

THE ADAPTIVE VEHICLE

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PURPOSE

The purpose of this study was to develop a concept for a vehicle which adapts its performance to the preferences and capabilities of different drivers under a wide range of driving and environmental conditions.

SUMMARY

A concept was developed for an Adaptive Vehicle which will optimize its performance for a wide range of drivers under a wide range of operating conditions. The technology required for the development of the Adaptive Vehicle was identified and a phased program was proposed for achieving various levels of adaptation. A feasibility study is now underway. This study will perform top-level mission definition, functional requirements analysis and concept development for an example high-technology adaptive vehicle. It will identify adaptation concepts, assess the feasibility and technology development risk for each concept, estimate potential benefits to the driver and provide recommendations for further development.

INTRODUCTION

With a few simple exceptions, current vehicles do not sense the driver or the driving environment, and, as a result, their performance can be optimized only for a specific driver under specific driving conditions. Consequently, present vehicle designs represent a compromise which tries to satisfy a wide range of drivers under a wide range of operating conditions. If a vehicle could adequately sense its environment, its internal state, and the driver's preferences and capabilities, and if this information could be analyzed on-board the vehicle in real time, then the performance of the vehicle could be modified to meet the driver's needs, expectations, and capabilities as they change with operating conditions [1].¹ This view is the basis for the Adaptive Vehicle concept.

The Adaptive Vehicle will break some of the "rules" we normally associate with vehicle operation:

- Rule 1. The vehicle does exactly what the driver tells it to do.

The Adaptive vehicle will analyze the driver's commands (from some explicit action, e.g., steering wheel or-brake pedal movement), as well as the current vehicle status and driving environment, and then take action to carry out the driver's intention in the best possible way. A simple example is anti-lock braking. The driver commands (with his foot) full brakeline pressure. The anti-lock system interprets this as an intention to stop as quickly and in as controlled a manner as possible and therefore modulates individual brake actuator pressures accordingly.

- Rule 2. The vehicle reacts only to what it physically encounters.

The Adaptive Vehicle will make use of extensive sensing of the driving environment to enable it to react in anticipation of uncomfortable or hazardous situations. For example, laser and millimeter wave radar could be used to detect potholes and begin actuation of active suspension-elements before a wheel falls into the hole. They could also be used to detect obstacles in the path of the vehicle so that appropriate action could be taken. Communication with central traffic, weather, and road condition information-services would make it possible for the vehicle to select routing to optimize an expressed

¹ Numbers in brackets designate references listed at the end of this report.

driver preference for minimum time, minimum workload, or other criterion.

Rule 3. The vehicle's performance deteriorates with time.

The performance of the Adaptive Vehicle, as perceived by the driver, should actually improve with time as the vehicle acquires knowledge about the driving habits, preferences, capabilities, and routes of its driver and adapts accordingly.

Rule 4. The driver supplies all the intelligence and decision-making for the vehicle.

The Adaptive Vehicle will exhibit intelligence-like behavior and assist the driver by making many decisions on its own to suit its performance to the immediate needs of the driver and the driving environment, thus making a safer, more efficient, and more enjoyable vehicle.

These capabilities and the technology to achieve them are under study at Project Trilby.

DIMENSIONS OF ADAPTATION

The Adaptive Vehicle must be able to modify its performance characteristics to adapt to changing needs of the driver, to changing requirements of the driving environment, and to changes in the vehicle itself.

Driver

Driver adaptation includes three domains:

1. Driver Preferences

Driver preferences represent the type of vehicle performance desired by the driver for a given situation or for a specific driving task. Such preferences are often reflected by vehicle classifications such as sporty, family, formal, luxury, prestige, or economy. Product Position Maps [2] are a possible source for exploring this adaptation domain.

2. Driver Capabilities

Driver capabilities represent the driver skills which are a function of the driver's experience, age, and physical state (e.g., drowsy).

3. Driver Habits

Driver habits include personal driving schedules for work or recreation, and personal driving style, which the vehicle control system will utilize to better meet the driver's needs and expectations. While the first two domains (preferences and capabilities) require short-term identification techniques, some of the driver-habit data may require very long-term identification.

Environment

Environmental adaptation treats a range of phenomena which affect the vehicle [3]:

1. Weather
This category includes temperature, humidity, precipitation, visibility, and wind gust phenomena.
2. Roads
This category includes the road type (e.g., paved, dirt, gravel, etc.), and its surface condition.
3. Traffic
This category includes traffic volume, its type (e.g., city or highway), and the location and behavior of other vehicles.
4. Topography
This category includes road geometry (e.g., straight, winding), its grade, and altitude variations.
5. External Disturbances
This category includes other external influences on the vehicle or its passengers, such as audible and electromagnetic noise, glare, and air quality.

Vehicle

The Adaptive Vehicle must sense and adapt its decision-making and control to changes within the vehicle itself. These changes can be sudden, like the loss of a sensor, or more gradual, like the slow deterioration of a fuel injector or other component. These changes may be detected directly, or inferred from other measurements of vehicle system and subsystem behavior. Once detected, the changes in capability and performance become factors in the analysis of the current driving situation and ultimately, in the adaptation decisions.

CONCEPT DESCRIPTION

Unlike current vehicles, the Adaptive Vehicle is intended to be self-optimizing for a wide range of drivers under a wide range of

operating conditions and thus should be able to meet an unprecedented range of mission requirements [4,5].

Figure 1 shows a schematic of the Adaptive Vehicle. It contains six major functional blocks: Sensing, Identification, Situation Analysis, a Knowledge Base, Adaptation, and Control.

The vehicle senses not only commands from the driver, but also the dynamic behavior of the driver as an element in a control loop, e.g. response times, precision of control, and perhaps physiological data. The vehicle also senses directly, and indirectly through a communications channel, the local and global driving environment, e.g., weather, road surface condition, traffic, behavior of other vehicles and similar information. It also monitors its own performance, its own internal condition and state of health.

The Identification block combines sensor data with models stored in the knowledge base to produce an updated description of the driver, the driving environment, and the vehicle. This information is passed to the Situation Analysis block where descriptions of the vehicle and the driving environment are combined to produce an analysis of the current operating conditions for the vehicle. This analysis takes into account weather, road condition, traffic, type of driving (urban, highway ...), vehicle condition, amount of fuel, and similar factors, drawing on the knowledge base as required. The results of this analysis are combined with information on the identity and performance of the driver, and with data from the knowledge base to determine the capabilities and preferences of that particular driver under the current operating conditions. The result of this analysis is a set of immediate functional performance goals for the vehicle -- a quantitative description of the way the vehicle is to behave under the current set of driver, environmental and vehicle conditions.

The Adaptation block uses vehicle models and design data from the knowledge base to determine the vehicle and control system configuration that best meets the performance goals. The vehicle subsystem parameters are adjusted to the appropriate values and a set of control objectives are established. The integrated vehicle control block coordinates control of the vehicle's individual dynamical elements to carry out these control objectives.

The Adaptive Vehicle, as described above, makes use of four distinct levels of control [6]. Figures 2a-d identify the major components of each level.

1. Subsystem control:

Control of individual vehicle subsystems to produce predetermined relationships between driver commands and subsystem response (Figure 2a).

2. Integrated control:

Adds coordination of subsystems to produce predetermined relationships between driver commands and vehicle response under specified environmental conditions (Figure 2b).

3. Adaptation to the environment:

Adds capability to account for changes in the vehicle's environment to maintain (if the laws of physics permit) the predetermined relationships between driver commands and vehicle response under all environmental conditions (Figure 2c).

4. Adaptation to the driver:

Adds capability to identify the driver, his preferences, capabilities, and performance. This information is used to modify the relationships between driver commands and vehicle response to meet changing functional requirements (Figure 2d).

The first three levels of control represent increasing span of conventional control, i.e., control aimed at achieving predetermined system performance. The fourth level of control extends the system behavior to a much more complex domain, i.e., dynamically modifying the specifications of the desired system performance.

ADAPTATION EXAMPLE

As shown in the previous section, vehicle adaptation is a multidimensional problem. Cross coupling between the driver and environmental domains can create an infinite number of adaptation states. To illustrate the adaptation process, the following simple example will describe adaptation among two driver preference states (namely: sporty and family), and two environmental states (namely: highway and city) resulting in a total of four adaptation states (Figure 3).

In this example, we will follow the process topology shown in Figure 1, namely:

1. Sensing
2. Identification
3. Situation Analysis
4. Knowledge Base
5. Adaptation
6. Control

to show how the vehicle adapts to each of the four functional performance states while driving from one city to another. It is a routine driving trip from home to work which involves the following sequence of states: family-city (FC) to> family-highway (FH) to> sporty-highway (SH) to> sporty-city (SC).

The trip starts as the driver enters the vehicle on a morning of a week-day.

Sensing begins as soon as the driver unlocks the door and enters the car.

Environment Sensing -- Includes time, day and date information as well as measurements of ambient temperature, pressure and humidity, location of the vehicle (using navigation data), wind characteristics, precipitation, visibility, road condition, traffic volume, location, behavior of nearby vehicles, and similar factors.

Vehicle Sensing -- Includes measurements of vehicle operating variables including those from start-up diagnostic tests (e.g., cranking voltage and current, cold-tire pressure, fuel and fluid levels, and the status of computer and electronic modules).

Driver Sensing -- Includes measurements to determine driver's identity either by recognition devices (e.g., image, voice, or handprint) or indirectly by a personal entry card or coded key. Additional measurements are performed of the driver's physiometric variables such as blood pressure, pulse rate, head and body motion, etc. More variables are monitored after the vehicle starts moving: They include the driver's throttle and steering response, his grip on the steering wheel, and his response to other vehicles on the road.

Identification processes begin based on the sensed data.

Environment Identification -- The environmental state is identified as a combination of the following phenomena: clear and dry summer weather (based on the season and on data measured by the temperature, pressure, rain and visibility sensors), paved and smooth road (based on road sensor data), medium-volume city traffic (based on location and the number of passing cars and data from a central traffic information service), sea-level altitude, flat terrain, acceptable audible noise-level, and an average level of electro-magnetic interference.

Vehicle Identification - Diagnostic test results are compared with stored reference data and test results from the last 30 trips. The vehicle state is identified as fully operational, all systems active, no immediate maintenance required.

Driver Identification -- The driver's identity is established and his personal driving log is accessed.

Trip Identification - To determine the objective of the trip, the system examines the driver's file, the day and time, and concludes with high probability that the driver is going to his place of employment. The vehicle queries the driver and receives confirmation.

Completion of the identification processes triggers Situation Analysis procedures.

Operating Condition Analysis - The combination of the vehicle state, the driving environment, and the trip objective define the operating conditions of the vehicle for this situation.

Driver Preferences and Capability Analysis -- The driver's personal file indicates a preference for comfortable and defensive driving, with a particular set of acceleration, steering, braking, and driver information-system characteristics under these operating conditions. The driver's physiological response data are continuously measured and compared with nominal driver models and with his personal data to confirm this conclusion. These preferences are expressed by a set of priorities assigned to the attributes of the vehicle functions. The first column in Figure 4 illustrates this description, with lower numbers reflecting higher driver preferences. The numbers in Figure 4 are for this example only. The system determines the driver is fully capable of performing the current driving task since no physiological limitation, such as drowsiness, is detected. It will therefore attempt to synthesize a system configuration for the current operating conditions that best meets his preferences.

Once the operating conditions and driver analysis is complete, adaptation can begin.

Configuration Synthesis and Parameter Selection -- The description of the preferred vehicle configuration is examined against stored data and models of the vehicle. Control system capabilities, vehicle parameters and operating envelopes under various potential vehicle configurations are analyzed to identify the set which comes closest to providing the functional performance preferred by the driver. This "optimal" set is used to define realistic, achievable performance specifications which become reference inputs to the integrated vehicle control system.

Integrated vehicle control then carries out coordinated control of the new vehicle configuration.

Integrated Vehicle Control -- The selected vehicle performance specifications are used by the top-level vehicle controller to determine the performance required of all vehicle subsystems and the nature of their interactions. The controller of each subsystem then acts to achieve its assigned objectives. In this example, the driver's preference for comfortable, defensive driving translates into the following control actions. The powertrain controller selects a configuration which minimizes the number of shifts, sacrificing some power and fuel economy. To do this, the engine is calibrated to operate at a wide dynamic range by adjusting spark timing, air-fuel ratio, and valve timing. In addition, during shifting, the transmission controller actuates the clutches smoothly so the changes in gear are not perceptible to the driver, allowing some decrease in the power transmitted to the wheels during a shift and some increase in fuel consumption. The suspension adjusts for a soft ride, allowing some deterioration in handling in sharp turns. The accessory cut-off point is set so that only under the highest vehicle power demand will comfort be sacrificed by disabling accessories. In addition, the chassis controller adjusts vehicle height and attitude for best comfort under stop-and-go, frequent-turn city driving (Figure 5). These processes and the updating of the subsystem control parameters are performed continuously during every driving trip.

This process is repeated as the vehicle transitions to other driving environments or other driver preferences.

Other Adaptation -- The following paragraphs describe transitions to other adaptation states, illustrating how changes in the driving environment or changes in the driver preferences initiate the adaptation process. Adaptation transitions are not sudden; they are performed gradually by the vehicle controller, and often only after receiving the driver's approval. The adjustments to the subsystem parameters are outlined in Figure 5 for all these states.

The transition to the FH state occurs in response to a change in the driving environment while driver preferences remain unchanged. The vehicle senses and identifies the highway by the geographical location and identification of the road, its number of lanes, the traffic, and driver-vehicle performance (speed, steering, etc.). To meet the driver's expectation of a comfortable and pleaseable ride in the new environment, the vehicle adjusts parameters, changes functional performance goals and, if necessary, reconfigures subsystem structure and interconnections.

The transition to the SH state occurs in response to a change in the driver's preferences while the environment remains unchanged. Based on the known driver's habits as recorded in his file, the system expects a transition to a more aggressive

driving style while still on the highway. It determines the desired transition point based on the driver's throttle and steering input patterns, distance maintained from other vehicles, and perhaps physiological measurements.

The transition to the SC state occurs similarly to the transition from the FC to the FH state, i.e., due to a change in driving environment which is detected through navigation, road, and traffic data.

The adaptation described in the above example covers only a limited part of the adaptation capabilities of the proposed Adaptive Vehicle. The environmental conditions did not include any changes in weather, road surface condition, topography or road type. The variations in driver preferences were limited to only two simple, specific states. The vehicle state was not varied at all. Variations in the availability and performance of vehicle subsystems adds complexity and dimension to the adaptation problem. For example, the system may conclude, based on comparisons of vehicle data with stored reference signatures, that the output of a sensor cannot be used reliably. Consequently, it estimates that sensor output from other measurements or replaces the nominal control algorithm for the subsystem with an algorithm which does not rely on this sensor. The adaptation logic will account for this change by reconfiguring interactions with other affected subsystems and adjusting appropriate parameters.

In addition to performance adaptation, the Adaptive Vehicle concept makes possible the integration of additional functions such as:

1. Interactive Navigation Assistance -- With present location and destination known, the system will contact a traffic-data center and examine traffic and road conditions for alternative routes. It would then perform minimum-time analysis and recommend the best available route.
2. Maintenance Scheduling -- Each trip will conclude with an off-line analysis of the vehicle and trip log. Trip data will be checked against reference data and recorded logs of past trips. Forecasts will be updated for scheduled maintenance along with unscheduled repairs (i.e., failure anticipations). These projections could be transmitted to a data center which would plan logistics and inventory using this information.
3. Driver Assistance -- Various functions to assist the driver in maintaining headway and lane on a highway, checking blind spots during turning, lanes changing and reversing maneuvers, providing collision warning and braking, and many others.

TECHNOLOGY REQUIREMENTS

To achieve a vehicle with the capabilities described in the report requires the targeted development of technology in the following areas (see Figure 6):

1. Driving-environment sensors and environment classification procedures.
2. Driver sensors and driver classification procedures.
3. Extended vehicle monitoring capabilities (e.g., failure prediction and detection)
4. Models of driver preferences and driver capabilities.
5. Long-term and short-term driver identification procedures.
6. Vehicle performance metrics and models of vehicle performance limits.
7. Functional analysis procedures for an Adaptive Vehicle.
 - a. Situation analysis and decision making procedures closely coupled with the vehicle control system.
9. Computer architecture and components which can provide on-board, real-time execution of the above processes.
10. New driver-vehicle interfaces.
11. Control-configured electromechanical subsystems with wide dynamic range.
12. A high level of integrated vehicle control.

ADDITIONAL ISSUES

While the above discussion focused on the adaptation options and required technology, the Adaptive Vehicle concept has potential benefits to the driver as well as to the Corporation which cannot be fully explored from an engineering standpoint alone. Some of the most intriguing issues associated with the Adaptive Vehicle include questions such as:

1. How does a driver respond to a vehicle which changes characteristics as a function of the driving environment and the current capabilities of the driver?
2. What would be the benefit to the Corporation if an Adaptive Vehicle could replace several existing models by providing performance which satisfies several market segments?
3. Which adaptation options are the most desired in the marketplace and by what type of driver?

STATUS

We have outlined a proposal for developing the Adaptive Vehicle capabilities. It includes three major phases: a Manual Adaptation phase, a Semi-Automatic Adaptation phase, and an Automatic Adaptation phase. In the Manual Adaptation phase, the driver manually selects predetermined performance settings. In the Semi-Automatic Adaptation phase, the performance settings can be modified by the driver for a small number of operating conditions and the transition among them is performed automatically by the vehicle. In the Automatic Adaptation phase, the vehicle selects configurations, control algorithms and parameters from a continuous range according to on-board analysis which considers driver identity, operating conditions, and vehicle state. Figure 6 summarizes the relationships among these phases, their technology requirements, and the four required levels of control.

Project Trilby is now conducting a feasibility study for the Adaptive Vehicle. This study will identify a set of adaptation options that are technically feasible, assess their development risk, and estimate their potential benefits to the driver and to the Corporation.

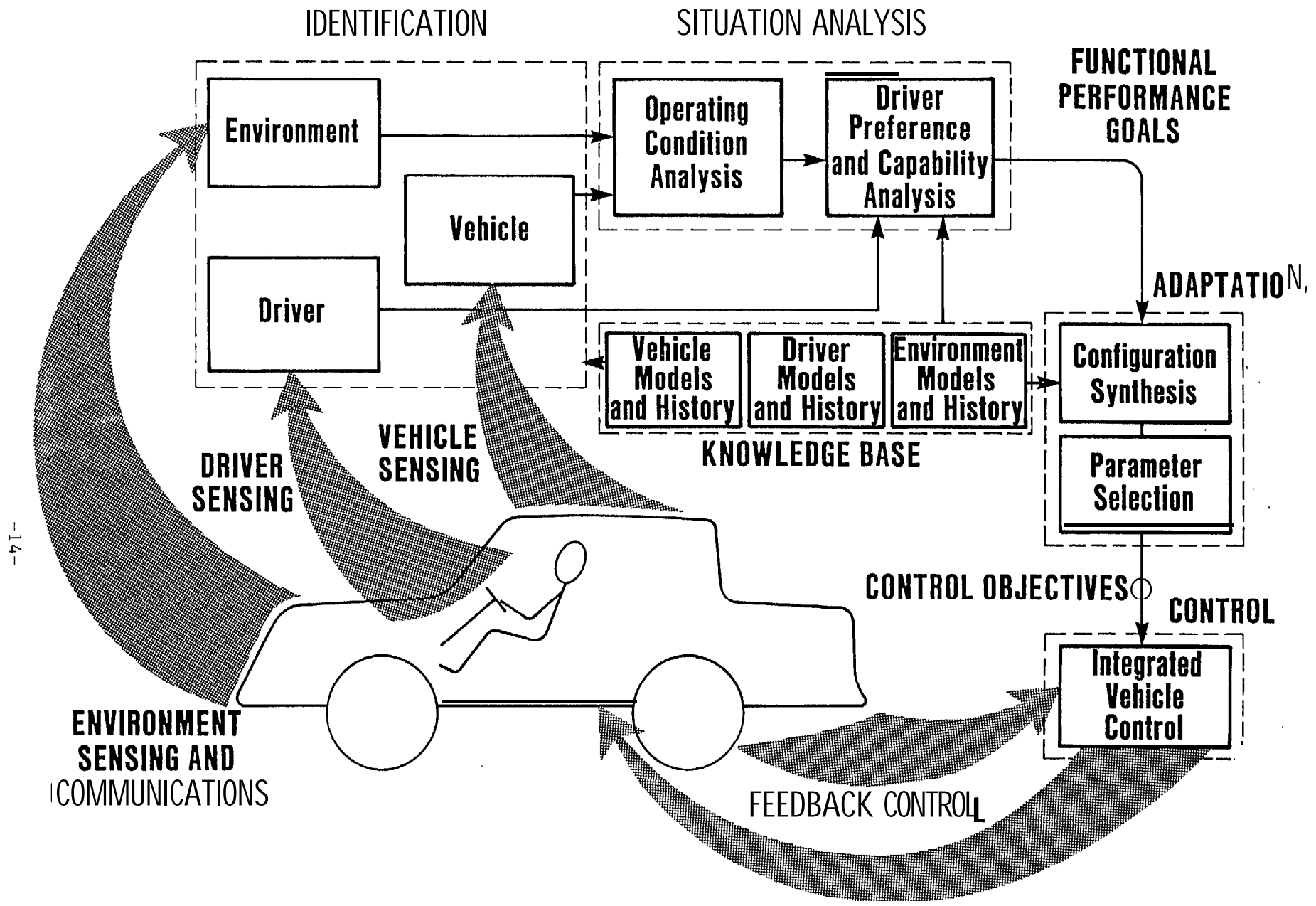


Fig. 1: The Adaptive Vehicle

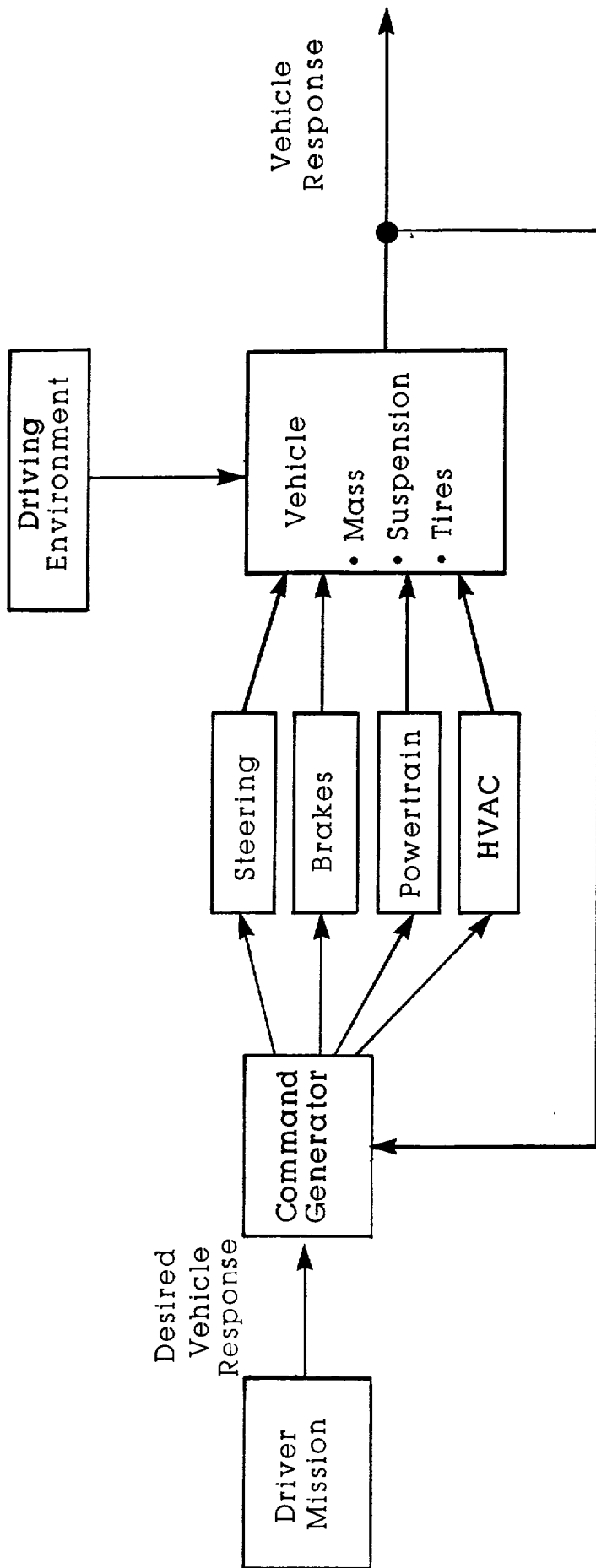


Figure 2a. Subsystem Control

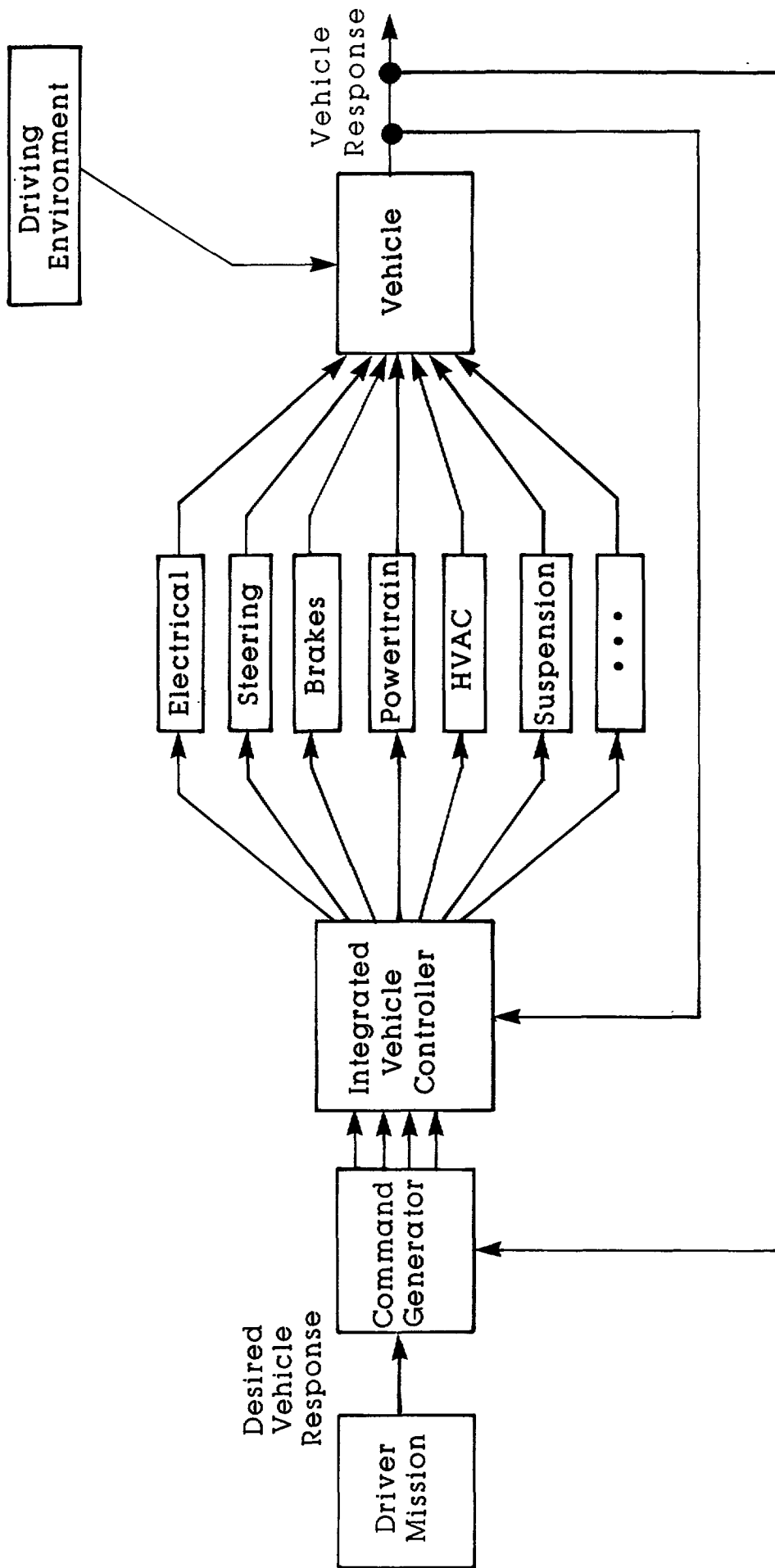


Figure 2b. Integrated Control

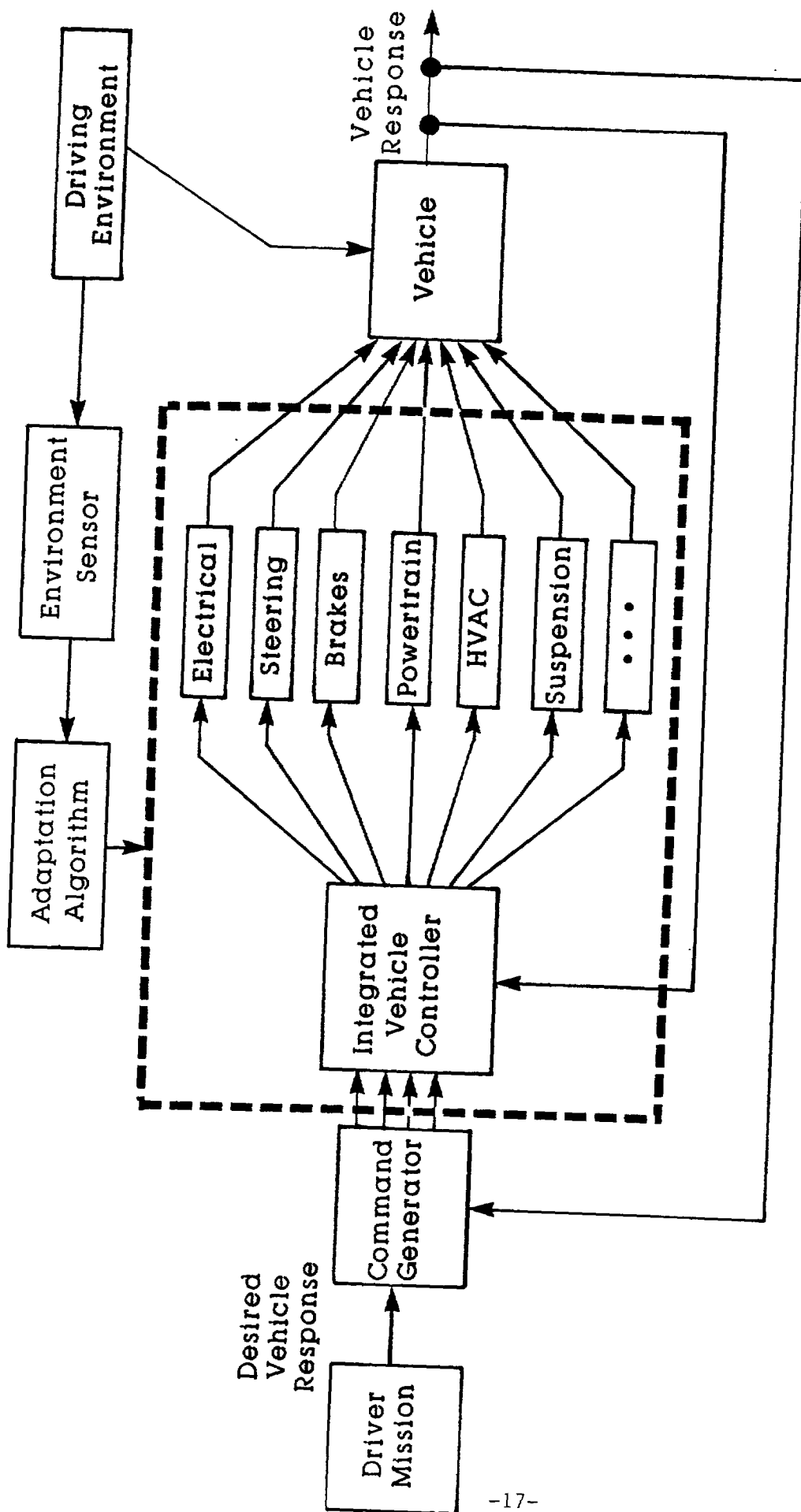


Figure 2c Environment Adaptation

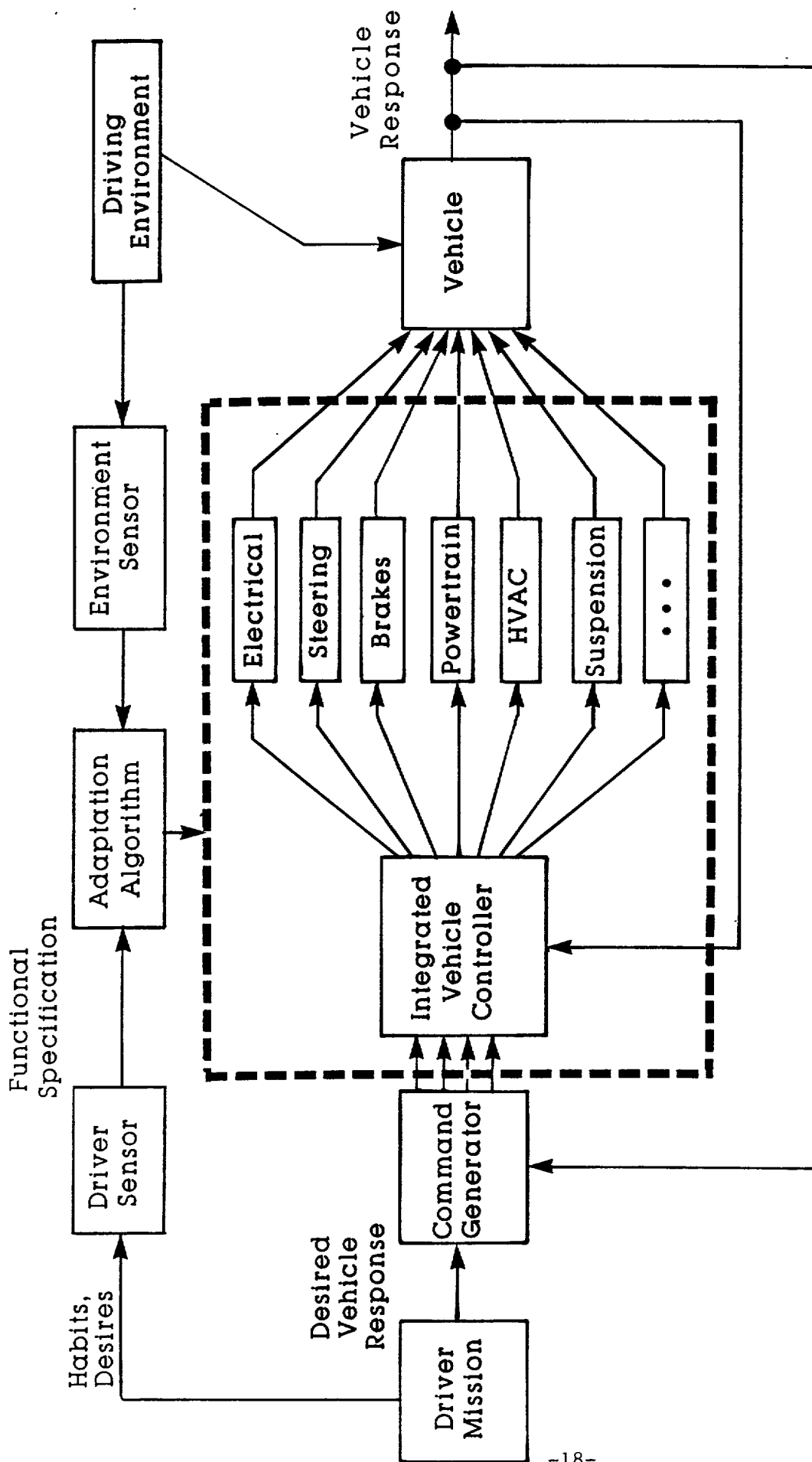


Figure 2d. Driver Adaptation

driver environ.	Sporty	Family
Highway	SH	FH
City	SC	FC

Fig. 3: Definition of Adaptation States for Environment and Driver Variations

	FAMILY	SPORTY
TRANSPORTATION:		
LONGITUDINAL	2	1
DIRECTIONAL	2	1
COMFORT:		
HVAC	1	2
RIDE	1	2
NOISE	1	2
COGNITIVE SUPPORT		
INFORMATION	2	1
ENTERTAINMENT	1	2
DRIVER INTERFACE		
SAFETY	1	2
EFFICIENCY	2	2
PLEASABILITY		
TRANSPORTATION	2	1
COMFORT	1	2
COGNITIVE SUPPORT	1	1

Fig. 4: Hierarchy of Driver Preferences

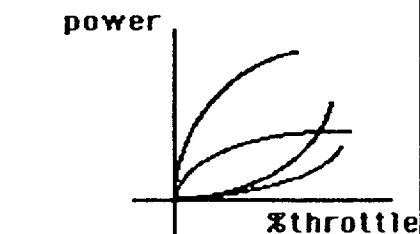
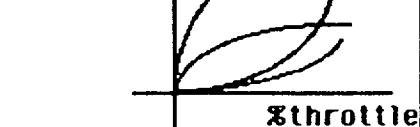
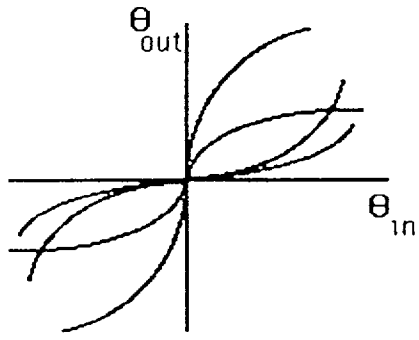

	DRIVER INTERFACE	VEHICLE CONTROL
SH	DISPLAYS	shift points: quick downshift at high gear moderate suspension accessory cut-off (low threshold) engine tuned for peak power vehicle attitude adjusted for best longitudinal motion at high speeds
	CONTROLS  throttle response	
FH	 throttle response	shift points: least perceived shift at high gears soft suspension accessory cut-off only at limit engine tuned for wide dynamic range vehicle attitude adjusted for best comfort
SC	 steering response	shift points: high, especially at low gears downshift before turns hard suspension accessory cut-off (low threshold) engine tuned for high torque (high jerk) vehicle attitude adjusted for best directional motion
FC	 steering response	shift points: least perceived shifts minimize # shifts soft-moderate suspension accessory cut-off (high threshold) engine tuned for wide dynamic range vehicle attitude adjusted for good comfort and directional motion

Fig. 5: Subsystem Adjustments for Different Adaptation States

VEHICLE PRODUCT	TECHNOLOGY REQUIREMENTS				DRIVER ADAPTATION
	FEEDBACK CONTROL	INTEGRATED CONTROL	ENVIRONMENT ADAPTATION	DRIVER ADAPTATION	
<div style="text-align: right;">AUTOMATIC</div> <div style="text-align: center;">SEMI-AUTOMATIC</div> <div style="text-align: left;">MANUAL</div>	✓	✓	✓	✓	
		✓	✓	✓	
		✓	✓	✓	
			✓	✓	
			✓	✓	
				✓	
		✓	✓	✓	
			✓	✓	
			✓	✓	
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		✓			
			✓	✓	
				✓	
				✓	
			✓		

Figure 6. Adaptive Vehicle Technology Requirements

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