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The Benefits and Impacts of Multi-Level Emission Standards on the Fuel Economy Characteristics of Small and Large Cars

Prepared by
The Mobile Systems Group

31 March 1976

Prepared for
U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Transportation Energy Conservation Division
Washington, D. C.

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Environment and Energy Conservation Division
THE AEROSPACE CORPORATION

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**THE BENEFITS AND IMPACTS OF MULTI-LEVEL
EMISSION STANDARDS ON THE FUEL ECONOMY
CHARACTERISTICS OF SMALL AND LARGE CARS**

Prepared by
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FOREWORD

This report, prepared by The Aerospace Corporation for the U.S. Energy Research and Development Administration (ERDA), Division of Transportation Energy Conservation, presents the results of a brief review of the fuel economy and emission characteristics of small and large cars to determine whether or not it is meaningful to implement multi-level emission regulations to enable an overall fuel economy improvement for the total vehicle fleet.

A concise review of important findings is presented in Section 1. Section 2 presents a brief review of the technical background and the rationale for the study effort. The results of a survey of the variation of fuel economy and exhaust emissions as a function of vehicle inertia test weight are presented in Section 3. Section 4 discusses the resultant effects of catalyst and non-catalyst use on both emissions and fuel economy for both large and small cars.

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SECTION 1

SUMMARY

The need to meet the 1975-76 passenger car hydrocarbon (HC) and carbon monoxide (CO) exhaust emission standards for both California and the 49 states has required the use of oxidation catalysts on most large cars. [These standards, and those for oxides of nitrogen (NO_x), are for California and the 49 states, respectively: HC = 0.9/1.5 grams per mile (gr/mi), CO = 9/15 gr/mi, NO_x = 2/3.1 gr/mi]. Use of these catalysts has been accompanied by improved fuel economy since they permit the engine ignition timing to be advanced (spark retard had been a principal control technique for HC prior to the catalyst).

The extent of the use of the catalyst on smaller cars was not known with certainty, since they could meet the emission standards more easily because of lower exhaust flow rates that permitted higher pollutant concentration levels. But if they were not using catalysts--with their associated fuel economy improvement--then the question arises as to whether it is meaningful to implement multi-level emission regulations (different values for small and large cars) to encourage or force such equipment changes on smaller cars, and by so doing improve the overall fuel economy of the total fleet while at the same time reduce overall emissions.

Therefore, a brief review of the small car vs. large car fuel economy and emission scenario was conducted to provide a perspective for resolution of this issue. The highlights of this review are briefly summarized below:

- a. The 1975-76 federal HC standard (1.5 gr/mi) is sufficiently low to effectively force the use of catalysts on larger cars (4000-lb inertia test weight and above) to avoid fuel economy losses, but not sufficiently low to require them on all smaller cars (3500-lb class and below). However, the 1975-76

California HC standard (0.9 gr/mi) is sufficiently low to do so, as evidenced by the fact that essentially all California cars do use catalysts.

- b. Whether or not small or large cars are equipped with oxidation catalysts, NO_x standards below the current federal level (3.1 gr/mi) and California level (2 gr/mi) will act to reduce vehicle fuel economy, although small cars are slightly less sensitive in this respect.
- c. To meet the projected federal and California HC standard of 0.41 gr/mi, both small and large cars will be forced to use catalysts, since this is the only available emission control technique for the conventional spark ignition engine.
- d. To ensure the fuel economy and emission benefits of catalysts, ERDA need only support the implementation of the proposed HC standard of 0.41 gr/mi. Making the federal standard the same as the California one would also produce this result.

SECTION 2

INTRODUCTION AND BACKGROUND

The original passenger car exhaust emission standards, commencing in 1966 in California and in 1968 for the rest of the nation, were based on the 7-mode federal test procedure. This test procedure involved dynamometer testing of a fully warmed-up vehicle at selected operating conditions (steady-state speeds, accelerations, decelerations, idle) which were "weighted" to represent a composite of an urban driving pattern derived from driving tests in Los Angeles; i.e., the LA-4 route. Although the emission standards were expressed in terms of grams per vehicle mile, the actual measurements of pollutants were based on the concentration of the individual species (HC, CO) in the exhaust stream, in terms of parts per million for HC and percent for CO. The pollutant concentration was converted to a mass basis by using an equation to determine the exhaust flow of each vehicle as a function of the inertia test weight, with the resulting variation as shown in Figure 1.

Figure 1. Exhaust Flow vs Inertia Test Weight (Based on 7-Mode Federal Test Procedure) (Ref. 1)

Since the emission standards in grams per mile were the same for both small and large cars, the lower exhaust flow rates of the smaller inertia weight vehicles permitted higher pollutant concentrations in their exhaust; Figure 2 illustrates this characteristic on a normalized ratio basis. Although the federal test procedures have been revised to incorporate the constant-volume-sampling (CVS) test procedure, wherein a portion of the exhaust is collected in bags, and the driving cycle has been altered to reflect both hot and cold start conditions, the standards are still expressed in grams per mile and are the same for both large and small vehicles.

Figure 2. Permitted Pollutant Concentration vs Inertia Test Weight (Based on 7-Mode Federal Test Procedure Exhaust Volume Flow Rates)

The more stringent emission standards for the 1975-76 model years in both California (HC = 0.9 gr/mi, CO = 9 gr/mi, NO_x = 2 gr/mi) and the 49 states (HC = 1.5 gr/mi, CO = 15 gr/mi, NO_x = 3.1 gr/mi) have resulted

in the use of oxidation catalysts on most large cars to meet the HC and CO limits. Incorporation of these catalysts permitted an advance in engine ignition timing with a resultant improvement in fuel economy (spark retard had been a principal control technique for HC control prior to the catalyst).

It was not known with certainty what the corresponding picture was with the smaller cars, which could meet the emission standards more easily (i. e., without catalysts) because of the higher permitted pollutant concentration levels. If they were not using catalysts--with the associated improved fuel economy--then the question arises as to whether it is meaningful to implement multi-level emission regulations (different values for small and large cars) to encourage or force such equipment changes on smaller cars and thus enable an improvement in overall fuel economy of the total vehicle fleet while at the same time reducing overall exhaust emissions.

Therefore, a brief review of the small car vs. large car fuel economy and emission scenario was conducted to provide a perspective for resolution of this question. The results are briefly summarized in the following sections.

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SECTION 3

VARIATION OF FUEL ECONOMY AND EMISSIONS AS A FUNCTION OF VEHICLE INERTIA TEST WEIGHT

Since to a first approximation the mass emissions and mass fuel consumption (the inverse of miles per gallon) are directly proportional to exhaust mass flow, this relationship was selected to form the basis of comparison between cars of different inertia test weights (I_w). As illustrated in Figure 3, a break-even factor is defined and normalized by reference to the I_w value of 4500 lb which has a value of 1.0. The "break-even" line is simply the ratio of vehicle exhaust flows (from Figure 1) at any I_w divided by the exhaust flow at $I_w = 4500$ lb. On this line, then, the pollutant or fuel consumption concentrations are equal. Any values obtained or reported which lie below the line indicate that the concentration of the emissions in the exhaust or the fuel in the intake air is lower than that for the reference I_w ; i.e., the emissions or fuel economy are better when points lie below the break-even line. This basis of comparison is used in the series of figures which follow.

3.1 FUEL ECONOMY

Figure 4 illustrates the variation of fuel consumption with I_w for the certification test vehicles for the 1973 model year, prior to the introduction of oxidation catalysts. At this time, the NO_x standard (3.0 gr/mi on the CVS-C test procedure) was equivalent to the federal 1975-76 NO_x standard (3.1 gr/mi on the CVS-CH test procedure). As can be seen, the vehicles below $I_w = 3000$ lb have lower fuel consumption [(i.e., higher fuel economy in miles per gallon (mpg)] than would be expected on the basis of equivalency.

Figure 3. Break-Even Factor for Emissions and Fuel Economy as a Function of Inertia Test Weight (Based on Constant Concentrations for All Inertia Test Weights)

Figure 4. 1973 Certification Vehicles: Fuel Consumption Variation with Inertia Test Weight, Non-Catalyst Vehicles (Ref. 2)

This is due to the fact that these smaller vehicles have lower horsepower-to-weight ratios and consequently operate at more efficient high mean-effective-cylinder pressures than the larger vehicles.

Figures 5 and 6 show the same factors for catalyst-equipped vehicles in California in the 1975 and 1976 model years. As can be noted, the 3000-lb and below I_w classes exhibit approximately the same fuel economy performance as before the addition of the catalyst, even though the NO_x standard in California was lowered to 2 gr/mi in 1975-76.

3.2 EMISSIONS

Figure 7 illustrates the variation of HC, CO, and NO_x with I_w for the certification test vehicles for the 1973 model year, prior to the introduction of oxidation catalysts. In this case, the HC and CO values of vehicles in the $I_w = 3000$ lb and below classes were essentially the same as those for larger vehicles, in terms of grams per mile. Thus their pollutant concentrations, in parts per million or percent, lie above the concentration equivalency line, as permitted by existing regulations. This implies that the vehicle manufacturers retarded ignition timing just enough to meet the standards (with deterioration and manufacturing margins) in the interest of fuel economy.

The NO_x value trends of small cars are less than those of large cars, in terms of grams per mile, but higher in terms of parts per million, or concentration. This is a natural result of the smaller engines operating at higher engine loadings, which produces more NO_x on a concentration basis. It should be noted, as mentioned above, that these same higher engine loadings result in improved fuel economy, at the expense, however, of increased NO_x concentration.

Figure 5. 1975 California Certification Vehicles: Fuel Consumption vs Inertia Test Weight (Catalyst-Equipped, Automatic Transmissions, Based on EPA Urban Cycle) (Ref. 3)

Figure 6. 1976 California Certification Vehicles: Fuel Consumption vs Inertia Test Weight (Catalyst-Equipped, Automatic and Manual Transmissions, Based on EPA Urban Cycle) (Ref. 4)

Figure 7. 1973 Certification Vehicles: Variation of Emissions with Inertia Test Weight, Non-Catalyst Vehicles (Ref. 2)

Figure 8 shows the variation with I_w of HC, CO, and NO_x emissions, respectively, for the 1975 model year in California and Figure 9 shows similar characteristics for the 1976 model year. With the addition of oxidation catalysts, on the average, it appears that the smaller cars are producing HC concentrations equivalent to those for larger vehicles; i.e., less HC in terms of grams per mile. This same trend is shown for CO in the 1975 model year, with somewhat higher concentrations in the 1976 model year. Normally, one expects HC and CO trends to be similar. However, it is well known that CO is very sensitive to engine choking characteristics during cold-start conditions; indeed, the major portion of CO measured in the federal test procedure occurs during the cold start, prior to catalyst warmup. It may be that the higher values of CO (and HC, to a lesser extent) in 1976 were the result of timing and carburetion modifications to improve cold-start driveability.

The NO_x picture in 1975-76 is much the same as in 1973. The addition of oxidation catalysts would not have been expected to cause a change here, and it did not; i.e., the NO_x values are a function of exhaust gas recirculation flow rate and spark retard.

(a) HC Variation

(b) CO Variation

(c) NO_x Variation

Figure 8. 1975 California Certification Vehicles: Variation of Emissions with Inertia Test Weight, Catalyst Vehicles (Ref. 3)

(a) HC Variation

(b) CO Variation

(c) NO_x Variation

Figure 9. 1976 California Certification Vehicles: Variation of Emissions with Inertia Test Weight, Catalyst Vehicles (Ref. 4)

In summary, then, the small cars are emitting less HC and CO than larger cars on a mass, or grams per mile, basis. With the addition of oxidation catalysts, they are emitting HC and CO concentrations at nearly the same levels as larger cars. This is as would be expected if the catalytic converters were similarly designed and the input feed gas conditions were controlled to comparable levels. The NO_x levels of small cars are commensurate with their lower horsepower-to-weight characteristics, which also contributes to the excess of their fuel economy advantage over large vehicles as predictable purely on the basis of equivalent air-fuel ratios and engine thermal efficiency.

SECTION 4

CATALYST VS. NON-CATALYST EFFECTS

To more clearly relate the variation in HC and NO_x emissions, and fuel economy, under conditions of catalyst vs. non-catalyst use, a simplified analysis was made to permit a graphical demonstration of the advantages of catalyst use in terms of fuel economy trends.

4.1 LARGE CARS

In the case of large cars, data from the Ford Motor Company for a 400 CID, 2.75 axle ratio, automatic transmission, 5000-lb I_w vehicle were used to form the basis of the analysis. These data are shown in Figure 10, where fuel economy in miles per gallon is plotted against NO_x levels in grams per mile, with parameters of HC feed gas (i.e., exhaust from the engine that has not been treated by a catalyst or thermal reactor) levels in grams per mile.

Figure 10. Maximum Fuel Economy CVS-H Projections Study No. 2 (5000-lb Inertia Test Weight Vehicle)(Ref. 5)

These same data are replotted in Figure 11(a) as fuel economy vs. HC, with parameters of NO_x level, and labeled "without catalyst." This data map was then converted to the "with catalyst" case shown in the left of the figure by assuming a constant catalyst efficiency of 85 percent. For each case, the 1975-76 federal and California HC and NO_x emission standards are indicated by symbols. Figures 11(b) and 11(c) more clearly illustrate the fuel economy effects at the federal and California standard levels.

At the federal level [Figure 11(b)], the use of a catalyst would improve fuel economy from 12.75 to 13.85 mpg, an increase of 8.5 percent. At the California level [Figure 11(c)], fuel economy would drop to approximately 9.35 mpg without a catalyst and increase to 13.7 mpg with a catalyst, an improvement of nearly 46 percent. This clearly illustrates why the overwhelming preponderance of catalyst use occurs in larger vehicles. Table 1 shows the catalyst/non-catalyst mix in a sampling of 1976 model year certification vehicles. Of the 499 vehicles surveyed, all vehicles weighing 4000 lb and over incorporated catalysts. In the 3500-lb class, only eight of 68 vehicles did not use catalysts. The situation for the smaller vehicles is discussed below.

4.2 SMALL CARS

To illustrate the HC, NO_x , fuel economy picture for small cars, an analysis was made based on the $I_w = 2250$ lb case. The "without catalyst" data for the large car in Figure 11(a) were scaled to the 2250-lb I_w case with the following assumptions:

- a. The HC level in parts per million of the small car was the same as that of the large car. For the $I_w = 2250$ -lb case, this means the grams per mile of HC emitted is approximately 60 percent that of the large car, based on the equal concentration equivalency line of Figure 3.
- b. At the same HC parts-per-million level, the NO_x mass emissions of the $I_w = 2250$ -lb car were 75 percent of those of the large car. This was based on the general NO_x vs. I_w trends of Figures 7, 8(c), and 9(c).

(a) Federal/California Emission Levels⁽¹⁾

(b) Federal Emission Levels

(c) California Emission Levels

Figure 11. Impact of Catalyst Use on Fuel Economy at 1975-76 Emission Levels (5000-lb Inertia Test Weight Vehicle)

Table 1. 1976 Certification Vehicles: Catalyst vs.
Non-catalyst Mix (Ref. 4)

Inertia Test Weight, lb	California		49 States		All States	
	With Catalyst	Without Catalyst	With Catalyst	Without Catalyst	With Catalyst	Without Catalyst
2000	0	0	0	4	0	4
2250	16	0	6	9	22	9
2500	16	0	0	18	16	18
2750	6	3	6	13	12	16
3000	34	0	30	25	64	25
3500	27	0	33	8	60	8
4000	27	0	49	0	76	0
4500	31	0	42	0	73	0
5000	19	0	31	0	50	0
5500	22	0	24	0	46	0
	198	3	221	77	419	80
	201		298		499	

The results of this procedure are shown as the "without catalyst" case in Figure 12(a). The "with catalyst" case was produced from these data using a catalyst efficiency of 85 percent. As can be seen, compared to the large car in Figure 11(a) the small car is much less sensitive to variations in both HC and NO_x . Again, for each case, the 1975-76 federal and California HC and NO_x emission standards are indicated by symbols. Figures 12(b) and 12(c) summarize the fuel economy effects at the federal and California standard levels.

In contrast to the case of the large car, at the federal level [Figure 12(b)] the use of a catalyst in the small car only improves the fuel economy from 27.7 to 28.0 mpg, or one percent. Thus, there is a little incentive to use a catalyst in many smaller cars to meet federal standards. This is shown in Table 1 where, at $I_w = 2750$ lb and below, only 12 of the 56 certification vehicles use catalysts in the 49-state case.

On the other hand, when California standards are considered [Figure 12(c)], the use of a catalyst can improve fuel economy from 25.1 mpg to 27.6 mpg, or ten percent. Thus, there is a clear incentive to use catalysts on small cars in California. This also is indicated in Table 1 where, for the California case, 38 of the 41 certification vehicles at $I_w = 2750$ lb and below incorporate catalysts.

4.3 SUMMARY REMARKS

The foregoing comparisons and the data of Figures 11 and 12 serve to illustrate that both HC and NO_x levels can have a strong influence on resultant vehicle fuel economy in both large and small cars. In the case of large cars, the fuel economy loss attendant to the non-use of catalysts for HC control is sufficiently high (approximately 8.5 percent) at the federal emission level (1.5 gr/mi) to effectively force their use. At the California level (0.9 gr/mi), the non-use of catalysts for HC control could result in a prohibitive fuel economy loss (approximately 46 percent). For the longer term control of HC (projected standard of 0.41 gr/mi), the catalyst is the only available emission control technique for the conventional spark ignition engine.

(a) Federal/California Emission Levels⁽¹⁾

(b) Federal Emission Levels

(c) California Emission Levels

Figure 12. Impact of Catalyst Use on Fuel Economy at 1975-76 Emission Levels (2250-lb Inertia Test Weight Vehicle)

In the case of small cars, the current federal standard for HC (1.5 gr/mi) does not effectively force the use of catalysts, whereas the California level (0.9 gr/mi) does so more forcefully by providing a ten percent fuel economy improvement potential. For the projected HC standard of 0.41 gr/mi, the small car with a conventional engine must also incorporate either catalysts or thermal reactors for more stringent control.

In either case, large or small car, and federal or California HC standard, the NO_x standard has a significant impact on vehicle fuel economy, as shown in Figures 11(a) and 12(a). The smaller car is less sensitive to it, but both classes show significant losses in fuel economy as the standard is lowered below the current 3.1 and 2 gr/mi respective levels.

In summary, if the projected HC standard of 0.41 gr/mi is implemented, it is most likely that both large and small cars will be forced to incorporate oxidation catalysts in order to meet it without suffering a prohibitively high fuel economy penalty. This use of catalysts should also result in the smaller cars emitting a proportionately lower amount of HC.

On this basis, then, no further type of regulation beyond the contemplated HC = 0.41 gr/mi standard would be required to force the use of catalysts in smaller cars with the attendant emission and fuel economy benefits noted above. Therefore, ERDA should support efforts to ensure that this standard is implemented.

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