California Inspection and
Maintenance Review Committee

Remote Sensing of Vehicle Emissions

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State of the Technology, Potential Applications, Cost Estimates, and Recommendations

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I. Introduction

Over the last several years, remote sensing, the on-road measurement of vehicle emissions, has been evaluated by policy makers and researchers as a potential enhancement to traditional inspection and maintenance (I/M) programs. California law includes remote sensing as a component of Smog Check II.[1] The remote sensing device (RSD)[2] measures vehicle tailpipe emissions as vehicles drive by on the road. RSD for hydrocarbons (HC) and carbon monoxide (CO) has existed since the late 1980s. More recently, the technology has been enhanced to measure nitrogen oxides (NOx) as well. The Inspection and Maintenance Review Committee (IMRC) established a sub-committee to evaluate the current state of RSD technology and report back with a discussion of findings and outstanding issues. The following is a report on the results of these investigations.

II. How RSD Works

The first RSD units measured only CO and HC emissions. Refinements and enhancements over the last decade have added additional capabilities, including automatic license plate readers, and technology to measure NOx and vehicle speed and acceleration. A typical field remote sensing set-up is displayed in Figure 1.

The RSD shoots beams of infrared and ultraviolet light of specific frequencies across a single lane of traffic. When the beams pass through the exhaust plume from a car’s tailpipe, the RSD unit measures concentrations of HC, CO, NOx, and carbon dioxide. An imaging system, combined with an automatic license plate reader, records the license plate number. More than 1,000 cars per hour can be measured on a heavily traveled road or street.

RSD measurements are reported in percents or in parts per million (ppm).[3] Table 1 displays the distribution of emissions based on RSD readings in two different studies. The Chicago readings are much lower than the Rosemead readings for three major reasons. First, the Chicago study was done six years after the Rosemead study. All other things being equal, we would expect the Chicago fleet to be cleaner due to six years of turnover to cars designed to meet more stringent emissions standards. Second, the cars in the Chicago study were, on average, two years younger than the cars in the Rosemead study. We expect newer cars to be cleaner, on average, than older cars. Third, there were hardly any very old cars in the Chicago study. Only one percent of the Chicago cars were pre-1981, while 18.4 percent of the Rosemead cars were pre-1981. This is due partially to the Chicago study being more recent, but also to the fact that car bodies and chassis deteriorate much more slowly in southern California than in Chicago due to the milder weather in southern California. Cars built before the widespread use of computer control, three-way catalysts, and fuel injection are more likely to become super-emitters.

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[1] See Health & Safety Code Sections 44011(a)(4)(B)(i), 44024.5, 44081(a)(1), and 44109.

[2] “RSD” is conventionally used to refer both to the remote sensing device itself and to the activity of remote sensing. For convenience, we will follow this convention.

[3] 1,000 ppm = 0.1%

Figure 1: Schematic of a Typical On-Road Remote Sensing Set-Up

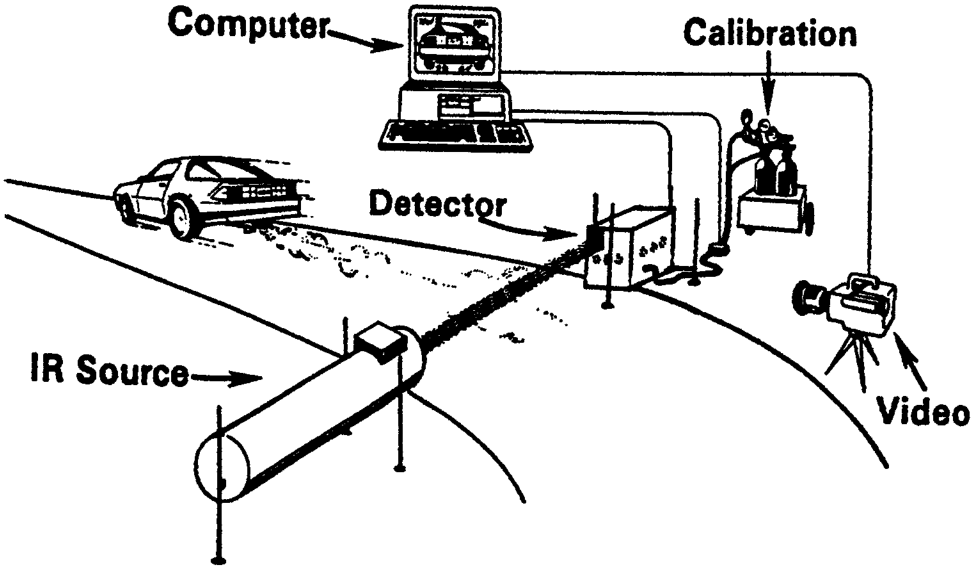

Figure from Bishop et al., 1998

Table 1. Distribution of RSD Emission Readings in Two RSD Studies

	Rosemead, CA 1991		**Chicago, 1997**	
	HC(%)	**CO(%)**	**HC(%)**	**CO(%)**
Median[4]	0.040	0.14	0.013	0.13
Average	0.076	0.82	0.021	0.43
Worst 5%	0.25	4.50	0.060	1.97
Average Vehicle Age	7 years		5 years	
Average Model Year	1985		1993	

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[4] The *median* is defined such that half of the cars have emissions above the median value and half have emissions below the median value.

III. Potential Advantages of RSD

Some researchers and policymakers have proposed that RSD has the potential to improve I/M programs in two ways. First, because on-road testing with RSD can be random and pervasive, RSD could be used to encourage motorists to maintain their cars on an ongoing basis. Second, because RSD measurements are inexpensive (on a per-car basis) and convenient, on-road testing has the potential to reduce the overall cost of an I/M program.

Scientists and policymakers have been aware for several years that I/M programs have had limited effectiveness in reducing vehicle emissions. For example, studies of the on-road emissions benefits of I/M programs in Arizona, Colorado, Minnesota, California, and Illinois have found that programs in these states have had little or no impact on vehicle emissions (see, for example, Arizona Auditor General, 1988; Ostop and Ryder, 1989; Stedman et al., 1991; Radian, 1992; Lawson, 1993; Zhang, et al., 1993; Scherrer and Kittelson, 1994; Lawson and Walsh, 1995; Stedman et al., 1997; and Stedman et al., 1998).[5]

The reason these programs have failed to achieve their goals appears to be that motorists take steps to avoid spending substantial sums of money on emission-related repairs (see, for example, Lawson, 1993; Long Beach Press Telegram, 1993; Arizona Auditor General, 1988; Stedman, et al., 1997; and Stedman, et al., 1998). I/M programs require a motorist to pass a test at a time of the motorist's choosing once every year or two. Many motorists have been able to do this without making substantive repairs that would ensure that their vehicles are low-emitting on the road.

RSD may have the potential to reorient the incentives created by traditional I/M program designs. RSD would allow inexpensive measurement of emissions under real driving conditions. On-road measurement might give motorists an incentive to have a low-emitting car on the road, rather than merely the requirement of passing a test every one or two years.

Potential applications of RSD in an I/M program include the following:

- ***Program Evaluation.*** RSD data can be used to inexpensively evaluate the effectiveness of an I/M program. For example, on-road RSD measurements can be used to determine if cars that recently went through their I/M test are lower-emitting than cars that are about to go through their I/M test.
- ***Identifying Gross Polluters.*** Both roadside pullover studies and on-road remote sensing have consistently found that about 10 percent of cars in the on-road fleet have very high emissions. Scheduled I/M programs have failed to ensure that these cars receive lasting repairs. RSD can identify some of these cars as they are driven on the road, providing an opportunity to direct them to a repair shop in between scheduled I/M tests.

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[5] Several other studies of I/M programs have found that I/M programs have generated significant reductions in on-road emissions (see for example, EPA, 1995; CDPHE, 1997; Office of the State Auditor, State of Colorado, 1998; and Tiao, et al., 1989). However, these studies suffer from problematic methodologies that make their results unreliable. We therefore have not included them here.

- ***Clean-Screening.*** The vast majority of cars on the road are low emitters. Eighty to 95 percent of cars[6] pass their scheduled I/M test. RSD could be used on the road to inexpensively identify cars that are consistently clean and excuse them from their scheduled test.
- ***Enforcement.*** BAR could use RSD data to identify where on-road gross emitters were tested to identify shops that improperly pass a large number of vehicles.
- ***"Smart Sign."*** RSD, combined with an on-road variable message sign, can be used as a public information system to inform drivers of their vehicles' emissions as they drive on the road. Figure 2 shows an example of a Smart Sign that currently operates in Denver.
- ***Greater Understanding of Motorist and Vehicle Behavior over Time.*** There are little or no data that track emissions of individual cars from month to month over a long period of time. RSD could be used for ongoing measurement of vehicles as they go about their everyday travels. Combined with Smog Check and change-of-ownership data, and survey information from motorists, these ongoing emissions data could help determine why cars become high emitters, and the relative importance of the motorist and intrinsic features of the car in determining whether a car will become a high emitter.

IV. Test Accuracy in Context

RSD accuracy is crucial for it to be an effective tool in an I/M program. If RSD measurements are unreliable, high emitters might escape detection (a "false pass" or "error of omission") and clean cars might be wrongly cited as gross polluters (a "false failure" or "error of commission"). False passes might reduce the potential maximum effectiveness of an I/M program. False failures might anger motorists inconvenienced by having to bring their car in for an otherwise unscheduled and unnecessary I/M test. However, the accuracy of RSD must be evaluated in the context of the accuracy of other emissions tests and the intrinsic variability of vehicle emissions. We provide this contextual discussion below.

Test And Vehicle Variability

Tests in I/M programs are generally performed only once, with the assumption that a single test is representative of the average behavior of the car being tested. I/M program designers have therefore placed great emphasis on developing tests with low errors of commission and low errors of omission. In studies to determine the accuracy of any given test, researchers have generally used one test as the standard of comparison against which all other tests are judged.

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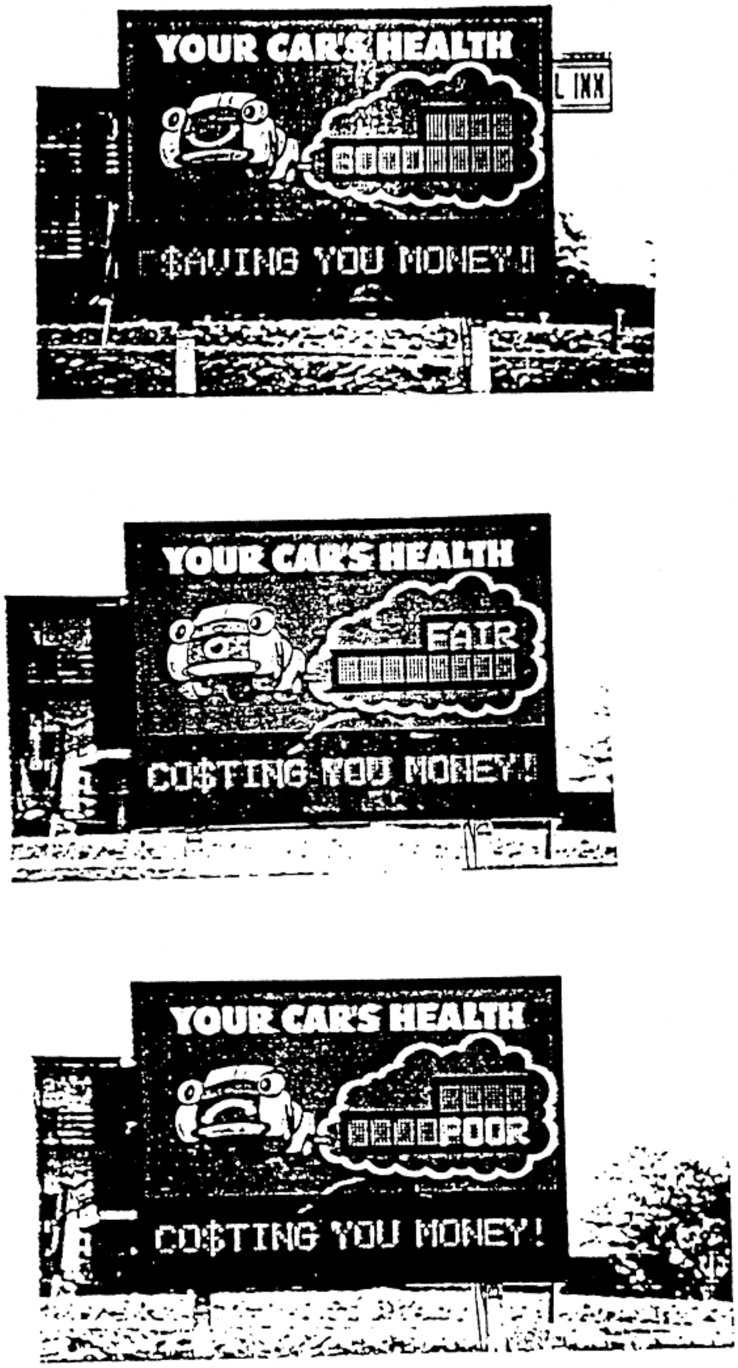
[6] Failure rates vary from program to program and vary with time within a program.

Figure 2: The Denver Smart Sign

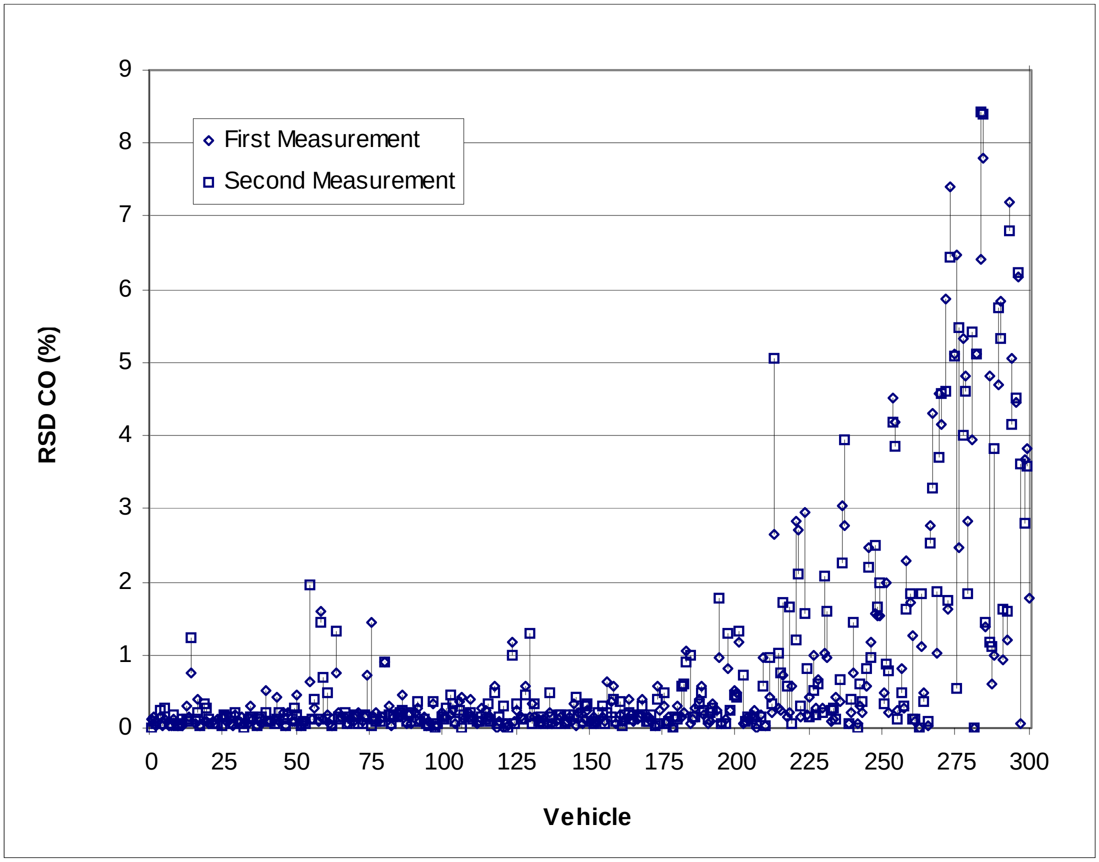


Drivers see one of three messages, depending on their cars' emissions levels

Previous studies have shown substantial variability in the outcome of repeated RSD measurements on the same cars. For example, Figure 3 displays the variation in the outcome of two RSD CO measurements on each of 526 cars (CARB, 1992) (a random sample of only 300 of the 526 vehicles is shown here to ease visualization). Vehicles were rank ordered from cleanest to dirtiest based on their FTP emissions. The RSD CO values were then plotted for each car. Note the large variability of the RSD results from test to test, particularly for the cars with the highest CO emissions. Some researchers have taken this as verification that RSD measurements are inaccurate and unrepresentative of the average emissions of vehicles (see, for example, Austin and Heirigs, 1995). However, as we will show below, much of the variability in vehicle emissions is caused by factors intrinsic to the vehicles themselves, and is independent of the type of emissions test equipment used to measure emissions.

Figure 3: Variability of Repeated RSD CO Measurements for 526 Vehicles Rank Ordered by FTP Emissions

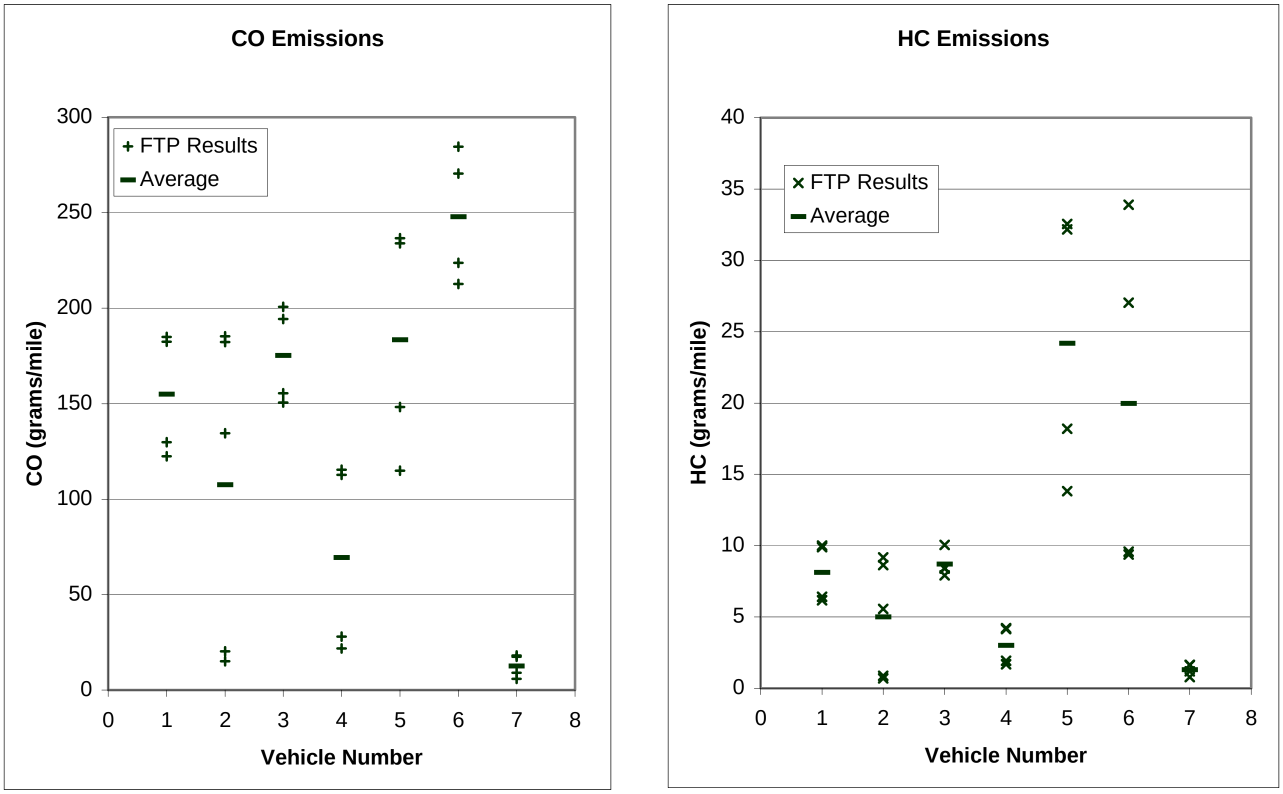
(Results for only 300 vehicles, randomly selected, are displayed to ease visualization)



The Federal Test Procedure (FTP) is the test used to certify that the emissions of vehicles sold in America meet federal or California standards. As such, the FTP has generally been considered the ultimate standard against which all other tests are compared. Because the FTP is expensive and time consuming, the IM240 test has often been used instead when performing test comparisons with large numbers of cars. The IM240 was designed by EPA to be a compressed version of the dynamometer test portion of the FTP, and is the test that EPA prefers for Enhanced I/M programs.

EPA intended the FTP and the IM240 to provide an accurate picture of the average emissions of a vehicle over a representative driving cycle. However, vehicles are intrinsically variable, and vehicles with higher emissions have, on average, greater emissions variability from moment to moment. Research conducted in 1992 (Knepper et al., 1992) demonstrated that even the FTP does not provide a “true” picture of a vehicle’s average emissions, particularly for high emitters. Figures 4a and 4b display data from repeated FTP tests on the same vehicles for CO and HC, respectively. Note the huge variance from test to test in the emissions of six out of seven of these vehicles. Even for vehicle seven, the lowest emitter in the group, emissions varied by more than a factor of two from test to test.

Figures 4a and 4b: Outcome of Repeated FTP Tests on the Same Vehicles



Studies have found similar variation on other emissions tests. For example, Figure 5 displays IM240 CO emissions for 507 vehicles solicited by USEPA at an Indiana I/M lane from 1990 through 1992.[7] The vehicles were tested on IM240 at the I/M lane and then taken to a lab for further IM240 testing under conditions similar to those at the I/M lane. The cars were not driven between the time of the lane test and the lab test although a median time of four days elapsed between them. As in Figure 3, the cars were rank ordered based on their FTP CO emissions and then the IM240 test results were plotted. As the figure shows, there is significant variability between repeated IM240 tests on the same vehicles.

Figures 6a and 6b show another way to compare replicate test results. In this case, the results of replicate hydrocarbon emission tests are plotted for each vehicle. Figure 6a displays remote sensing results and Figure 6b displays IM240 results. If all the cars gave the same result for each of the replicate tests, then the points on the graphs would all fall along a straight line. Spreading of the points indicates greater variability between the results of repeated tests. Based on the spread in the points in the figures, we can see that both RSD and IM240 measurements have significant variability from test to test.

We have shown three examples of vehicle variability affecting the outcomes repeated tests on RSD, IM240 and the FTP. This variability is caused by several factors, including ambient temperature and pressure, how the vehicle was driven (or not driven) in the days and weeks leading up to the test, how the vehicle was pre-conditioned just before the test (e.g., was it idling or driven hard down the freeway), whether the vehicle has any malfunctions, etc. When these conditions are carefully controlled, much test variability can be eliminated.

Figures 7a and 7b show the results of repeated IM240 tests under artificially controlled conditions. Once again, EPA collected data on 411 cars solicited at an I/M lane in Indiana.[8] The cars were kept at a constant temperature for at least 24 hours before testing. They were then pre-conditioned by driving them on a dynamometer for several minutes. They were also fueled with 100 octane, low-sulfur gasoline. The tests were performed back-to-back so that the vehicle was not sitting around or being driven between tests. As can be seen in figures 7a and 7b, under these artificial conditions, test-to-test variability is indeed greatly reduced, although, even here, some vehicles still show high variability. In the real world, however, the factors that cause test variability are mainly out of our control. Furthermore, the more we do control sources of variability, the less representative the test results are of the way cars are actually emitting on the road.

Test variability of the kind described above can have a substantial effect on test outcomes. For example, of the cars in the above IM240 study, 19 percent would be classified as either false failures or false passes when comparing the lane results with the lab results. Furthermore, of cars that failed the lane test, 28 percent passed the lab test. A recent USEPA-commissioned study that included replicate IM240 testing of 664 vehicles found similar results. Eight percent of vehicles tested on IM240 were falsely failed.[9] Of vehicles that failed the first IM240 test, 25 percent passed the second IM240 test (Sierra Research, 1998). The vehicles that were falsely failed or falsely passed tended to be marginal emitters, that is, vehicles with emissions relatively close to

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[7] Data supplied to the IMRC in 1994 by Larry Landman EPA's Mobile Sources Division

[8] Ibid.

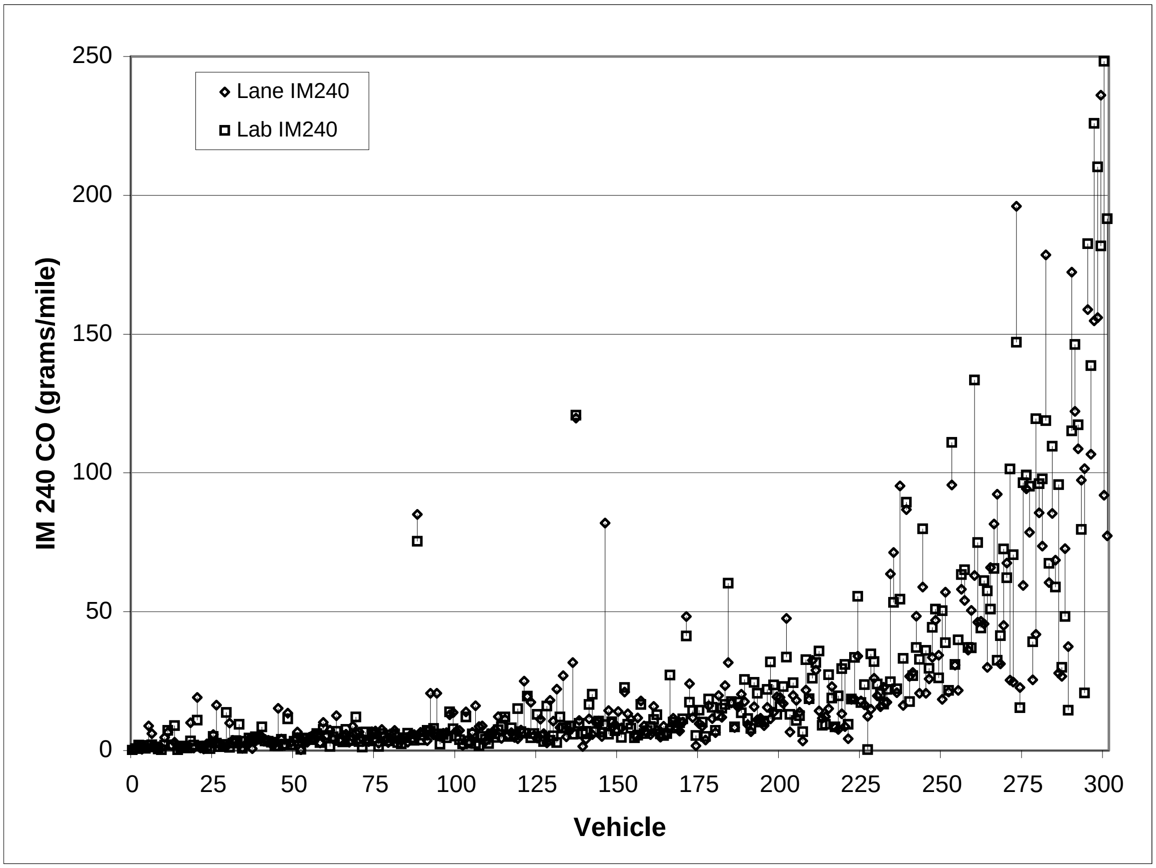
[9] Results for false passes were not reported.

the failure cut points. As can be seen in figures 3, 4, and 5, even with their high emissions variability, the highest emitters would usually fail any test.

Based on the analysis above, we conclude that any given emissions test, including the FTP, provides only an approximate picture of the "true" emissions of a vehicle.[10] Intrinsic vehicle variability and other factors that are out of our control ensure that any given pass or fail result on an emissions test will have some probability of being incorrect.[11]

Figures 5: Variability of Repeated IM240 CO Measurements for 507 Vehicles Rank Ordered by FTP Emissions

(Results for only 300 vehicles, randomly selected, are displayed to ease visualization)



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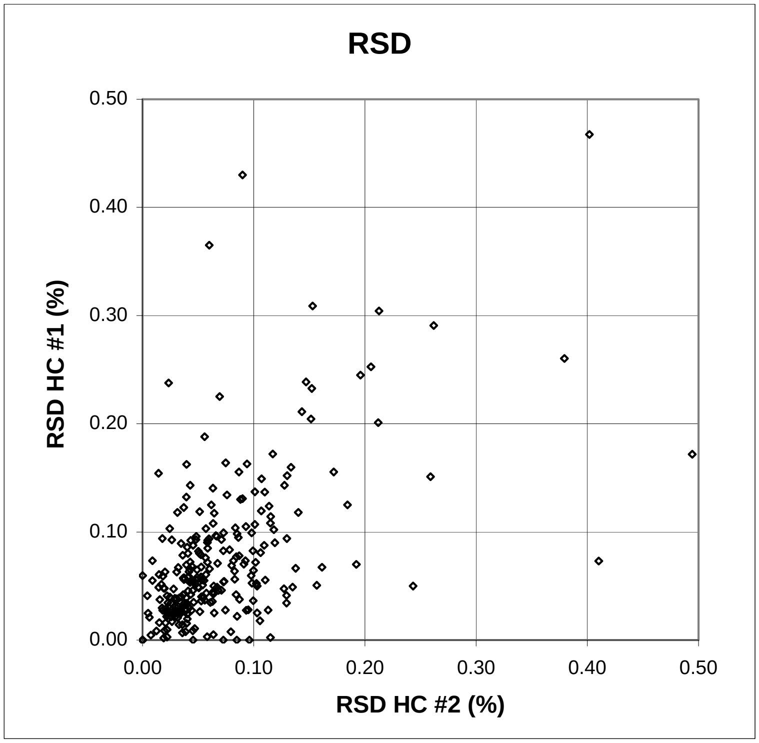
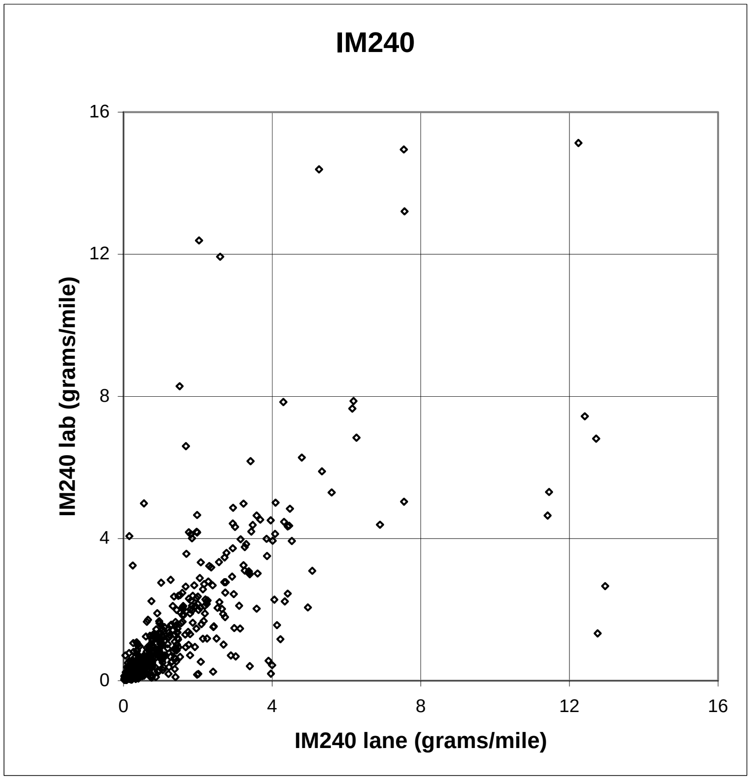
[10] We have limited our discussion to variability of vehicles from test to test. Another source of error in determining true vehicle emissions is that the IM240 and the FTP use a specific driving cycle designed to be somewhat representative of average driving behavior of motorists on the road. However, the FTP and IM240 do not include very high accelerations typical of aggressive driving. In addition, the actual average driving cycle of any individual car likely departs significantly from the specific cycle in the FTP and IM240. While these sources of error may be significant, they are not relevant to the present discussion and we will not analyze them further.

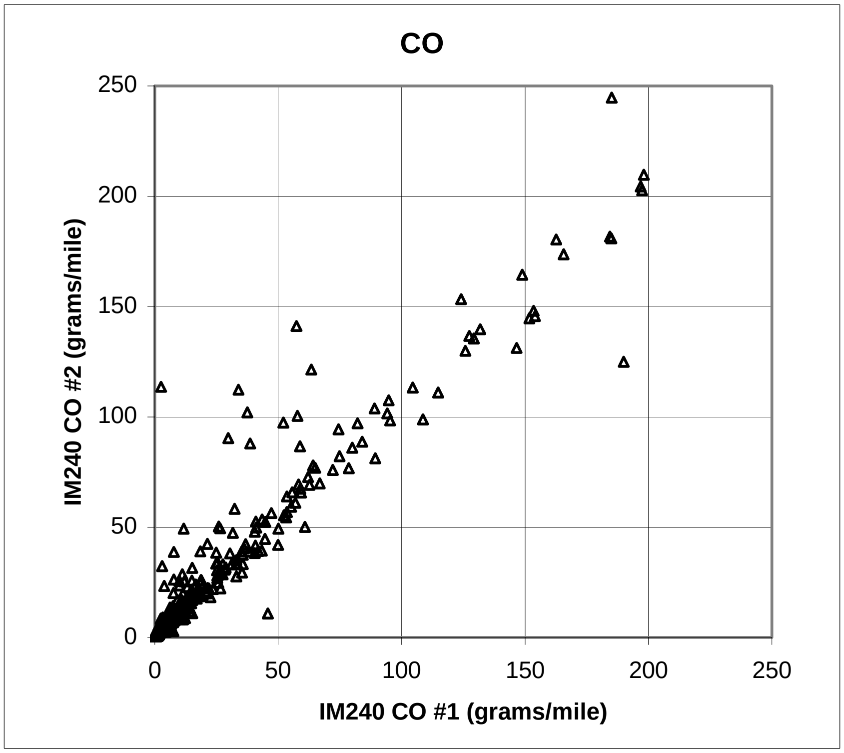
[11] "Incorrect" is of course a relative term in this context. A test result can be incorrect only in comparison to some standard, either another test, or a repeated measurement using the same test.

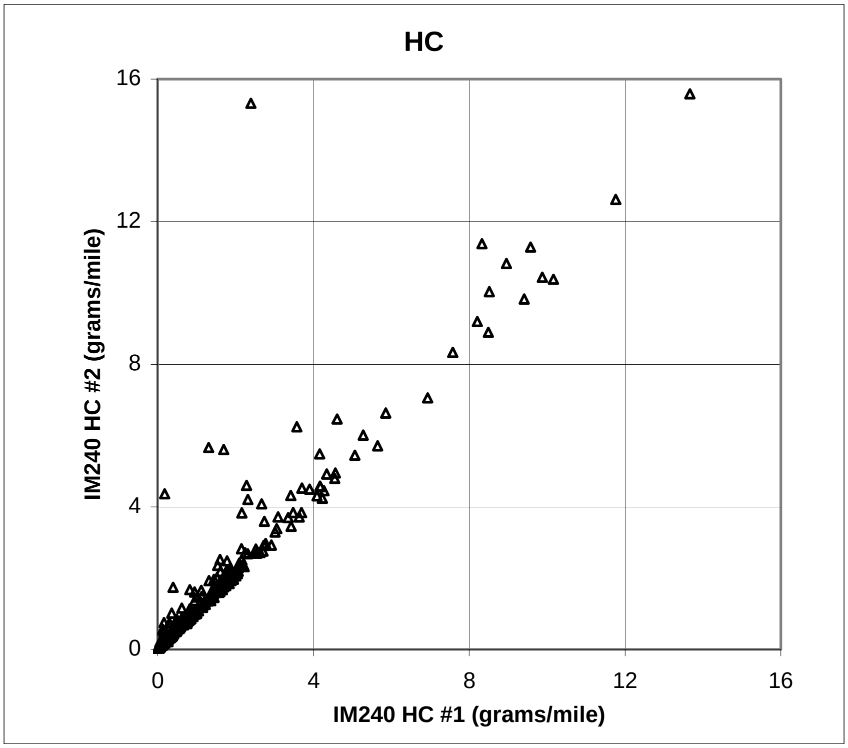
Figures 6a and 6b: Variability of Repeated HC Measurements of Vehicles on RSD and IM240





Figures 7a and 7b: Results of Repeated IM240 CO and HC Tests of 411 Vehicles Under Artificially Controlled Conditions





V. Accuracy of RSD

Now that we understand the context in which vehicle emissions are measured, we can proceed to a focused discussion of the accuracy of RSD. We evaluate the various sources of uncertainty in RSD measurements below.

Measurement Error

We want to know, first of all, if RSD accurately measures what is coming out of a car's tailpipe at the moment when the car passes by. All measurements are, to some extent, intrinsically imprecise. Any given RSD measurement will have some error associated with it. If this error is too large, then the RSD measurement will not be useful in distinguishing low emitters from high emitters.

There are two components to measurement error, *random error* and *systematic error*. Random error will cause repeated measurements to be randomly higher or lower than the "true" value of the quantity being measured. If several measurements are averaged, these random errors will therefore cancel out. The uncertainty of the averaged measurements will then be much lower than the uncertainty in any individual measurement.

Systematic error causes measurements to always be higher or lower than the true value by a specific amount or a specific percentage. Systematic error can be controlled through, for example, calibration to a standard. For example, an RSD unit can be calibrated by using gases of known concentration. Random error must be addressed by improvements in process and/or technology that increase the sensitivity and repeatability of the RSD system.

Numerous lines of evidence demonstrate that RSD measurements are an accurate reflection of a car's emissions at the instant the car passes by. As early as 1991, instantaneous RSD measurements of CO and HC were shown to be accurate. Figures 8a and 8b compare remote sensing measurements of CO and HC, respectively, to on-board measurements from an instrumented vehicle. The high r^2 values (0.98 for CO and 0.87 for HC)[12] show that RSD was accurately reflecting the vehicle's actual instantaneous emissions, as measured by on-board instruments (Stedman et al., 1994). Other studies have found similar results (see, for example, Bureau of Automotive Repair, 1995).

Current instruments have improved on these results. Figures 9a and 9b display certification tests for CO and HC, respectively, for one of the latest RSD units.[13] The data were collected in on-road tests under controlled conditions. The data points in the figures represent the RSD reading for a known concentration of a gas. For example, in the case of CO, the standardized concentrations are 0%, 1%, 3% and 5%. The small range of scatter, and high r^2 values for the CO and HC measurements demonstrate high reliability of instantaneous RSD measurements. Within the last few years, RSD capabilities have been extended to include NOx measurements. Figure 9c displays the NOx certification results for the same RSD unit. Once again, the r^2 of 1.00 with low scatter demonstrates that instantaneous NOx measurements are also quite reliable under controlled conditions.

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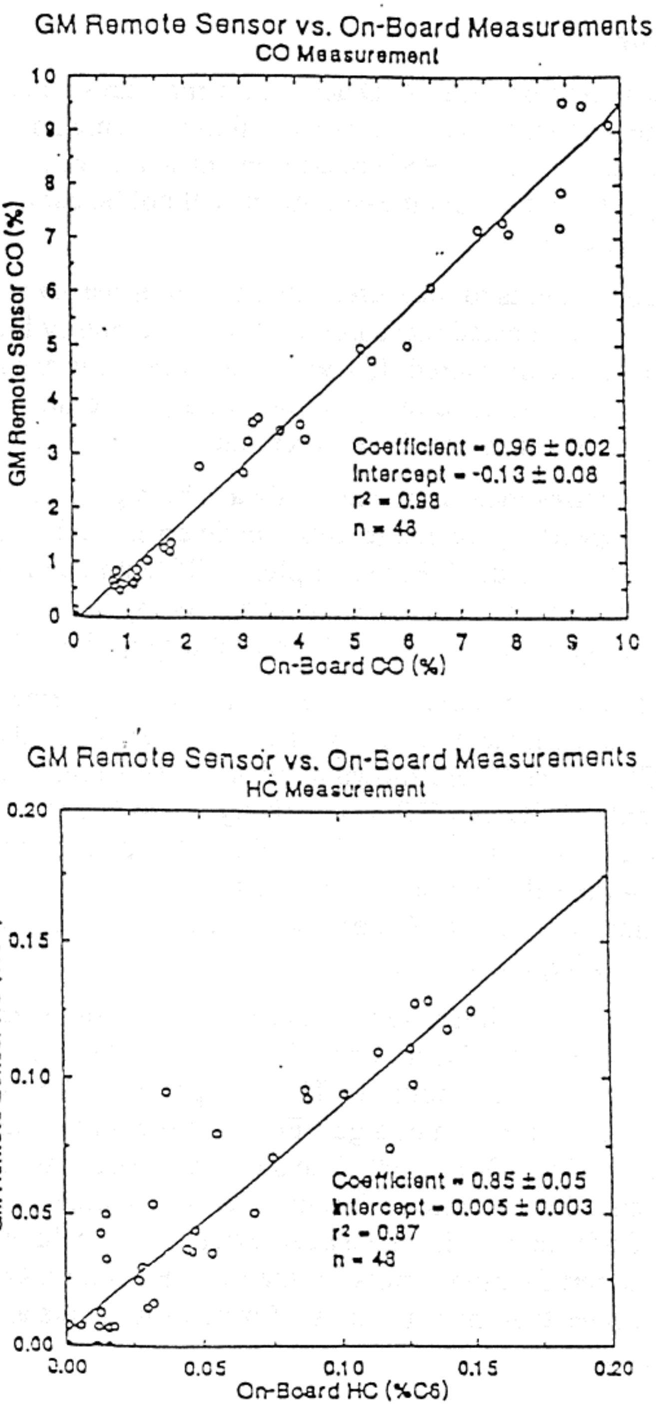
[12] r^2 is the "coefficient of determination" and is equal to the square of r, the correlation coefficient. r^2 can have a value between zero and one. The closer the value is to one, the greater the ability of one measurement to predict the value of the other. A value close to zero indicates that there is little or no relationship between two variables. In this case, the high r^2 values for RSD when compared with the instrumented vehicle show that RSD accurately measures instantaneous vehicle emissions.

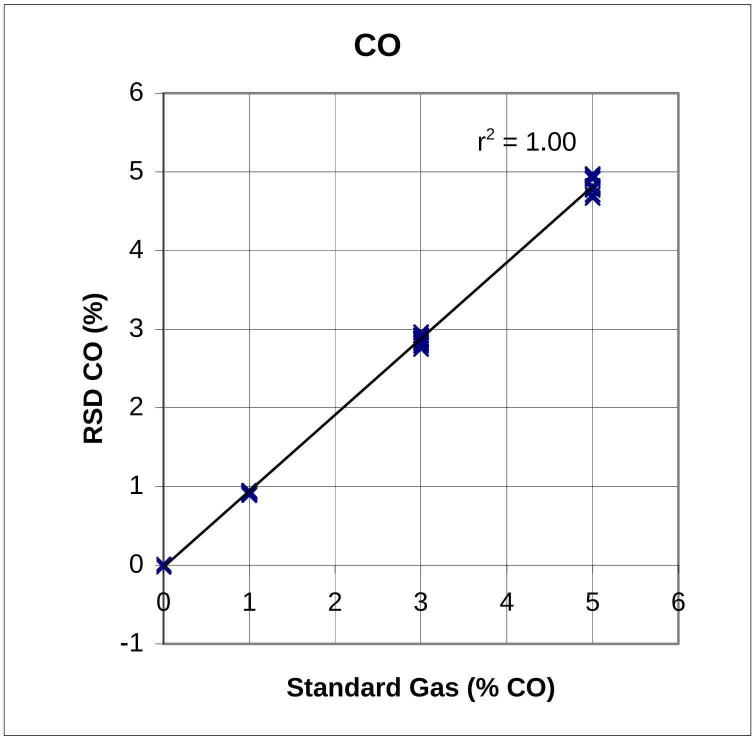
[13] Thanks to RSTi for supplying the data used to generate figures 9a, 9b and 9c.

Figures 8a and 8b: Comparison of RSD CO and HC Measurements with an Instrumented Vehicle



Figures from Stedman et al., 1994

Figures 9a and 9b: CO and HC Certification Test Results for the RST3000 RSD Unit



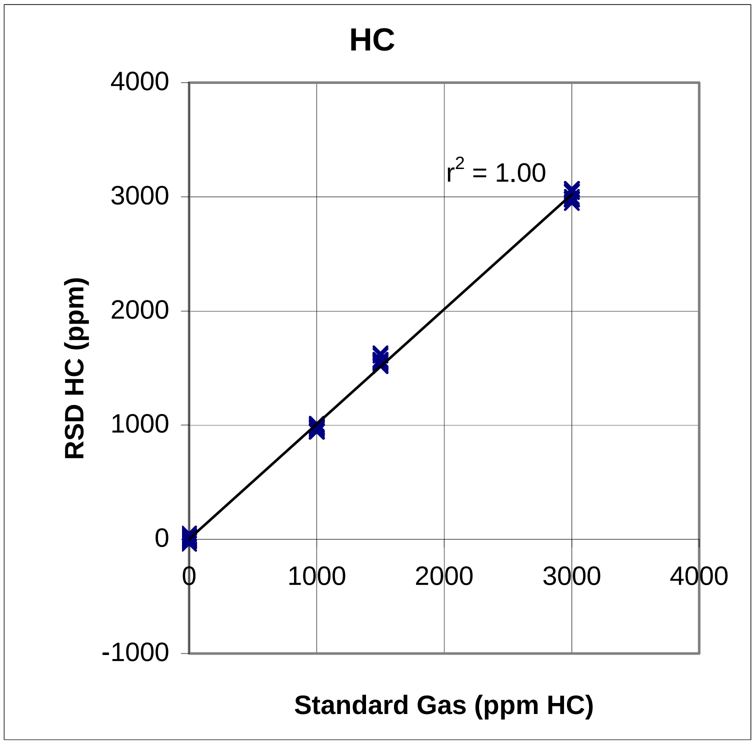
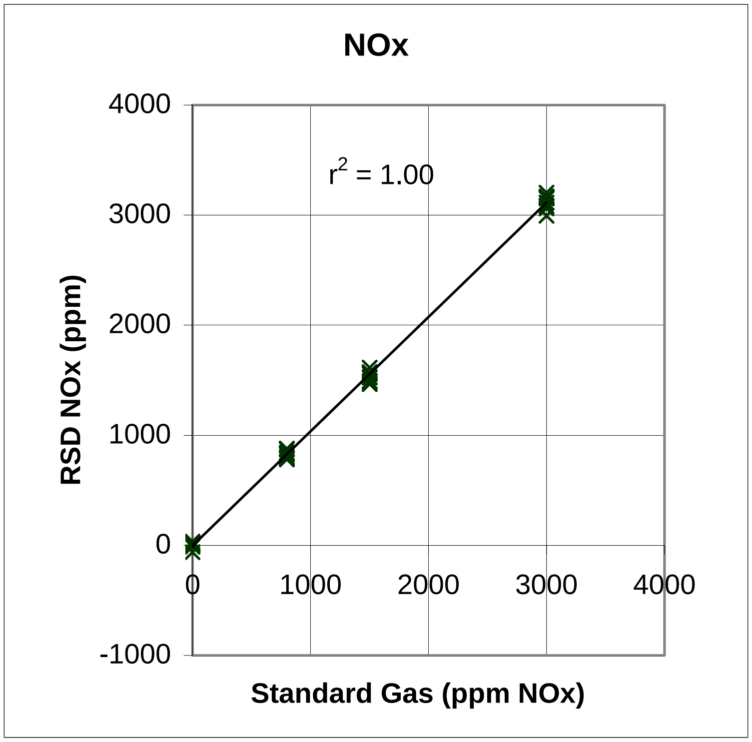


Figure 9c: NOx Certification Test Results for the RST3000 RSD Unit



The data in figures 9a, 9b and 9c can be used to show that RSD measurement error is small compared to the range over which vehicle emissions vary. Note, for example, that the maximum scatter in the RSD measurements for CO is no more than a few tenths of a percent. The vast majority of cars on the road have CO emissions below 1%, while gross polluter cut points are typically greater than 3% or 4%. The difference in emissions between a gross polluter and a clean car is therefore several times greater than the measurement error in an individual RSD measurement. It is thus rare for an RSD unit to read low when a car's instantaneous emissions are high, and vice versa. The same line of reasoning holds for HC and NOx.

The latest research instruments developed by Don Stedman's group at the University of Denver have still greater accuracy and lower detection limits than the instruments described above.[14] In addition, competing RSD technologies developed by Unisearch and Aerodyne may have even smaller measurement errors and greater sensitivity (Jiménez et al., 1998; Nelson et al., 1998; MacKay et al., 1995). This suggests that the accuracy of production RSD units will improve still further over the next few years. We conclude that (1) intrinsic measurement error is not a significant source of uncertainty in RSD measurements for the purposes of distinguishing low and high emitting cars, and (2) RSD measurements provide an accurate reflection of the instantaneous emissions of a vehicle at the moment the vehicle passes by the RSD unit.

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[14] Unpublished results supplied by Peter Popp of the University of Denver and presented to the Committee by Professor Stedman at its July 14, 1998 meeting.

How Representative Is an RSD Measurement?

While RSD measurements are instantaneously accurate, we also need to know whether this instantaneous measurement is an accurate reflection of a vehicle's emissions in general. There are a number of ways to pose this question. However, for the purposes of current I/M programs, we are specifically interested in whether RSD is a good predictor of whether a car will pass or fail an I/M test.[15]

The California Air Resources Board (CARB) collected data in 1992 comparing RSD CO and HC measurements to Federal Test Procedure (FTP) measurements for a fleet of 526 cars solicited as part of CARB's ongoing fleet surveillance program.[16] The RSD measurements were taken under controlled conditions of speed and acceleration. We used the average of two RSD HC and CO readings as a predictor of FTP failure. We set RSD cut points for two different scenarios: (1) fail vehicles that are in *either* the highest 10 percent of emissions for CO or for HC, and (2) set cut points for CO and HC of 4% and 0.1%, respectively, and fail vehicles that exceed *either* of these cut points. The results for each scenario, displayed in Table 2, show that RSD can capture a substantial portion of excess emissions[17] with a relatively low false failure rate.[18]

Table 2. RSD Performance when Compared with the FTP Under Controlled On-Road Conditions

RSD CO Cut Point	RSD HC Cut Point	Failure Rate	Excess Emissions Captured			False Failures
			CO	HC	NOx	
2.5%	0.13%	16%	65%	70%	27%	6%
4%	0.10%	20%	65%	72%	39%	7%

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[15] Another way to pose this question would be to ask whether RSD measurements *correlate* well with, say, IM240 measurements. While such a question might be intrinsically interesting, it is not relevant for I/M purposes where we are simply interested in determining which vehicles will fail and which will pass.

[16] Thanks to Mark Carlock of CARB for supplying this data set.

[17] Excess emissions are those emissions that are above a predetermined cut point. We have used EPA's recommended final cut points for I/M programs (EPA, 1995) as follows (in grams per mile):

Model Year	HC	CO	NOx
1983+	0.8	15	2
1981-1982	0.8	30	2
1980	0.8	30	4
1977-1979	3.0	65	4
Pre-1977	3.0	65	6

[18] We used the same RSD cut points regardless of age in the illustrative example above. In an actual I/M program, RSD gross emitter cut points would likely vary by vehicle age to reflect different certification standards in different model years.

The data above were acquired under controlled conditions on a test track. On-road measurements should introduce greater uncertainty because speed and acceleration can not be directly controlled, but can be only indirectly constrained through site selection. In 1991, Don Stedman and co-workers measured cars with RSD on the road in Rosemead, California (Stedman, et al., 1994). Of cars with at least one RSD reading greater than 4% CO or 0.1% HC on either of two remote sensors, 66 of 68 cars failed the IM240 test; a false failure rate of three percent. In this same study, 92 percent of 334 cars with high RSD readings failed a roadside BAR90 test. In another study in Orange County in 1996, Doug Lawson pulled over cars with at least two high readings using the same RSD cut points (Lawson, et al., 1996). In this case, 95 out of 103 vehicles failed the IM240; a false failure rate of eight percent. These false failure rates are consistent with the false failure rates obtained with replicate IM240 testing (recall the discussion in the previous section), suggesting that the differences between RSD and IM240 results are due largely to variability in the vehicles rather than to inaccuracies intrinsic to an RSD measurement.[19]

In the discussion above, we found false failure rates for RSD of between three and eight percent at the chosen RSD failure cut points. Higher cut points would reduce false failure rates, but would also reduce the number of gross emitters detected in any given group of cars. There is thus a tradeoff between false failure rates and number of gross emitters detected that must be weighed by policymakers in designing a gross polluter identification program.

Based on these results we can conclude that (1) under controlled conditions and also in on-road research studies, RSD measurements accurately predict whether a car will fail an I/M test when the tests are performed at about the same time, and (2) RSD cut points can be set so that a substantial portion of excess HC and CO emissions are captured, while still maintaining relatively low false failure rates.

VI. Factors That Affect the Quality of RSD Data

The data and analysis presented above tell us how well RSD can perform when on-road locations are chosen judiciously, and when experienced researchers ensure proper functioning and calibration of the RSD equipment. In a large-scale RSD program, ensuring the ongoing acquisition of high-quality RSD data might be more challenging. Below we survey the conditions that result in acquisition of high-quality RSD data.

Site Selection

The nature of the locations chosen for collecting RSD data will determine the quality of the data collected. A number of factors can cause invalid RSD readings. For example:

- ***Cold Starts.*** If a car is not warmed up (i.e., the car is in “cold start” mode) then its emissions will be high even though the car is otherwise functioning properly. RSD sites must be chosen so that the cars that are measured have been operating for a least a few minutes

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[19] The Ontario Clean Screen Study, the Greeley RSD study, and the Arizona Clean Screen study all include data that could be used to assess the ability of RSD to accurately predict IM240 failure. These data sets are not currently available. We are attempting to acquire these data and hope to analyze them in the future. In addition, to the extent that BAR collects RSD data along with its roadside pullover data, it will be possible to compare RSD and the ASM test. These data will also be useful for determining how well RSD NOx measurements predict failure of I/M tests.

before driving by the RSD unit. For example, sites situated next to residential areas will likely include some cars in a cold start mode if measurements are taken during morning commute hours. RSTi is attempting to develop a cold start sensor that will detect whether the underside of a car is hot when it goes by a remote sensor.[20] It might also be possible to determine whether a car is warmed up by using remote sensing to measuring the temperature of its exhaust.[21]

- ***High Load.*** If a car is accelerating at greater than about three miles per hour per second, or is otherwise under a heavy load (such as on a steep grade), the car may go into "power enrichment" mode. Under these circumstances, cars that are otherwise low emitters and have no repairable defects will have very high emissions. This problem can be controlled in two ways. First, RSD sites can be selected so that few cars are under very high acceleration or load. Second, speed and acceleration of cars can be measured as they pass the RSD unit. Speed and acceleration data, combined with a measurement of the road grade, can be used to determine vehicle load, allowing invalid RSD measurements to be removed from the data set.
- ***Weather.*** Wet roads, rain, and high winds can prevent RSD equipment from collecting valid data. Because metropolitan areas in California have little or no rain for large portions of the year, weather is unlikely to have a major impact on RSD in the state.
- ***Traffic Control.*** RSD measurements must be made across only a single lane of traffic. Thus, RSD must be performed in areas where there is already a single lane of traffic, or traffic flow must be reduced to a single lane. This may reduce the number of sites available for RSD in an ongoing program.

To the extent that fewer appropriate RSD sites are available, the portion of the fleet that can potentially be measured might be reduced. On the other hand, metropolitan areas likely have some very productive sites that would allow measurement of a large portion of the fleet at just a few locations. For example, the Denver Smart Sign RSD unit is located on a heavily trafficked off-ramp where it measured about 10 percent of the entire Denver metropolitan vehicle fleet at least once in one year (Bishop et al., 1998).

Instrument Quality Control and Calibration

An ongoing RSD program would include several RSD instruments operated in an area on a routine basis. Collection of high-quality data will require a combination of relatively easy-to-use instrumentation and crews with training adequate to ensure proper operation of the equipment. For RSD equipment to function properly, the light beams that cross the roadway must be aligned, and the instrument must be properly calibrated with standardized gases of known concentration.

Research instruments and early commercial models generally have few or no built in fail safe systems that alert the user when the instrument is not operating within proper parameters. However, recent commercial models include sensors and software to (1) alert users of calibration and alignment problems, (2) require periodic calibration and alignment checks in order to continue collecting data, and (3) reject measurements that do not meet quality control criteria.[22] In addition, the Denver Smart Sign unit has demonstrated that an unmanned RSD unit, controlled

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[20] Presentation by Craig Rendahl of RSTi at the IMRC meeting on July 14, 1998.

[21] Personal communication with Bob Slott, August 19, 1998.

[22] Personal communications with Gary Bishop of the University of Denver, and Jack Marino and Craig Rendahl of RSTi. Presentation by Craig Rendahl of RSTi at the IMRC meeting on July 14, 1998.

remotely and with biweekly maintenance, can collect valid data on an ongoing basis. (Bishop et al., 1998).

VII. RSD in Practical Applications

We have seen how vehicle variability adds another level of complexity to the evaluation of the relative accuracy of different emissions tests. However, practical applications of RSD won't occur in the relatively idealized circumstances of the studies described above. We will now evaluate the use of RSD in situations that more closely approximate an actual I/M program.

Gross Polluter Identification

In an operating I/M program, weeks might pass between the time a car is identified with a remote sensor and the time the car is brought in for repair. As we have seen, cars undergo intrinsic changes in their emissions. The greater the time between two emissions tests, the greater the likelihood that the state of the vehicle has changed, resulting in greater variability between tests. In addition, motorists might perform maintenance actions on their cars that change the cars' emissions. As a result, vehicles identified as high emitters on the road might not fail when they are actually brought in to a Smog Check station for a confirmatory test. While these factors don't necessarily mean there was something wrong with the quality of the RSD measurements, they can create an apparent discrepancy between the RSD results and results of the confirmatory test.

Gross polluter identification is inherently more risky than clean screening because the factors that cause spurious RSD readings often result in clean cars being identified as dirty, rather than the reverse. Motorists might be displeased if they are cited for driving a gross polluter in the first place. If they are required to bring their car in for a test, only to find out that the test was unnecessary, their ire would likely increase.

Arizona has the only operational gross polluter identification and repair program in the country.[23] In the Arizona program, motorists cited as high emitters on the road are sent a letter requiring them to bring in their car to an I/M test lane within 30 days. Of the motorists cited by RSD, 40 to 45 percent never show up at the I/M test lane. Of those who do show up, 45 to 50 percent do not fail the I/M test.[24] A number of factors probably contribute to the high apparent false failure rate:

- As discussed in Section IV, all tests have significant false failure rates when compared against themselves or against another test, because vehicle emissions are intrinsically variable.
- Arizona I/M officials have found that 25 percent of motorists who pass the test say they actually repaired their car before arriving for the test.[25]
- Motorists who do not show up after being cited as gross polluters are probably more likely to be driving high emitting vehicles when compared with those who do show up. There is evidence that some motorists know they are driving a high emitting vehicle. For example, in

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[23] Texas will begin an RSD gross polluter identification and repair program beginning in September, 1998.

[24] Motorists that don't bring their car in have their registration revoked. However, no fines are assessed and motorists can reregister their car at the next regularly scheduled time that it comes due.

[25] Personal communication with John Schneider of the Arizona Department of Environmental Quality, June 28, 1998.

an RSD study in northern California in 1991, motorists who refused a roadside BAR90 test had RSD emissions that were 2.4 and 2.8 times higher for CO and HC, respectively, when compared with cars of motorists who accepted a roadside inspection (Stedman et al., 1994). This factor will result in higher false failure rates in the cars that do show up, because they are a lower-emitting sub-group of all the cars cited as gross emitters.

- Arizona uses relatively stringent RSD cut points, and relatively loose IM240 cut points. For example, for 1983-1990 model year vehicles, the RSD HC failure cut point is 0.05%, which is at least 50 percent below the gross polluter cut points typically used in RSD studies. On the other hand, Arizona's IM240 cut point for HC is 2 grams per mile, five times higher than the certification level for these vehicles, and 2.5 times higher than EPA's recommended final IM240 cut points.[26] As the separation between the IM240 and RSD cut points decreases, the false failure rate will increase.
- Some of the RSD measurements might be of poor quality. For example, the set-up or calibration of the RSD units might be sub-optimal, or some cars measured by RSD might be under high acceleration or in a cold start mode. We have no information with which to assess to what extent these concerns might be applicable to the Arizona RSD data.

While numerous studies have looked at identification of gross emitters on the road, Arizona's brief experience represents the only example of a complete program to both identify and ensure repair of gross emitters in a real-world situation. From a technical standpoint, false failures can probably be reduced to some extent through more sophisticated fine-tuning of RSD cut points and increased use of speed and acceleration measurements. However, acceptable levels for false failure rates must be determined through value judgements by policymakers and by motorists affected by the I/M program.

Clean Screening

A number of studies have reported on RSD as a means to identify consistently low-emitting vehicles. Under a clean screen program, cars that are consistently low-emitting could be excused from their next scheduled I/M test. For example, a clean screen requirement might be that a vehicle have at least two RSD readings below a pre-determined cut point (and no readings above the cut point) during the year prior to the next scheduled Smog Check.

A concern with clean screening is that some cars that are actually high emitters might be mistakenly passed by a clean screen, allowing them to avoid repair. However, this concern is unlikely to be realized to a great extent in a clean screen program for two reasons. First, poor RSD siting decisions tend to result in spuriously *high* RSD measurements, reducing the risk of false passes. Second, cars that are high emitters on dynamometer tests are unlikely to be consistently low-emitting in on-road measurements. A number of recent studies have assessed the potential for clean screening. For example:

- ***Arizona Clean Screen Pilot.*** Data collected in a recent clean screen pilot study in Arizona (Radian, 1996) confirmed that RSD accurately identifies cars that are low emitting on a dynamometer test. Cars were measured by RSD as they arrived for their scheduled IM240 test in Phoenix, thereby providing RSD and IM240 measurements on the same day. The

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[26] IM240 and RSD cut points for Arizona were listed in program documents supplied by John Schneider of the Arizona Department of Environmental Quality

study found that, using the average of two RSD HC and CO readings for each vehicle, 40 percent of the vehicle fleet could be clean screened, with a loss of a few percent of total excess tailpipe emissions of HC, CO and NOx. Figure 10 displays the results of this study.

The Phoenix study may actually provide a conservative estimate of the clean screening potential of RSD. In the Arizona I/M program, cars that are very low emitting are "fast-passed", that is, the IM240 test is terminated early if a car's emissions are below a certain cut point. Cars that are fast-passed therefore do not receive a full IM240 test. About half of the cars in the clean screen pilot data were fast-passed, and these cars were removed from the data set. The remaining cars that were used for the clean screen analysis were therefore depleted in very clean cars and enriched in marginal cars, relative to the actual on-road fleet. Marginal cars are the ones that are most likely to be incorrectly passed or failed by RSD and other tests because their emissions are more likely to be near the failure cut point on average. Had the fast-pass cars been included in the analysis, RSD would have incorrectly passed fewer cars at any given total pass rate.

Figure 10: Arizona Clean Screen Pilot: Excess Emissions Forgone as A Function of Percent of Fleet Excused from Scheduled Test

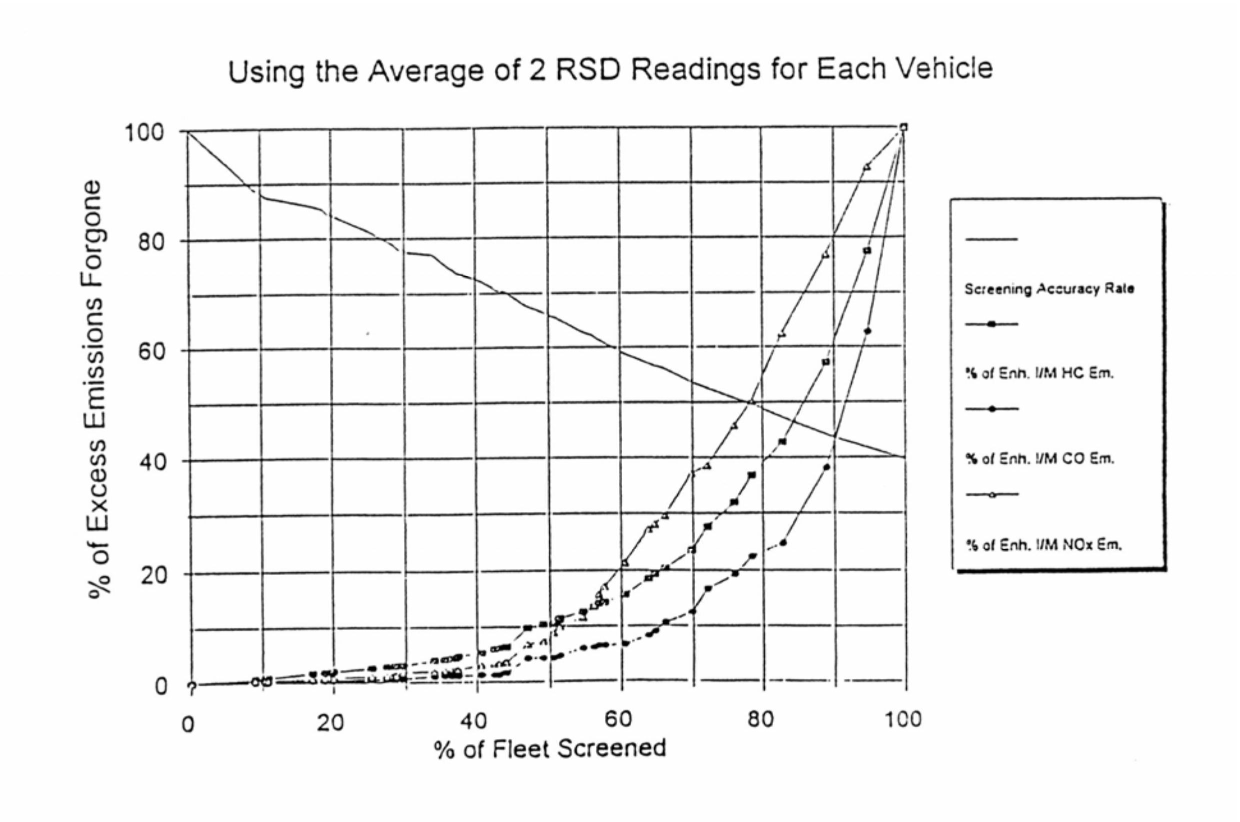

Figure adapted from Radian, 1996

- ***Greeley, Colorado Remote Sensing Pilot.*** The Colorado Department of Public Health and Environment funded a remote sensing pilot program that included on-road RSD measurements combined with solicitation of vehicles for IM240 measurements (Klausmeier and McClintock, 1997). Based on vehicles with at least two RSD readings, 34 percent of the fleet could be excused from scheduled testing with a loss of about eight percent of excess CO and HC emissions (results for NOx were not reported).
- ***Ontario Clean Screen Pilot.*** The Ontario Ministry of Transportation conducted a pilot project in 1993 to assess the ability of RSD to clean screen vehicles. About 10,000 vehicles were measured by three remote sensors under controlled conditions, and then tested on an IM240. Results published for the first 4,000 vehicles indicate that about 30 percent of the fleet could be excused from further testing, while forgoing capture of about 10 percent of excess emissions for all three pollutants (Petherick, undated).[27]

Each of the studies above reported the amount of excess emissions forgone for any given percentage of the fleet that is excused from further testing. Desirable levels for the percentage of the fleet excused from further testing, and acceptable levels for excess emissions not captured will depend on many factors, including: (1) the actual emission reduction effectiveness of the program with any given level of clean-screening, (2) the ability of mechanics to repair marginally failing cars – the cars most likely to be incorrectly passed by a clean screen, (3) the importance assigned to cost reduction, and (4) the importance assigned to consumer convenience. These and other factors must be weighed by policymakers in determining the appropriate role for clean screening in the Smog Check program. In any case, RSD seems capable of identifying significant portions of the on-road fleet that are low-emitting, while allowing relatively few high emitters to slip through the cracks.[28]

Based on the above studies, EPA is developing guidance on clean screening that will be released soon. This guidance will include EPA's decision regarding how much emission reduction credit EPA will deduct as a result of clean screening. EPA expects that states will be able to excuse up to about 40 percent of vehicles from testing while maintaining acceptable levels of emission reduction credit (EPA, 1998).

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[27] The Ontario RSD measurements were acquired under highly controlled conditions, while the Greeley and Arizona RSD measurements were acquired on the road. Nevertheless, the on-road measurements achieved better results. The reasons for this counterintuitive result require further investigation.

[28] We have not discussed the issue of evaporative emissions here. The percent of total hydrocarbon (HC) emissions from vehicles that are due to evaporative emissions is unknown, but is probably substantial. RSD does not detect evaporative emissions, so it is possible that some cars that are clean-screened could nevertheless have high evaporative emissions. However, recent studies have shown that a substantial portion of evaporative emissions problems are not detected by traditional I/M program tests. For example, in a recent study of evaporative emissions, 46% of cars with high evaporative emissions did not fail either the pressure or purge tests that EPA recommends for Enhanced I/M programs. These high emitters that did not fail accounted for 52% of evaporative emissions from the high evaporative emitters, and 40% of evaporative emissions from the entire fleet of 300 randomly chosen vehicles in the study (Brooks, 1994). Clean screening would have less impact on the effectiveness of I/M to the extent that cars with high evaporative emissions would also not be detected by a traditional I/M program without clean screening.

Program Evaluation

RSD allows relatively inexpensive collection of emissions data from hundreds of thousands of vehicles. These data can be used to determine if cars that have been through I/M are lower emitting than cars that haven't. Because this use of RSD relies on averages of measurements for hundreds or thousands of cars, the pitfalls that can arise in measurements of individual cars, such as in gross polluter identification, will not occur. The random errors of the individual measurements (regardless of whether they are due to measurement error in the instrument, or to an individual measurement being unrepresentative of that individual car) will cancel out when averaged over a large sample, giving a fleet-average result that is very accurate.[29] Two recent studies have employed remote sensing data to evaluate existing I/M programs (Wenzel, 1998; Klausmeier et al., 1997).

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[29] However, the RSD measurements must be made on cars that are not highly accelerating and not in a cold start mode as these factors would introduce bias into the data.

IX. Recommendations

BAR’s 1998-99 budget includes $5.3 million for remote sensing. BAR should use these funds to lay the groundwork for increased implementation of RSD in the coming years.

Research Oriented Activities

BAR should undertake the following research activities:

- ***Ongoing Standardized RSD Data Collection.*** Begin an ongoing program to collect high-quality RSD emissions and license plate data at several sites around the state. Results of data collection can be used to: (1) evaluate the effectiveness of Smog Check II, (2) develop experience in the routine use of RSD and determine whether a relatively foolproof use of RSD equipment is possible, (3) determine ways to minimize errors of commission and omission, and (4) understand changes in the emissions behavior of individual cars, and of the fleet overall, with time.
- ***Clean Screening Feasibility Study.*** BAR should determine the feasibility of clean screening in California and develop plans for a clean screen pilot program. The pilot program should include a determination of the relative cost and cost effectiveness of clean screening under conditions in which motorists know that clean screening is available.
- ***Combine RSD with Roadside Pullovers.*** Make RSD data collection a standard part of BAR’s roadside pullover data collection in order to (1) gather more data comparing RSD with traditional I/M tests, and (2) determine emissions for cars in which motorists refuse to submit to a roadside Smog Check.
- ***Assess RSD NOx Capability.*** Assess the effectiveness of new RSD NOx technology under on-road conditions.
- ***Compare the Unisearch and RSTi RSD Systems.*** BAR should evaluate the capabilities of the Unisearch and RSTi RSD systems, as well as any commercial units available from other suppliers.

Consumer Information

- ***Implement A California “Smart Sign.”*** BAR should install Smart Signs in one or more areas of the state to inform motorists of the emissions performance of their cars. The program should include follow-up surveys to assess motorist reaction to the information provided. Goals of this program would include: (1) develop a positive image for remote sensing among motorists, (2) acclimate motorists to the ongoing use and potential benefits of remote sensing, and (3) determine if some motorists voluntarily repair their cars based on the information provided by the Smart Sign. Data from the Smart Sign program could also inform the research activities detailed above.

Process Issues

- ***Foster Competition.*** BAR should foster competition by not locking the state into any one supplier of RSD services. BAR should also not lock the state into long term RSD contracts so that the state can take advantage of potential future reductions in costs for RSD equipment and services.
- ***BAR Updates on RSD Activities.*** BAR should keep IMRC members and staff informed of BAR's RSD activities, and provide an opportunity for the IMRC to comment on RSD-related activities, such as research studies and RFPs, before BAR goes forward with them.

Appendix: Cost Estimates of an RSD Program

We are interested in three aspects of the cost of RSD: Total cost, cost per vehicle, and cost effectiveness (cost per unit of emission reduction). Unfortunately, because large-scale, ongoing RSD programs are a relatively new phenomenon, there are few sources of data on which to base cost estimates. Furthermore, current costs provide only a snapshot of a dynamic process that depends on several factors that change both with time and with the specific context of each state that implements RSD. Thus, even good data from other states today will not accurately predict what RSD will cost in California tomorrow. Even though definitive cost estimates are not currently possible, we can still identify the major factors that determine the cost of RSD and make rough estimates of likely costs for different types of RSD applications.

The cost of RSD depends on at least the following factors:

- ***Market Competitiveness.*** RSD costs will be higher to the extent that there is little or no competition in the RSD industry. Competition in the RSD market could increase in two ways. First, new RSD technologies could be developed. Until recently, Remote Sensing Technologies, Inc. (RSTi) was the exclusive producer of commercial RSD equipment.[30] Unisearch and Aerodyne have recently developed their own parallel RSD technologies. Unisearch RSD units will be deployed in the Texas gross polluter identification program, scheduled to begin in September.

  Of the three companies, RSTi has the most refined and well-integrated system, having had several years to engineer the technology. Furthermore, the RSTi system measures all three pollutants, while the Aerodyne system measures NOx and CO, and the Unisearch unit measures only CO. Both companies plan to expand capabilities to all three pollutants in the near future. Mustang Dynamometer Corporation has combined with Unisearch to form a new company called MD LaserTech to refine and market the Unisearch device.

  A second way for competition to increase would be for the companies that control patented RSD systems to sell RSD units to other companies that wish to provide RSD services. There are probably only a limited number of commercially practical RSD technologies. If the companies that own the rights to these technologies also control their deployment, then competition will be limited to a small number of companies. However, there might be dozens of companies that would be interested in deploying remote sensors if RSD systems were available for purchase. The second form of competition probably becomes more likely to the extent that there is more than one supplier of the equipment. Prices for RSD equipment and services will likely come down as new companies become serious players in the RSD market.

- ***Total Number of RSD Measurements and Productivity of RSD Sites.*** Two major factors affect the total number of RSD measurements that are necessary: (1) the percentage of the fleet that we wish to measure, and (2) the minimum number of times we wish to measure each car. Furthermore, the incremental number of total measurements required increases more rapidly at both higher percentages of fleet coverage, and at higher minimum numbers of measurements per car.

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[30] RSTi has an exclusive license on the patent for the Stedman RSD unit.

Data on the number of measurements necessary for a given level of fleet coverage are limited. However, recent studies in Sacramento and in Greeley, Colorado suggest that in order to measure, say, 50 percent of the fleet at least twice, the total number of measurements necessary is equal to between 2.0 and 2.4 times the size of the registered fleet (Radian, 1995; McClintock and Stock, 1998). For fleet coverage of 70 percent, these values rise to 3.4 and 3.8. This represents a 58 percent increase in the number of measurements for a 40 percent increase in fleet coverage. It should be noted, however, that RSD is more likely to see cars that are driven more. At any given percent fleet coverage, RSD is sampling a higher percentage of total vehicle miles traveled (VMT). For example, if we measure 70 percent of cars by RSD, we might be capturing, say, 80 percent of total VMT.

There are two caveats to the above estimates. First, these estimates are based on studies in which cars were sampled under “natural” conditions. That is, the cars were measured under conditions that represented the normal driving patterns of the respective regions. Motorists had no incentive or disincentive to drive by a remote sensor.

Second, the data for these estimates were obtained by measuring emissions at a wide range of sites, some of which might not have been very productive. Large metropolitan areas will probably have some very productive sites with a high traffic volume and/or a large number of unique vehicles. Such sites might include roads near stadiums, convention centers, and large shopping malls. Sites such as these could allow more efficient measurement of large numbers of vehicles, lowering costs. For example, the Denver Smart Sign RSD unit, located on a major exit ramp in Denver, measured 250,000 unique vehicles at least once in one year — roughly 10 percent of all vehicles in the Denver metropolitan area (Bishop, et al., 1998).

- ***Motorist Response to RSD.*** If motorists seek out remote sensors, as they might under a clean screen program, then fewer total measurements would be necessary in order to measure a given percentage of the fleet. Conversely, under a gross polluter program, motorists who suspect their cars are high emitting might purposely avoid driving by remote sensors. Incentives, such as subsidized repairs or annual (rather than biennial) testing for cars not seen by RSD, might be necessary to encourage drivers of potential high emitters to drive by RSD units.
- ***Level of Automation.*** Most aspects of RSD are susceptible to substantial levels of automation. RSD data can be collected by unmanned, bunkered units. These bunkered units can be designed to run automatic periodic calibrations, and can be equipped with software to reject readings that do not pass a series of quality checks. Some portions of the post-collection data processing could also be automated, as could generation of notices for mailing. The greater the level of automation, the lower the overall cost.
- ***Economies of Scale.*** There are potential economies of scale in an ongoing, massive RSD program when compared with the typical research studies that have been carried out to date. First, RSD equipment will likely be cheaper when purchased in bulk rather than in single units. Second, labor can be used more efficiently in a large program. For example, a highly trained engineer is necessary to keep RSD units maintained and in service. But one engineer could probably service ten or 15 units as well as three or four. Similar arguments apply for other aspects of RSD, such as data auditing and analysis.

- ***Short-Term vs. Long-Term.*** RSD costs will likely decrease with time for several reasons. First, as discussed above, competition is likely to increase due to new companies entering the market. Second, more opportunities for automation will be exploited as program managers learn how to achieve greater integration and computerization of program components. Third, incremental improvements in RSD hardware and software will reduce the need for labor-intensive auditing and quality assurance. Fourth, RSD siting will improve with experience, increasing the percentage of readings that are valid and usable. Overall, these factors will likely result in a more routine and mature program with mid-term and long-term costs that are lower than early program costs.

Current and Future Costs for an RSD Reading[31]

On a research basis, the cost of RSD is about 75¢ per valid reading (Rodgers, 1998; McClintock and Stock, 1998).[32] This cost includes labor and equipment for emissions measurements, manual data entry for license plates that can't be read automatically, data quality assurance, and license plate matching with the state's vehicle registration database. Also included is the fact that some measurements will be invalid due to problems with some of the RSD readings themselves and due to some cars being unregistered or from another state.

These costs could almost certainly be brought down in a large-scale California program. The main reason is that RSD research projects are more labor intensive than an ongoing routine program would be. For example, at the Air Quality Laboratory at the Georgia Institute of Technology, a single remote sensing site crew includes two equipment operators, an engineer, and a technician, plus a data entry clerk and a technician to process the data after it is collected (Rodgers, 1998). An ongoing RSD program would likely require only one technician to staff each remote sensing site, and could also include a substantial number of unmanned, bunkered units that do not require any on site staff.[33]

On the other hand, there are countervailing factors that could increase the cost of RSD in an actual program. For example, most remote sensing to date has been done with research units or early commercial models. The newer commercial units that would be used in a California program might be more expensive due to the inclusion of significant research and development costs in the price of the units. However, even if added R&D costs raised the price of an RSD unit by $50,000 (current RSTi units cost about $300,000), this would only add about 2¢ to the cost per valid RSD reading.[34] Absent a monopoly situation, it appears likely that the cost of an RSD reading in a large-scale California program will be lower than costs in current research programs.

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[31] The cost estimates in this section are based on past experience and future projections of costs based on the real costs of the labor and equipment involved in RSD. If the RSD market has only one supplier of equipment, then costs will undoubtedly be higher than would be expected by looking only at the real costs of delivering RSD services.

[32] Arizona's gross polluter identification program has a cost per valid RSD measurement of 43¢ (calculated from data supplied by John Schneider of the Arizona I/M program that included the annual cost of the contract with RSTi and the number of valid readings collected each month). However, this cost may be an underestimate of the true costs of RSD measurements in this program. Hughes originally entered into the contract for the Arizona program. RSTi assumed responsibility for the contract when it purchased Hughes's RSD interest. RSTi has asserted that this contract is not profitable and will not be renewed under the same terms (Adams, 1998). For this reason, the 43¢ figure should probably not be considered as a reliable estimate of real costs for this program.

[33] One unmanned, bunkered RSD unit is already operating in Denver, but commercial versions are not yet available.

[34] Assuming $50,000 amortized over five years, and 600,000 valid readings per year, we get $10,000/600,000 = 1.7¢

We have attempted to estimate the cost of a routine RSD program that would be less labor intensive than previous research studies. We assume the following program elements:

- Total program cost of $7.9 million per year, consisting of the following:
  - Fifteen central-office staff at $1.1 million per year including salaries, benefits, operating expenses, and overhead, plus $200,000 per year for information technology.[35]
  - Fifty RSD units each costing $300,000, amortized over five years, plus replacement parts and other consumables costing $500,000 per year. Total cost: $3.5 million per year.
  - Fifty-five field staff (50 site operators and five engineers to maintain the equipment) costing $3.1 million per year, including salaries, benefits, operating expenses, and overhead, as well as 50 vehicles for the field staff.
- The average RSD unit collects 600,000 valid readings per year, for a total of 30 million emissions measurements per year.

Then the cost per valid reading would be $7.9 million/30 million, or 26¢ per valid reading. This cost estimate is sensitive to the cost per RSD unit, the productivity of the RSD units (i.e., the number of valid readings per year) and the amount and cost of the labor involved in collecting the data. We have attempted to use conservative assumptions for these values. If the units were instead unmanned, labor costs would drop and productivity would increase because the units would be operating 24 hours per day rather than, say, seven hours per day. Assuming unmanned units and a 50 percent increase in valid readings per year, the cost would drop to about 12¢ per valid reading. On the other hand, if RSD units cost $400,000 instead of $300,000, then costs would rise to 30¢ per valid reading.

Cost Per Vehicle Clean Screened. In an RSD program we are actually interested not in the cost for an individual measurement, but in the cost per vehicle clean screened or identified as a gross polluter. In a clean screening program, for example, we might want to measure a vehicle at least twice during the year before its biennial test in order to be sure that it is low emitting on an ongoing basis. To be sure of measuring most of the vehicles at least twice, some vehicles would end up being measured more than two times. For example, based on experience with the Greeley RSD pilot program, McClintock and Stock (1998) have estimated that to measure 70 percent of vehicles two times, one would need a total number of RSD measurements equal to 3.8 times the size of the registered fleet.

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[35] We assumed benefits equal to 30 percent of salary, and operating expenses and overhead equal to 35 percent of salary. These are typical values for state programs.

We make the following assumptions to determine the cost per vehicle for clean screening:

- Of the vehicles with valid measurements:
    - About 25 percent of cars are already exempt from biennial testing.[36]
    - Half of the vehicles otherwise eligible for clean screening are more than one year away from their next biennial test.
- Seventy-percent of the registered fleet will be measured at least two times per year requiring, on average, 3.8 measurements per vehicle.
- Thirty-five percent of vehicles otherwise eligible for biennial testing will be clean screened out. That is, of the 70 percent of the fleet actually measured, 35 percent will be exempted by clean screening. Cars that are not measured are, of course, ineligible for clean screening.
- The cost per valid test is 75¢, where a valid test is assumed to include at least one valid pollutant measurement and a license plate matched to the registration database.[37]

Under these circumstances, about 9.2 percent of the entire vehicle fleet, or 25 percent of the cars that would otherwise have been required to go in for a Smog Check, would be clean screened out of biennial testing each year.[38] About 41 valid RSD tests would be performed at a total cost of about $31 for each vehicle clean screened. The cost would be substantially lower if (1) motorists purposely seek out remote sensors to avoid the time and cost of scheduled testing, and/or (2) the cost per valid RSD reading decreases due to automation, or other technological improvements. For example, if 90 percent of the fleet could be measured at least twice with an average of three measurements per registered vehicle, and the cost per valid reading were 26¢, then we would need 25 RSD measurements at a cost of about $7 for each vehicle clean screened.[39] Under this scenario, about 32 percent of the cars that would otherwise have to go for a Smog Check would be excused.[40]

There might be other ways to reduce the cost of clean screening. For example, RSD units could be situated in areas that have more low-emitting cars, or a larger percentage of the fleet could be made eligible for clean screening by using higher cut points. Different strategies entail their own risks. Seeking out areas with mostly low-emitting cars might raise equity concerns among people who live in lower income areas where there are fewer low-emitting cars. Raising

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[36] Cars that are three or less years old make up about 21 percent of the fleet (cars in their fourth year are eligible for clean screening because they must be tested at the end of their fourth year) and cars that are older than the 1974 model year make up about 4 percent of the fleet.

[37] This cost per *valid* test includes the fact that some readings will be invalid due the car being unregistered, being from out of state, having an unreadable license plate, etc.

[38] To get the percent of the total fleet clean screened, we proceed as follows: (75% of the total fleet is subject to biennial testing) x (70% of these are measured at least twice) x (35% of these are low-emitters eligible for clean screening) x (50% of these will be Smog Checked within one year) = 0.75 x 0.7 x 0.35 x 0.5 = 0.092 = 9.2% of the total fleet clean screened each year. To get the percent reduction in the number of cars that would otherwise have been required to go in for a Smog Check in a given year, proceed at follows: (70% of cars that will require a Smog Check within one year are measured at least twice) x (35% of these are low-emitters eligible for clean screening) = 0.7 x 0.35 = 0.245 = 24.5% of the cars that would have required a Smog Check are now clean screened.

[39] We have not included an additional cost for notification of motorists by mail because we assume that motorists would be notified of their clean screen eligibility at the same time that their registration is due.

[40] 32% = (90% of the fleet measures at least twice) x (35% of those measured are exempted by clean screening).

clean screen cut points might allow more high emitting cars to be improperly clean screened (though such cars might still be caught at a later time through an on-road gross polluter program).

We have calculated a reasonable cost range for clean screening of $7 to $31 per vehicle clean screened. To determine whether this is a good deal, we need to compare it to alternatives. The obvious alternative is the current emissions test in the Basic and Enhanced programs. Given our high-end estimate, clean screening would cost substantially less than the average of $52 for an Enhanced Smog Check and a bit more than the $25 for a typical Basic Smog Check. Given our low-end estimate, clean screening would be substantially cheaper than either type of Smog Check. If the cost of motorists' time is included, the case for clean screening is even more favorable.[41]

Gross Polluter Identification. The costs of gross polluter identification are similar to those for clean screening in terms of the actual RSD measurements. However, a gross polluter program includes the additional cost of generating and mailing a letter to the motorists whose cars are identified by the program. Furthermore, because of the political sensitivity of citing motorists for driving gross polluters, greater quality control might be prudent to ensure that cars with low emissions are not incorrectly identified as gross polluters. Recall that the factors that tend to vitiate remote sensing readings, such as cold starts and high accelerations, tend to make the readings spuriously high, rather than spuriously low. A manual system for generating and mailing letters would probably cost about $1 per letter. With automation and bulk mailing discounts, the cost could drop below 50¢.[42]

If a gross polluter program correctly identifies three percent of vehicles measured as gross polluters on the road, the average vehicle is measured 3.8 times per year, and the cost per test is 75¢, then the cost per gross polluter identified would be about $164 (including the cost of a confirmatory test).[43] If the cost per RSD test decreases, then this figure would drop accordingly. On the other hand, fleet coverage effects might work to the disadvantage of a gross polluter program. Motorists driving high-emitting cars might avoid remote sensors. Furthermore, older cars, which are more likely to be high-emitting, are driven less, making them less likely to be seen by a remote sensor. Incentives might be necessary to encourage some motorists to drive by remote sensors.

A cost of $164 per gross polluter identified compares favorably with the cost of identifying failing vehicles through biennial testing. At the current failure rate of about 12 percent in the Enhanced program, it costs about $430 to identify each failing car. At the gross polluter failure rate of 3.6 percent, it costs about $1,400 for each gross polluter identified. Thus, even if RSD avoidance reduces the percentage of gross emitters to 1.5 percent instead of three percent, thereby increasing RSD costs to $259 per gross polluter identified, identifying gross emitters

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[41] We are discussing only cost savings here. Who benefits from these savings is a separate issue. For example, all clean screening benefits would accrue only to the people actually clean screened if they pay for the clean screening but are exempted from their scheduled test. However, if *all* motorists pay a small extra charge each year to cover the costs of clean screening, then motorists who are not clean screened would pay more than they are paying now, and motorists who are clean screened would save even more than they would if they paid all the costs of clean screening themselves. Finally, if the state elected to pay for all testing, both on-road and at Smog Check stations, by assessing a fee to all motorists, the cost savings due to clean screening would be distributed equally to all motorists.

[42] Personal Communication with Jerry Gallagher of the Colorado I/M Program, August 19, 1998.

[43] This includes $95 in RSD costs per gross polluter correctly identified plus $52 for a confirmatory test and the assumption that only 75% of cars cited as gross polluters actually fail the confirmatory test at a Smog Check station.

with RSD would still be cost competitive with the alternatives. Furthermore, cars identified as high emitters on the road have slipped through the cracks of the scheduled testing system making on-road identification the only means available to ensure that these vehicles are found and potentially repaired.

There are too many unknown factors to allow a reliable estimate of the actual cost of clean screening or gross polluter identification in a large-scale program in California. For example, under monopoly conditions the cost of remote sensing might be significantly higher than would be justified by the actual costs of the labor and equipment involved. On the other hand, our estimates of labor costs or of RSD coverage could turn out to be too conservative, resulting in an overestimate of actual costs. This analysis is simply intended to provide a rough guide to the range of costs that are likely to be encountered based on the current real costs of the inputs and reasonable estimates of a real-world implementation scenario.

Smart Sign. The Smart Sign in Denver cost $300,000 for initial implementation plus an additional $30,000 per year to operate. Over a five-year period, the annual cost would thus be $90,000 per year. The sign is located at a major freeway off-ramp where it measures three million vehicles per year and 250,000 unique vehicles per year. The cost per test is thus about 3¢, or about 36¢ per unique vehicle. RSTi recently quoted a price of $368,000 to implement a Smart Sign in Oregon (RSTi, 1998), a bit higher than the cost of the original Smart Sign in Denver. Because the cost of the Smart Sign is fixed, the cost per test will vary based on the traffic volume at the Smart Sign's location. If the sign is occasionally moved around to several different locations, total costs would rise slightly, but the cost per unique vehicle might drop because a different group of vehicles would be sampled at each location.

Total Cost of an RSD Program

Assume that an RSD program measures 70 percent of the fleet subject to biennial testing by measuring the average car about 3.8 times per year. This would require about 46 million RSD measurements per year in the Enhanced areas to clean screen about 1.1 million cars (about 25 percent of the cars required to get an Enhanced Smog Check in a given year) at a cost of $34 million. At $52 per Enhanced test it would have cost $57 million for Smog Checks on these cars, plus the value of motorists' time. Thus, clean screening is likely to result in a savings of at least $23 million per year when compared with scheduled testing in the Enhanced areas.

Costs could be reduced further if motorists respond to the opportunity for a clean screen by seeking out remote sensors and/or if the cost for each remote sensing reading can be reduced. For example, if we use our low-end estimate of $7 per clean screen with 32 percent of the fleet (or 1.4 million cars) exempted by clean screening, then cost savings would rise from $23 million to $63 million. Thus, based on our estimates, clean screening would reduce aggregate costs for initial tests by anywhere from 10 percent to 27 percent (costs would drop by 40 percent to 87 percent for the people actually exempted by clean screening)[44] in the Enhanced program. Table 3 summarizes these results. The value of clean screening in the Basic areas will depend on whether costs and the number of measurements required can be brought below the high-end levels assumed in this analysis, but savings here could also be substantial.[45]

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[44] See footnote number 41.

[45] Note that we have ignored the cost of motorists' time in obtaining a Smog Check. At equal cash costs for clean screening and a regular Smog Check, motorists would likely choose clean screening because it is more convenient. This effect is not included in our analysis, but would make clean screening more attractive.

Cost Effectiveness

Cost effectiveness is the cost per unit of emission reductions obtained and is usually stated as the dollar cost per ton of emission reductions. We would like to know the relative cost effectiveness of the Smog Check program with and without remote sensing. These quantities depend on the actual costs and emissions reductions obtained by the Smog Check program with and without remote sensing. Because the emission reduction effectiveness of Smog Check either with or without remote sensing is unknown, we can not make reliable estimates of the absolute cost effectiveness of Smog Check or RSD. However, we can look at relative cost effectiveness using the estimates made above for the cost of an RSD program.

We estimated that clean screening would reduce aggregate testing costs by between 10 and 27 percent in the Enhanced Smog Check program. The cost per vehicle in the Enhanced program is the testing cost (currently about $52 per vehicle) plus the average repair cost plus the administrative cost of the program. About 12 percent of cars fail the test and average repair costs are currently about $108 per vehicle. Administrative costs for the program are about $70 million per year. Averaging across all vehicles in the Enhanced program, the average repair cost is then about $13 per vehicle and the administrative costs are about $9 per vehicle per year.[46] Total costs are then $74 per vehicle tested, per year, on average. If we reduce aggregate testing costs by 10 percent or 27 percent through clean screening, the average total cost per vehicle would drop to $69 and $60, respectively.

On the other hand, clean screening might reduce the emission reduction effectiveness of Smog Check by allowing some high emitters to escape detection. For the purposes of this analysis, assume that clean screening reduces program effectiveness by eight percent, the value estimated in the Greeley Clean Screening Pilot (McClintock and Stock, 1997). Combining these estimates and assumptions, the relative program cost effectiveness with clean screening would range from an increase of one percent to a decrease of 12 percent when compared with the cost effectiveness without clean screening.[47] That is, given our assumptions, Smog Check with clean screening would cost between one percent more and 12 percent less per ton of pollution reduced.[48] Costs per ton can increase even when total costs decrease if the percentage decrease in effectiveness is larger than the percentage decrease in total costs. Table 3 summarizes these results.

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[46] Administrative costs are calculated as follows: BAR's total Smog Check budget is about $70 million per year. We assign 60% of this to the Enhanced program to reflect the fact that 60% of cars are in the Enhanced areas. About 4.5 million cars are subjected to testing each year in the Enhanced areas. Thus, $70 million x 0.6 ÷ 4.5 million = $9.33

[47] Calculate the change in cost effectiveness as follows: (average cost per car with clean screening ÷ relative emission reduction effectiveness) ÷ average cost per car without clean screening. For example, for the low-end case this is ($60/0.92)/$74 = 0.88 or 12% less than the cost effectiveness without clean screening.

[48] Note once again that we have ignored the cost of motorists' time in getting a scheduled Smog Check. Including this cost would increase the estimated benefits of clean screening. Note also that these estimates depend of course on our assumptions regarding the costs of clean screening and the impact of clean screening on the emission reduction effectiveness of the program.

Table 3. Estimates of the Effect of RSD Clean Screening on Total Cost and Cost Effectiveness of Enhanced Smog Check

	High-End Estimate	**Low-End Estimate**
Assumptions	• 75¢ per test • 70% of fleet measured at least twice with average of 3.8 measurements per registered vehicle • $31 per car clean screened • 8% reduction in Smog Check effectiveness	• 26¢ per test • 90% of fleet measured at least twice with average of 3 measurements per registered vehicle • $7 per car clean screened • 8% reduction in Smog Check effectiveness
Fraction of Fleet Clean Screened	25%	32%
Total Reduction in Testing Costs*	$23 million (10% reduction)	$63 million (27% reduction)
Change in Cost Effectiveness	1% increase in cost per ton of pollution eliminated	12% decrease in cost per ton of pollution eliminated

* Percent reduction includes only the cost of initial tests and not retests after failure

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