EPA-AA-SDSB-80-11

Technical Report

Electronic Engine Controls - Availability, Durability, and Fuel Economy Effects on 1983 and Later Model Year Light-Duty Trucks

by

Thomas Nugent
Zachary Diatchun
Timothy Cox

June 1980

NOTICE

Technical Reports do not necessarily represent final EPA decisions or positions. They are intended to present technical analysis of issues using data which are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments which may form the basis for a final EPA decision, position or regulatory action.

Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air, Noise and Radiation
U.S. Environmental Protection Agency

I. Introduction

The application of microprocessor technology to optimize the functions of the internal combustion engine is underway. Passenger car model years 1980 and 1981 have seen the widespread introduction of electronic engine controls of varying degrees of complexity. These controls hold the promise of lowering engine emissions and raising engine fuel economy through the optimization of the combustion process at all engine operational conditions.

This paper examines the potential of this technology for use in the future light-duty truck fleet. The implications of this technology on fleet fuel economy, in conjunction with the more stringent emission standards in 1983, will be examined along with projections as to the future availability and durability of these microprocessors and their associated engine sensors.

II. Availability

Three factors are identifiable in analyzing the availability of electronic engine controls for 1983 light-duty truck application to meet emission and fuel economy requirements. The first factor concerns the availability of sufficient technology to implement such controls. Secondly, production limitations are an important factor. Finally, costs of electronic engine controls using the selected technology may be prohibitive.

The use of electronics in automotive applications, especially in the area of engine controls, is one of the fastest growing areas of electronic development and has been stimulated at an accelerated pace by emission and fuel economy requirements. Electronic engine controls first appeared in the early 1970's with the introduction of ignition modules and increased in complexity and application to controlling spark timing in the late 1970's. Chrysler's "Lean Burn engine," General Motors' "MISAR" system, and Ford's "EEC-I" are all examples of modules that controlled spark timing. Although no statute exists requiring the use of electronic engine controls, future emission and fuel economy requirements dictate that further increases in electronic control of the powertrain will accompany downsizing, aerodynamic changes, and improvements in catalyst technology to meet fuel economy and emission requirements of the 1980's.

The initial development effort in the early seventies used analog circuitry. This development technique illustrated that electronics could provide a substantially more accurate engine control system but would not improve fuel economy and emission levels unless a more advanced methodology was developed. With the advent of microprocessors and large scale integration (LSI) techniques developed in the late 1970's, the automotive world became a prime candidate to reap the benefits of what many social observers refer to as the second industrial revolution. This advanced LSI technology brings about an unprecedented level of functional complexity and intelligence for engine control systems and replaces many previous mechanical and electromechanical solutions.

Parallel to the development of LSI techniques for engine control applications, sensor development became the pacing factor for using microprocessor based engine controls. The more important sensed parameters that are used in 1980 model year light-duty vehicle applications are: 11/

- Crankshaft angle position. This indexes ignition timing for spark advance control and injection timing for electronic fuel injection systems. There are five current technologies commonly used to sense this parameter: magnetic reluctance, Hall-effect, Weigand-effect, optical, and variable-inductance.

- Pressure. This includes manifold absolute pressure (MAP), manifold vacuum, and ambient absolute pressure (AAP). MAP parameters are used with speed/density fuel control systems; manifold vacuum is used for ignition control and load sensing; AAP parameters are used for exhaust-gas-recirculation (EGR) flow correction and for altitude compensation. Technologies in production include aneroid/ LVDT, diaphragm/silicon strain gage, capacitive, surface wave diaphragm, aneroid/linear inductor, and metal diaphragm/ semiconductor strain gauge.

- Coolant temperature. These are now mature components with thermistors and wire-wound resistive elements used for cold start emission requirements.

- Oxygen partial pressure is monitored in three-way catalyst systems. Two sensors are of interest; zirconia oxygen sensor and the titania oxygen sensor.

- Throttle position is monitored for engine power command and idle shut-off on coastdown. As in the case of coolant temperature, throttle position technology is mature with plastic and ceramic element potentiometers dominating the market.

With the assistance of the LSI revolution and the necessary peripheral sensor developments, electronic engine controls have increased. In light-duty vehicle (LDV) applications, General Motors plans to use a three-way catalyst system with feedback carburetor for all 1981 LDV applications; Ford is also contemplating full usage of a similar system (EEC III) for full LDV application in 1983.

The usage of such complex systems (three-way catalysts and feedback carburetors) is not necessary to meet emission standards for 1983 LDTs since the equivalently stringent 1980 LDT California emission standards are met without any electronic engine controls or three-way catalyst systems. The 1980 California standards are more stringent than the 1983 Federal standards (see Fuel Economy section). A simple spark advance/EGR electronic engine control system, developed in the late 1970's, should be all that is necessary to meet emission and fuel economy standards.

Therefore, regarding technological availability for 1983 LDT electronic engine control application, the question is no longer "can it be done," but rather "when, what quantity, and for what price."

Another area affecting availability of electronic engine controls for 1983 LDT application is production limitations. Total LDT electronic engine control application could increase production volume up to 33 percent over LDV applications. Tooling, production leadtime, and facilities are all limiting factors in production. Any design changes necessary to meet 1983 LDT requirements would principally involve a rewrite of the microprocessor software in already existing systems. An industry standard currently held by microprocessor manufacturers is 26 weeks for complete microprocessor development. Discussions with Motorola, a manufacturer of electronic engine controls and associated sensors, indicated that a production volume increase of about 3 times would take 22-30 weeks to implement and would be paralleled by any necessary microprocessor software changes. Additionally, Motorola acknowledged that such a production volume increase would require an accelerated program, but by no means an impossible program, for the 1983 model year implementation. Ford engineering also made comments consistent with Motorola on the production availability of electronic engine controls, i.e., an accelerated program would be necessary and feasible.

The last factor which may limit electronic engine control availability is prohibitive costs. Surveys have been done on the percentual share of manufacturing costs of LDV for electronics in the next decade. Figure 1 indicates that a 4 percent increase in percentual share cost in 1983 is expected compared to the uncontrolled LDV emission baseline (pre1968) electrical system share cost of 8 percent. A 1-2 percent deletion from the 4 percent incremental level is justified if only electronic engine controls are considered. The 1-2 percent deletion is attributable to increased electronic technology applications to instrument panels and driver convenience devices such as clocks, air conditioning controls, and diagnostic warning systems.12/ A further, detailed cost analysis has been developed and presented on the anticipated application of electronic engine controls for 1983 LDTs in the Regulatory Analysis and Environmental Impact of Final Emission Regulations for 1983 and Later Model Year Light-Duty Trucks.10/ The net increase in retail cost is anticipated to be $95 (1980 dollars), and is similar in percentual share cost to LDVs.

While there are incremental costs associated with the application of electronic engine controls for 1983 LDTs, cost would not be a limiting factor affecting the availability of such controls.

III. Durability

There have been three generally accepted techniques used in predicting the durability of any system used in automotive application:13/

a. Accumulated data from actual field experience.

b. Analytical techniques.

c. Accelerated life testing.

The first method applied to electronic engine controls is currently not extensively available because of the newness and rapid evolution of LSI technology applied to the automotive field; 1983 electronic engine control systems are being developed now in 1980. Analytic techniques require a mature data base; life testing usually produces a generic failure rate and relies heavily upon extrapolation. Both of these methods, b and c, would have to be used in establishing confidence in an electronic engine control system for 1983 LDT application.

A reasonable durability confidence level may be established for LSI techniques used in electronic engine controls. The latest circuits contain up to 100,000 transistors in memory arrays, or up to 50,000 transistors in random logic. Even with this semiconductor complexity, the actual reliability has increased. Figure 2 illustrates the failure rate per function versus time or device complexity.

Factors affecting the increase in durability are threefold. First, a system using LSI techniques results in a decrease in the number of peripheral electronic components. Second, as device complexity increases, the number of external LSI chip interconnections, such as chip lead bonding, is significantly reduced. Chip lead bonding has been identified by the industry as one of the principal causes of failure when exposed to the automotive environmental factors of temperature extremes and humidity. Third, and perhaps most importantly, significant advances in device manufacturing techniques and knowledge of device mechanisms has facilitated production of LSI devices which improve failure resistance when exposed to extremes in environmental conditions.

There have been identified, however, some problems unique to LSI technology when applied to the automotive field as compared to discrete devices. Discrete devices are reasonably immune to effects of power supply variation and little or no protection has been taken in the past against control transients, steady-state noise, and voltage regulation. Automotive environments contain complex signals under each of these areas including load dump transients, electromagnetic interference, alternator field delay transients, and accessory noise.

The nature of LSI failure rates may be further discussed by using two partitions: intrinsic and extrinsic. Intrinsic failure rates are associated with manufacturing defects such as masking areas, process contamination, and passivation defects. These defects dominate the failure rate in applications where the environment is controlled, e.g. computers. Extrinsic failures are caused by environmental factors. As environmental severity increases, the contribution of the extrinsic failure rate increases. Figure 3 illustrates the influence of environmental severity on device failure rates.14/

Sensors used for engine controls have been identified as the limiting factors in durability, especially electro-mechanical devices. Even though guidelines have been set on the specification and testing on some of the sensors,15/ the most crucial factor in establishing confidence in a 100,000 mile durability factor for LDTs is actual in-use experience, which is currently not available at mileages up to 100,000. However, a reasonable degree of durability confidence may be applied to the sensors that will potentially be used on 1983 LDTs to meet emission and fuel economy requirements. Such sensors are the crankshaft position and the manifold vacuum sensor. These particular sensors have a high durability potential as they are either non-mechanical, use solid state technology, have a long aerospace history, and exhibit no severe environmental deterioration problems, as is the case of the oxygen sensor used with three-way catalyst systems.

Concluding, both the electronics and sensors that may be used on 1983 LDTs have a high durability potential because of increases in the development of large scale integration and the already secure sensor development.

IV. Fuel Economy

Manufacturers' comments to the National Highway Traffic Safety Administration's (NHTSA) light truck fuel economy proposed standards for 1982 through 1985 model years, and to EPA's Light-Duty Truck (LDT) proposed emission regulations for 1983 are consistent. According, to the manufacturers, the 1983 and 1985 emission standards will result in a fuel economy penalty ranging from 3-14 percent. The EPA staff's intention in this report is to address manufacturers' comments concerning the fuel economy penalty associated only with the 1983 emission standards.

Most manufacturers further agree through passenger car research that Electronic Engine Controls (EEC), more specifically fully interactive EEC systems, have shown promise in combating the loss of fuel economy as demonstrated by application of the more stringent California standards to passenger vehicles. Manufacturers further claimed, however, that such systems are not generally planned to be used to achieve 1983-1985 LDT standards due to what the manufacturers view as their high variable cost.

One manufacturer indicated that while a system of this type was not necessary to attain 1983 emission standards, it could be justified if cost effective with regard to fuel economy. The same manufacturer referred to computer simulations with EEC that resulted in a fuel economy benefit of at least 2 percent.

On the other hand, additional manufacturers' research yielded no fuel economy benefit with EEC with or without three-way catalysts, and then concluded that the fuel economy penalty could not be offset, and also dismissed the use of EEC for 1983 due to leadtime requirements.

Finally, when questioned in Public Hearings before EPA about the use of electronic controls in future product lines, the industry refused to comment on the grounds that such information was "proprietary." Given the widespread use of EECs in the LDV fleet and given the constantly growing amount of published research on EECs, this is highly suggestive that the research and development programs needed to incorporate EECs into the LDT fleet are already underway.

These inconsistencies in the manufacturers' comments indicate the need for a more critical review of current EEC technology with respect to fuel economy, emission standards, and the future LDT fleet.

Industry projections for fuel economy impact arise from anticipated use of current technology at emission levels near the 1980 California standards. The magnitude of this Federal to California fleet fuel economy penalty was estimated in Reference 1 to be approximately 4.0 percent, as determined from EPA certification tests on an average vehicle-by-vehicle basis. A conservative estimate of 1983 production mix for different engine sizes and corrections for relative stringencies of standards also entered into the derivation of the average penalty.

A separate source for evaluating the effect of California emission standards upon LDT fuel economy is a recent SAE paper published by EPA personnel.2/ Data from that report is reproduced in Table 1. The average penalty for each manufacturer is broken down in Table 2. Note that the average sales-weighted fuel economy impact per manufacturer of the California emission standards was found to be a loss of 4.2 percent. (This is comparable to the overall 5.2 percent loss derived by the EPA staff in Reference 1, before adjustments were made for future engine mix and for the relative stringencies of 1980 California and 1983 Federal emission standards.) Note also the significant impact of the changing marketplace; an increase in sales of products by manufacturers of more fuel efficient vehicles in California has resulted in a net improvement in overall fleet fuel economy of 6.5 percent relative fo the Federal fleet! Significant increases in fleet fuel economy and simultaneous reductions in emissions have occurred. This is not to say that market mix negates the effects of tighter emission standards. It is in the context of an anticipated 4.0 percent loss* in average engine fuel efficiency using current technology that the fuel economy effects of future technology, electronic engine controls in particular, will be evaluated. (This change in market mix to more fuel-efficient vehicles and its overall effect on fleet mpg should not go unnoticed, however.)

Given the availability of electronic engine controls, EPA anticipates their incorporation into the LDT fleet to achieve compliance with increasingly stringent emission and fuel economy standards. This judgement is based upon the documented potential for engine optimization attributable to EECs, and their already widespread use in the light-duty vehicle (LDV) fleet.

The level of complexity of electronic controls can vary. Parameters controllable by electronics include fuel/air ratio, spark advance, EGR rate, idle speed, auxiliary air injection, torque converter clutch, fuel injection profile, and ignition voltage. Electronic controls permit infinitely variable calibration settings for each parameter and for changes in engine operating demands - including idle, acceleration, deceleration, cruising, and transient temperature (warm-up) effects. Calibrations and response times of each feedback control loop can be set to optimize fuel economy and driveability at any level of emissions. A method of engine parameter mapping and control algorithm generation is presented by Auiler, et al.5/ A complete description of a comprehensive electronic control system is given by Grimm, et al.6/

The degree of complexity required for 1983 LDTs to attain emission standards while incurring no net fuel economy penalty was judged previously to be less than that of a comprehensive system, i.e. electronic control of only a few parameters will be sufficient. Most likely controlled will be spark advance and EGR rate. The option still exists for more complex systems to be introduced at the manufacturer's discretion. With forthcoming NOx reductions in 1985, manufacturers may choose to phase in comprehensive control systems because of varying leadtimes for microprocessor programming and engine optimization - see the conclusions in Reference 4. We do not judge these leadtimes to be prohibitive to introducing less complex, less costly EEC's in 1983, however, due to the previous design experience acquired with light-duty vehicles.

Several reports have outlined the fuel economy and emission reduction potential of electronic spark advance (ESA), and of comprehensive EECs including ESA. Schwarz, in a report to the Institute of Electrical Engineers8/, reported that at a given emission level, use of a digital ESA system produced a 8-11 percent fuel economy improvement over a mechnical system in a

* As derived in Reference 1.

four cylinder passenger car engine. Evernham, et al, reported in 1978 9/ that the first microprocessor unit installed on a production passenger car (GM MISAR system on the 1977 Oldsmobile Toronado), a simple electronic spark advance system, improved fuel economy by 1.2 mpg (9 percent)* over the mechanical system. It is difficult to understand the industry's claims that technology first applied in 1977 cannot be applied to LDTs in 1983 to preclude a fuel economy penalty, which will at most be a fleetwide 4.0 percent using current LDT technology, while technology introduced six years prior to 1983 on passenger cars produced fuel economy improvements of 8-11 percent.

Comprehensive EECs, although not anticipated to be widely used in 1983 LDT's, nevertheless incorporate ESA, and evaluation of a comprehensive system fuel economy potential can indicate to some degree a range of ESA's potential. Ikeura3/ reported that the comprehensive system developed by Nissan and currently marketed extensively in Japan produced an overall improvement in fuel economy of 10 percent. (The Nissan system controls fuel injection, spark advance, EGR rate, and idle air flow). Some fraction of this improvement must be attributable to ESA and EGR control, and its certainly reasonable to conclude that at least 4.0 percent of the overall 10 percent is attributable to ESA and EGR control.

Lockhart4/ reported different magnitudes of improvements, but which are highly informative nevertheless. Table 3 lists the emission levels and fuel economy improvements obtained in a GM prototype fuel economy vehicle equipped with, among other technologies, a GM EPEC (Electronic Programmed Engine Control.) While simultaneously reducing emissions from 1978 to 1981 levels, an overall fuel economy benefit of 12.5 percent was achieved, of which 3.5 percent was attributable to the comprehensive EPEC (which controlled fuel injection, spark advance, idle air, and EGR.) Emission reductions were reported to decrease net fuel economy by 2.5 percent. In extrapolating these results to future LDTs, it is understood that a comprehensive system is not anticipated for 1983, but also note that the relative degree of emission reductions required for 1983 LDTs are far less than that seen by passenger cars from 1978 to 1983 (although differences in inertia weights certainly affect attainable emission levels.) Therefore, although a comprehensive EEC is not anticipated, the emission reductions are not quite so drastic (most importantly for NOx) as achieved in Reference 4. The fuel economy impacts of lower LDT standards and the use of ESA and electronic EGR controls are judged comparable in magnitude and opposite in sign, i.e. no net fuel economy penalty is expected. In fact, based upon data presented in the earlier reference, it is conceivable that the fuel economy benefits of the expected EECs may be larger than those penalties associated with the 1983 emission reductions.

---

* EPA combined fuel economy ratings for the 1977 Toronado was 15 mpg. Presuming 15 mpg represents 1.2 mpg more than 13.8 mpg, the ESA resulted in a 9 percent gain.

In summary, the 1983 emission reductions are not drastic and are attainable with today's technology. Today's electronic control technology as applied to light-duty vehicles will permit no net fuel economy penalty to be experienced as a result of these emission standards. Industry claims of fuel economy penalties are not consistent with the cost-effective* technological options available. Looking at the engine alone, there is no reason to presume that fuel economy effects attributable to the 1983 standards will be negative. We believe it is a conservative judgement based upon the published data that no net fuel economy loss will occur.

---

* See Reference 1, Chapter F; Reference 10, Chapter 5.

References

1/ "Summary and Analysis of Comments on the Notice of Proposed Rulemaking for Gaseous Emission Regulations for 1983 and Later Model Year Light-Duty Trucks," U.S. EPA, May 1980.

2/ "Passenger Car and Light Truck Fuel Economy Trends Through 1980," by J.D. Murrell, et al, SAE Paper No. 800853.

3/ "Microprocessor Control Brings About Better Fuel Economy with Good Driveability," by K. I. Ikeura, et al, SAE Paper No. 800056.

4/ "A Fuel Economy Development Vehicle with Electronic Programmed Engine Controls (EPEC)," by Bruce D. Lockhart, SAE Paper No. 790231.

5/ "Optimization of Automotive Engine Calibration for Better Fuel Economy - Methods and Applications," by J. Auiler, et al, SAE Paper No. 770076.

6/ "GM Micro-Computer Engine Control System," by R. Grimm, et al, SAE Paper No. 800053.

7/ "Chrysler Microprocessor Spark Advance Control," by J. Lappington and L. Caron, SAE Paper No. 780117.

8/ "Features and Facilities of a Digital Electronic Spark Advance System and its Advantages Compared with Mechanical Systems," by H. Schwarz from Automotive Electronics, IEE Conference Publication No. 181, November 1979.

9/ "MISAR - The Microprocessor Controlled Ignition System," by T. Evernham and D. Guetershlok. SAE Paper No. 780666.

10/ "Regulatory Analysis and Environmental Impact of Final Emission Regulations for 1983 and Later Model Year Light-Duty Trucks, U.S. EPA, May 1980.

11/ "Automotive Engine Control Sensors '80," by William G. Wolben, SAE Paper No. 800121.

12/ "Current Status of Automobile Electronic in Europe," by K. Ehlers, from Automotive Electronics, IEE Conference Publication No. 181, November 1979.

13/ "Electronic Reliability Issues Relating to Automotive Product," by J.G. Rivard, SAE Paper No. 780833.

14/ "The Automobile and the Microcomputer Revolution -- Solving the Reliability Problem," Automotive Electronics, IEE Conference Publication No. 181, November 1979.

15/ "Guidelines for Establishing Specifications and Test Methods for Automotive Sensors," by R.K. Frank, SAE Paper No. 800022.

Table 1 2/

Percent Difference in 1980 California Truck MPG Due to:

Manufacturer	1980 49-States Truck SWMPG	System Optimization	Transmission Mix Shifts	Engine Mix Shifts	Weight Mix Shifts	All Changes Combined	1980 California Truck SWMPG
American Motors	16.6	-5.3	0.3	-1.3	-4.3	-10.2	14.9
Chrysler Corp.	17.3	-5.9	-0.2	-10.8	16.0	-2.8	16.8
Ford Motor Co.	16.8	-5.0	-0.8	-1.8	7.5	-0.8	16.7
General Motors	16.6	-5.1	0.1	-0.9	3.9	-2.2	16.2
Nissan (Datsun)	25.3	-5.1	0.0	0.0	-0.2	-5.3	24.0
Toyo Kogyo (Mazda)	30.4	-4.7	0.0	0.0	-0.1	-4.8	29.0
Toyota	20.5	-6.3	-0.1	0.1	3.4	-3.2	19.9
Volkswagen	24.9	-1.2	0.0	0.0	-1.1	-2.3	24.3
Fuji (Subaru)	26.3	-6.7	0.0	0.0	0.0	-6.7	24.6
Fleet	17.0	-5.3	0.0	-1.9	14.6	6.5	18.1

Table 2*

Relative Fuel Economy by LDT Manufacturer

Manufacturer	Federal SWMPG	California SWMPG	% Less
AMC	16.6	14.9	-10.2
Chrysler	17.3	16.8	-2.9
Ford	16.8	16.7	-0.6
GM	16.6	16.2	-2.4
Nissan	25.3	24.0	-5.1
Toyo Kogyo	30.4	29.0	-4.6
Toyota	20.5	19.9	-2.9
VW	24.9	24.3	-2.4
Fuji	26.3	24.6	-6.7
Fleet	17.0	18.1	+6.5

Average Loss per Manufacturer (%): -4.2

* From Table 1

Table 3 4/

Emission and Fuel Economy Results

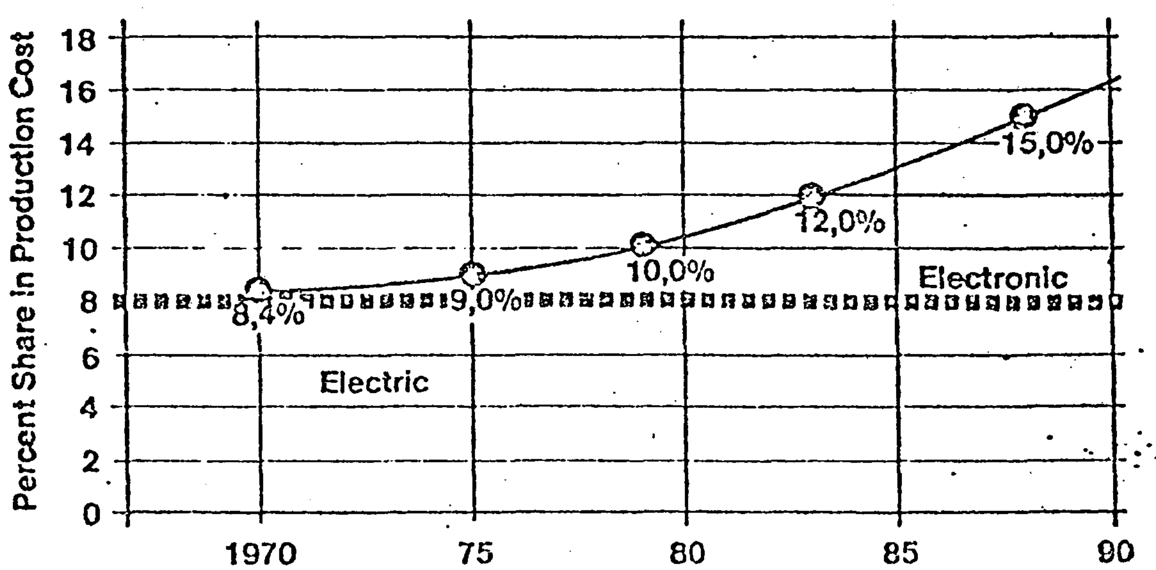
	HC	CO	NOx
1978 LDV standards:	1.5	15	2.0
1981 LDV standards:	.41	3.4	1.0
Percent reduction:	73%	77%	50%
1980 LDT standards:	1.7	18.0	2.3
1983 LDT standards:	.76*	9.1*	2.0*
Percent reduction:	50%	49%	13%

% Fuel Economy Improvements:

All efficient technologies:	+15%
Calibration to 1981 LDV emission standards:	-2.5%
Overall improvement of 1978 base case:	+12.5%
Improvement attributable to full EPEC:	+3.5%

* A revised definition of useful life and stricter assembly line testing procedures essentially increase the stringency of the 1983 LDT standards. The increased stringency, as derived on page 69 of Reference 1, has been taken into account by lowering the actual standards by the amount by which stringency is increased.

Figure 1 12/



Share of cost of electric & electronic components in total vehicle cost

Figure 2 14/

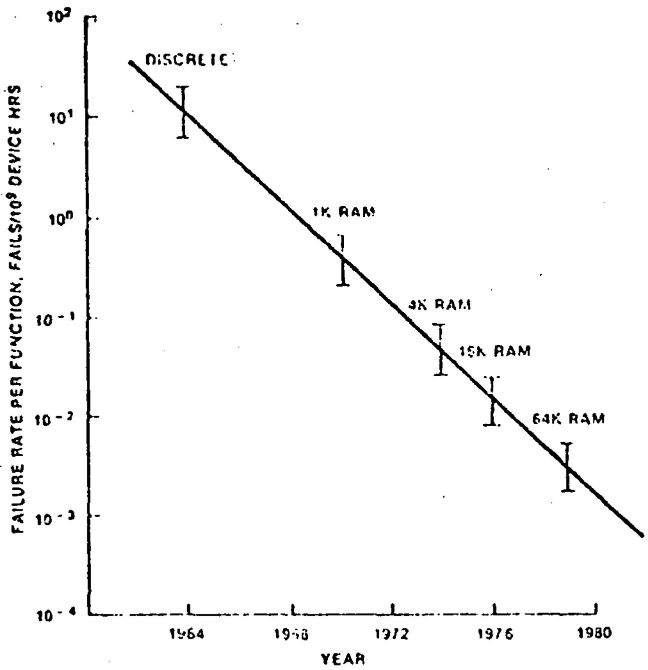
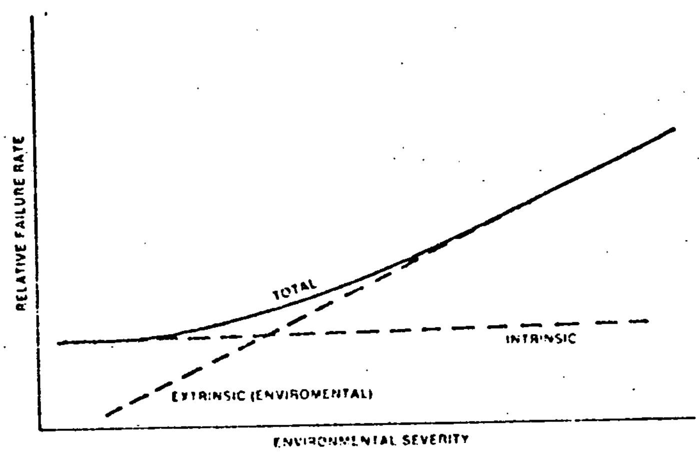

FAILURE RATE PER FUNCTION, FAILS/10^9 DEVICE HRS
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
DISCRETE
1K RAM
4K RAM
16K RAM
64K RAM
1964
1968
1972
1976
1980
YEAR

Figure 3 <u>14/</u>



	COMPUTERS	GAMES, WATCHES	INDUSTRIAL PROCESS CONTROL	AUTOMOTIVE
TEMPERATURE, °C	0—55	0 - 40	0—100	-40 - 125
MAX HUMIDITY at 25°C	[illegible]	100%	100%	100%
TEMP/HUMIDITY CYCLING	NO	MODERATE	MODERATE	SEVERE
CORROSIVES	NO	NO	SOME	SEVERE
ELECTRICAL NOISE	NO	LOW	MODERATE	SEVERE
MECHANICAL SHOCK	NO	LOW	MODERATE	SEVERE