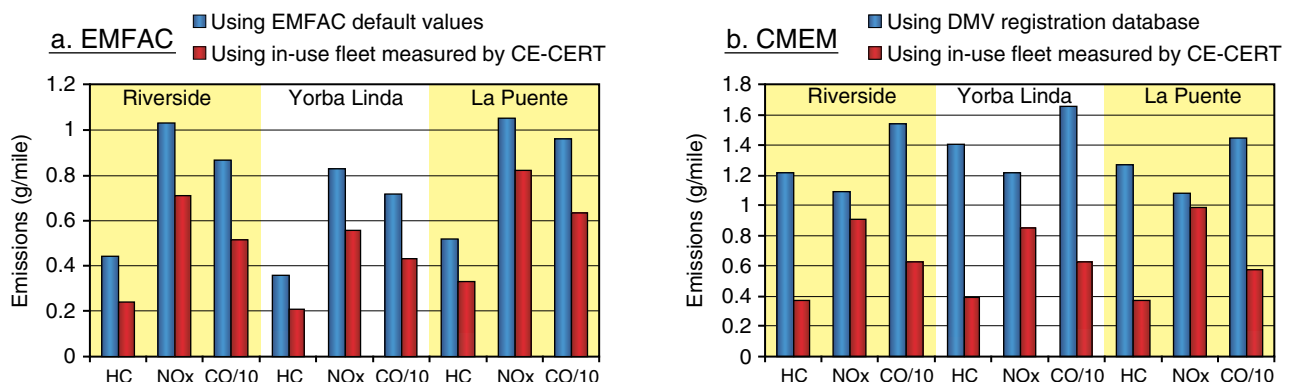


Fig. 10a and 10b Effect of using CE-CERT-measured in-use fleet composition data as inputs to emission models, compared to using default values.

to emission models. The default data used in many such models are based upon vehicle registration data, which has been shown to be a poor predictor of the actual on-road vehicle composition⁽⁹⁾.

3.4. SELEV public symposium and response

In September of 2002, the University of California, Riverside, held a symposium at which interim results of the SELEV Center research program were presented. The response to this event greatly exceeded expectations. Regarding regulatory policy, a number of publications cited the SELEV Center results as being a factor in the CARB's recent changes to the ZEV regulation; one article called it a "primary catalyst for the change of heart from CARB^{(10) - (12)}." The SELEV results also reached the general public, thereby helping to foster interest in and promote understanding of low-emission vehicle technology, such as that developed by Honda. The SELEV story reached a nationwide audience; it has been estimated that 32 million people heard about the SULEV results in some way⁽¹³⁾. The largest audiences were reached with a front-page article in "USA Today⁽¹⁴⁾," and a prime-time story featured on the "CBS Evening News with Dan Rather."

4. Conclusion

A new research center has been established to determine the impact of extremely low emission vehicles (ELEV) upon the environment. The SELEV Center has applied a methodical and technically sound approach to achieve this objective, beginning with the measurement of vehicle emissions under real-world, on-road conditions. Extensive measurements have also been made of vehicle activity and class distributions. Supplemented by laboratory measurements, this collection of unique data is being used to produce inventory models that can accurately predict the emissions of advanced technology vehicles.

The significance of the SELEV Center findings has been recognized by the regulatory agencies and has been reported in the national media. The California Air Resources Board now has a better understanding of the positive impact ELEV technology can have towards their goal of improving California's air quality.

Research at the SELEV Center continues, with a focus on the assessment of the long-term, full-cycle air quality impact of extremely low emission vehicles.

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