PHASE I OF THE NEAR TERM HYBRID PASSENGER VEHICLE DEVELOPMENT PROGRAM

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FINAL REPORT

APPENDIX B: TRADE-OFF STUDIES

Volume I: Final Report

Prepared for
JET PROPULSION LABORATORY
by
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The research described in this publication represents the second of the several Tasks of the "Phase I of the Near Term Hybrid Passenger Vehicle Development Program" being carried-on by Centro Ricerche FIAT (CRF) on Contract No. 955187 from the Jet Propulsion Laboratory, California Institute of Technology.

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This Report, prepared by:

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FOREWORD AND ACKNOWLEDGEMENTS

This Report on the "Trade-off Studies" is the results of a joint effort between Centro Ricerche FIAT (CRF) S.p.A. (FIAT Research Center) and the following Subcontractors:

Brown Boveri Corp. (B.B.C.) (Sodium-Sulphur batteries)

M. Marelli S.p.A. (Lead-Acid batteries)

Pirelli S.p.A. (Tires)

Pininfarina S.p.A. (Body styling)

The Authors wish to express their appreciations to Messrs. Gross of B.B.C., Clerici of M. Marelli, Chiesa of Pirelli,Fioravanti of Pininfarina, Ippolito and Montalenti of CRF and their staff who made the essential contribution to the study development, to Messrs. Morello and Brusaglino of CRF for their advise and support to the programm effort as well as to Messrs. Vercelli of CRF, Fiandrotti and Guerci of SCL-SIPAL and their staff for their fine work in the concluding typing and editing effort of the Report preparation in compliance with JPL's Data Requirement Description.

SECTION 1

BACKGROUND INFORMATION: SOURCES AND REFERENCES

1.1. INFORMATION SOURCES

The pertinent reference material needed to perform the Trade-off study activities was obtained using the following modes of information retrival and acquisition:

1) CRF technical data files on vehicle components performance and characteristics
2) Library technical literature searches and retrieval
3) Information obtained from personal contacts (meetings or long distance phone calls) or via Telex from Phase I Subcontractors B. Boveri, M. Marelli, Pirelli and Pininfarina.

For the last item, the following List of meeting and/or Telex referencing is provided:

A – Brown Boveri Corp

1) Design Review Meetings:

[1] HEIDELBERG, Jan 29, 79
[2] TURIN, Mar 21, 79 - CRF Meeting Report SRE - 023/79
[3] TURIN, Apr 27, 79 - CRF Meeting Report SR 540/79

2) Telexes

[4] FEB 2, 79 TWX - Data on 32 kW Na-S battery
[5] APR 4, 79 TWX - Data on 36 kW Na-S battery

B – M. Marelli Co.

Design Review Meeting:

[6] MILAN, Mar 12, 79

C – Pininfarina

Design Review Meetings:

[7] TURIN, Jan 25, 79
[8] TURIN, Feb 16, 79

1.2 REFERENCES

Appropriate references for the material used to perform the Trade-off Studies have been provided in the text.

While a list of references to the Subcontractors' contributions has already been provided on the previous Subsection 1.1, this subsection, related to items 1) and 2) of said subsection, is presented to explicitly comply with JPL data requirements.

Since some references are referred to on more than one Report section, a single list was used covering the remaining Sections 3 through 5.

[1] L. Morello et al., "FIAT Research Center Hybrid Vehicle Prototype" SAE Technical Paper Series 790014. Congress & Exposition Cobo Hall, Detroit, Feb. 26 - Mar. 2, 79.

[2] "Van Doorne Automatic Transmission Characteristics" CRF Report No. SAS 11/78, May 24, 78.

[3] "Van Doorne Automatic Transmission Efficiency" CRF Report No. SAS 31/78, Sept 19, 78.

[4] "DAF Variomatic Transmission: Bench Testing" CRF Report No. 0398/75, Jun 23, 75.

[5] "DAF Variomatic Transmission: Vehicle Dynamometer Testing" CRF Report No. 0123/74, Feb 13,74.

[6] "DAF Variomatic Transmission: Vehicle Consumption Testing" CRF Report No. 0750/74, Aug 20, 74.

[7] "Engine Powertrain Electronic Control Strategies" Special Report for DOT-TSC (unpublished) Nov 78.

[8] "Test Data Gearbox Efficiency" FIAT 124 A.100 Gearbox, CRF Report, Aug 26, 74

[9] "Test Data Differential Gear Efficiency" FIAT 124/131 Differential CRF Report 10/43, Jul 5, 74.

[10] D.C. Motor Type 910.411 - Test Data on Serial No. MT 290-20/144, Jan 25, 79.

[11] Rinolfi et al., "Optimization of Vehicle Engine Operation by means of an Electronic Control System using on-board Ultrasonic Air Flow Measurements", International Meeting of Industrial Electronics, Turin EXPO,Sept 29-30, 77.

[12] "Engine Mapping: Test Run Automation and Data Processing" CRF Report No. RIC 889/78, Nov 9, 78.

[13] "Mission Analysis and Performance Specifications Studies", Apr 79, Phase I of the Near Term Hybrid Passenger Vehicle Development Program.

[14] Torque Converter. Make: Ferodo, Type 216.02.02.14 - Serial No. 1193.

[15] Dadone:"Machine Fundamentals", Clut Edition, Turin, 74.

[16] "Chevrolet's Eurosedan Supercars", Motor Trend Nov 77, pages 64-67 and 106.

[17] "Facts and Figures 78", Ibid 106.

[18] "The New Chevrolet - 1977 Caprice Classic and Impala" GM Pamphlet 3411, Sept 76.

[19] "Design Handbook 1985", Automotive Industries, Jan 1, 79.

[20] "GAMMA SEDAN" Pamphlet by Lancia Advertising and Promotion, Apr 79.

[21] DC MOTOR TYPE 910.411 - Manufacturing Drawings FIAT CRF-RIE, Electrical Systems, DWG No. Pr S/1729, Jan 9, 76.

SECTION 2

SIGNIFICANT ASSUMPTIONS

The following assumptions have significantly influenced the decisions made in setting the Trade-off studies strategy or in identifying the required methodology and results. The assumptions of the first type have been listed as General Assumptions on Subsection 2.1 while those of the second type have been listed as Operating Assumptions on Subsection 2.2.

2.1 GENERAL ASSUMPTIONS

2.1.1 To meet the 1985 fuel economy requirements with the projected new car fleet mix, the large size 1985 vehicle shall incorporate all the available advanced design concepts contributing to the improvement of fuel economy characteristics. This assumption will be validated during the Preliminary Design Task.

2.1.2 While the "hybridization" of any conventional car could provide significant fuel savings, only advanced design concepts would provide maximum petroleum savings with respect to the fuel economy characteristics of the 1985 new car fleet.

2.1.3 The optimization of an advanced vehicle design, which initially contains a significant number of uncertainties on various items and components, should be properly accomplished when the vehicle design characteristics definition has reached an acceptable level of preliminary detail.

2.1.4 The unavoidable presence of design uncertainties on advanced components and materials should not let loose approximation to be used in the design characterization of the well established items which, on the contrary, must be analyzed in all the available details so that the overall expected accuracy of the design results is maximized and kept within acceptable limits.

2.2 OPERATING ASSUMPTIONS

2.2.1 Due to the fact that a hybrid vehicle could be operated in the hybrid mode by means of appropriate control strategies without discharging the battery, it is assumed that the battery choice will not be made as a function of the required driving range capability but as a function of the attainable fuel economy.

2.2.2 The battery size and weight should be therefore defined and selected as the maximum which could be conveniently carried by the vehicle without significantly affecting the vehicle size and handling characteristics.

2.2.3 The thermal engine size and characteristics are defined to let the vehicle reach its maximum speed on flat road using thermal power only at the maximum engine power.

2.2.4 The electric motor size and characteristics are defined to provide the vehicle with the additional power required to meet the various performance requirements.

2.2.5 A Max/Min ratio of 4 is assumed to be appropriate for the Continuous Variable Ratio Transmission, the maximum ad minimum ratios being symmetrical with respect to the direct ratio.

2.2.6 Production costs are evaluated for production levels of 1,500 vehicle/day or above.

SECTION 3

METHODOLOGY DESCRIPTION

The Mission Analysis results have confirmed the validity of the basic assumption of our Proposal with respect to the Trade-off Studies expected results.

In line with JPL statement of work:

> "Identify, by means of Trade-off studies of design elements, the most promising design concept in terms of achievable petroleum savings to be developed during the preliminary design",

our strategy in defining and setting up the Trade-off task of the Phase I effort was accordingly based upon the following key points and corresponding CRF positions.

1) To be conscious of requirements to achieve job objective.

   Awareness of the fact that, by assumption, only advanced design concepts (to be validated within the Phase II timeframe) could provide maximum petroleum savings through the development of a hybrid vehicle as defined by the JPL RFP and contract.

2) To be conscious of existing know-how/know-what constraints

   Awareness of the need to reach reasonable design definition of the various vehicle components and systems before reliable assessments could be made on design elements optimization of such a complex entity like an advanced type vehicle.

3) To be conscious of the limited comparability among independent optimized approaches.

   Awareness of the fact that independent design approaches to the solution of an identical set of basic design and performance parameters through the "optimization" of loosely defined advanced concepts or data, could lead to alternative results which can be hardly weighed against each other.

4) To be conscious of the need for adequate design tools.

   Availability to support our Phase I effort of an advanced and powerful design tool such as the "computer simulation model for vehicle performance calculations", which allow CRF to simulate any combination of vehicle configurations (conventional, hybrid and electric), components and design parameters and calculate any significant performance parameter under any operating condition.

As a conclusion we had proposed to extend the scope of CRF effort during Phase I by thoroughly comparing, under similar conditions, a wide choice of configurations and components and carry-over the design optimization process of what, in a broader meaning, can be assumed a single hybrid vehicle design into the preliminary design stage.

The identification of a single basic vehicle model (e.g. Engine, Motor, Battery), on which a limited number of design alternatives can still be analyzed, optimized and compared with greater accuracy and detail and maybe mantained at the end as ranked option choices was therefore set in our Proposal and mantained throughout the accomplishment of the Task-2 effort, as the main goal of the Trade-off Studies.

3.1 SUMMARY OF PRINCIPAL STUDY ACTIVITIES

The Trade-off studies described in this report, being in-line with the following slightly modified contractual statement of work:

> "Analysis of vehicle design elements to develop grounds for H.V. design which best achieve vehicle specifications through: 1) the availability of systematic means of estimating effects of design elements on vehicle performance; 2) examination of Trade-offs between significant performance parameters to obtain comparable rather than optimal operation; 3) definition of effects of design alternatives on the energy consumption measures aiming at the selection of a single basic design concept which can be optimized during the preliminary design for a limited number of surviving alternatives",

have been somewhat adjusted to match the design approach our experience in the development of advanced vehicles has proven to be the most fruitful and rewarding.

We have therefore anticipated,in some instances,depths of analysis more proper of a preliminary design stage, while leaving to the preliminary design itself the optimization effort on the basis that the available vehicle simulation model can provide us with a complete set of new vehicle performance characteristics, within a day from the definition of an updated set of vehicle design parameters.

Parametric analysis during the Trade-off studies has been therefore limited to those cases where major design decisions where involved (e.g. potential impact on achievable fuel economy of the aerodynamic drag coefficient) or where initial design assumptions had to be revised to obtain proper compliance with minimum requirements and/or performance specifications, or matching of some performance parameters to improve the visibility of trade-off conditions between alternative solutions.

On the other hand we have concluded that other major design decisions (e.g. control strategy) did not significantly influence the Trade-off stage,as they could be optimized almost indipendently for various paramaters at no appreciable extra cost. It was therefore felt appropriate to limit the effort to the assessment of whether a design optimization could appreciably alter the performance ratios between the alternatives under evaluation.

Stretching out in conclusion the above concepts, it can be stated that, in our approach,Design Trade-off and Preliminary Design are almost concurrent activities: during the first stage, accounted for in this report, Preliminary Design type activities have been carried out to the extent required to define trade-offs between conceptual alternatives. During the second stage, corresponding to Task-3 of Phase I, Trade-off type activities will continue to the extent required to optimize the preliminary design being developed.

Having outlined the main criteria which our strategy in setting up the Trade-off study methodology was based upon, the methodology itself can now be specifically addressed.

Once again it must be emphasized the role played by the availability of a design tool such as the "computer simulation model for vehicle performance calculations": having been a conditioning element in our strategy's choice, it has represented an effective backbone supporting and conditioning most of the Trade-off activities. A detailed description of the model's characteristics and capabilities is provided in appendix A.3-1(1).

The various sides of the methodology used in the Trade-off studies can be summarized as follows

1. Trade-off study activities
2. Trade-off analysis process

They will be analyzed in their main aspects and interrelationships in this subsection: the Trade-off Study activities will be also described in greater detail in the following subsection or in the related appendices.

It is appropriate to point out that, while the actual effort performed and know how developed under this contract are fully covered in this methodology section, the concepts already presented in our proposal or specific design tools and methodologies previously developed and therefore significantly contributing to the existing CRF capabilities in accomplishing the task's objective, are presented as references in the appendix section.

3.1.1 Trade-off Study Activities

The methodology used during the study can be best illustrated by the following list of activities that were conducted. A discussion of each activity is contained in the detailed description that follows on Subsection 3.2:

a) Review of alternatives – reviewing all the available alternatives to select the alternatives to be analyzed and evaluated for Trade-off purposes.
b) Vehicle architecture – identifying vehicle architecture(s) applicable to the alternatives under evaluation and defining basic vehicle scheme (s).

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(1) See Ref. [1] Subsection 1.2

c) Analysis and evaluation of alternatives – definition of design parameters and calculation of the performance parameters going through the following steps for each of the selected alternatives

   (1) Identify Power, Ratios, Battery Weight etc.
   (2) Identify detailed Vehicle Weight and Size.
   (3) Calculate Vehicle Consumptions and Emissions
   (4) Analyse Production Costs
   (5) Calculate Vehicle Performance
   (6) Assess Reliability, Availability, Maintenability.
   (7) Analyse Life Cycle Costs
   (8) Assess Operational Quality and identify Safety Requirements

d) Review of Trade-off Data – assessment of trade-off studies results, identification of optimal design concept and solution(s) to be developed during the preliminary design.

A data flow diagram indicating the relationship between the various activities and the corresponding major outputs is shown in Fig. 3.1 - 1.

3.1.2 Trade-off Analysis Process

The Trade-off Analysis process carried-out during the Trade-off studies is shown in Fig. 3.1.-2; it has been substantially in line with that described in our proposal. This Subsection provides some comments on the differences or scope adjustments that the accomplishment of Task-2 more properly required.

In the block diagram of Fig. 3.1-2 dotted line blocks identify alternatives which, while analyzed during Task-2 did not lead to a Trade-off conclusion (at least for some of them, e.g. batteries as far as COMPONENTS are concerned) or activities which could not be fully covered as planned since they have resulted to be more appropriate for the following stage of Trade-off assessment in support of Preliminary Design decisions, due to the more in-depth knowledge then available.

While therefore the Trade-off studies have defined the optimal configuration of the power train, battery alternatives and corresponding engine/motor power and characteristics will be, in accordance with our proposal, more in depth analysed during the Preliminary Design. The evaluation of the Available Operational Strategies also has

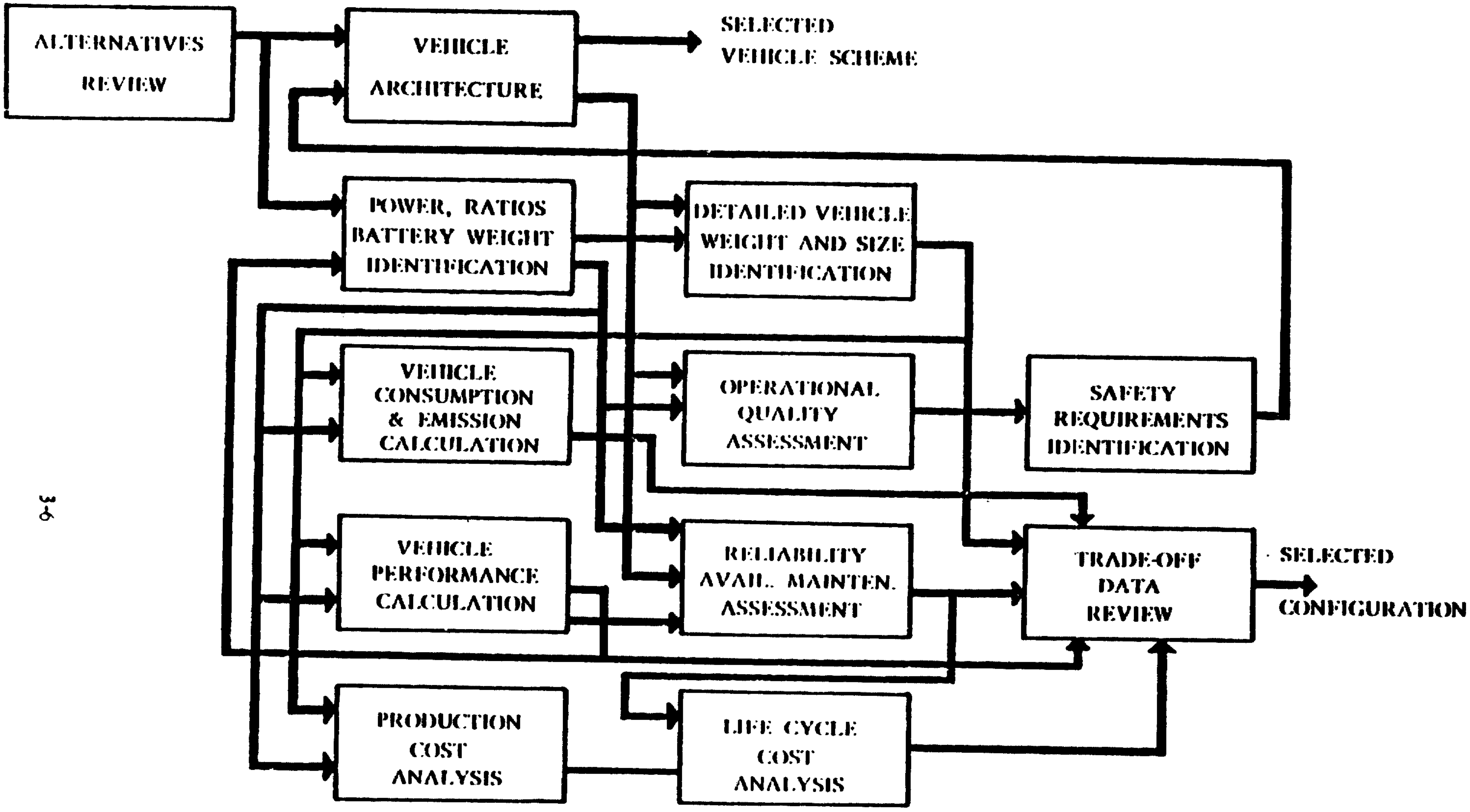

FIG. 3.1-1 — DATA FLOW DIAGRAM OF STUDY ACTIVITIES

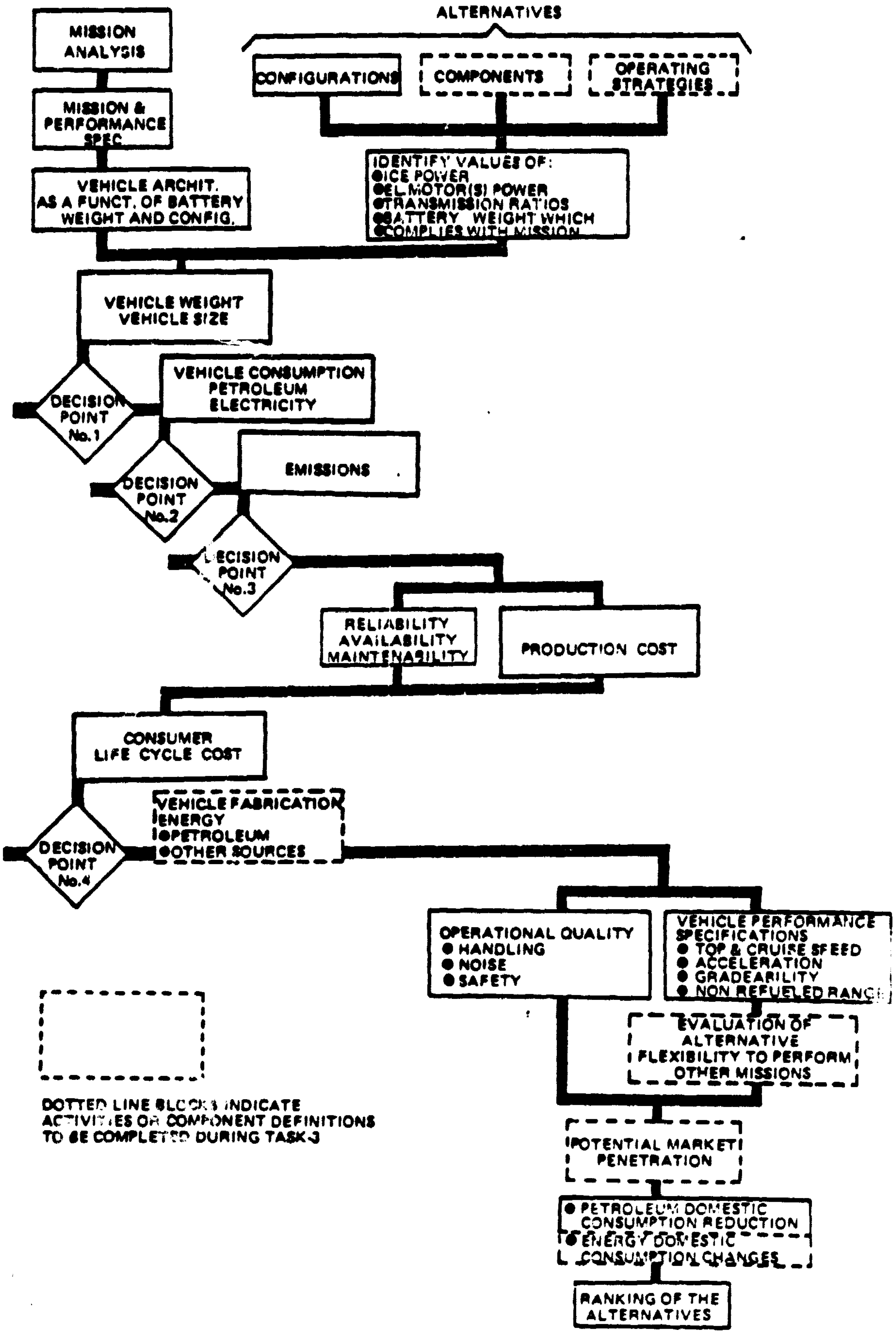

FIG. 3.1.2 – TRADE-OFF ANALYSIS PROCESS
(TO BE REPEATED FOR EACH SET OF ALTERNATIVES)

shown that, for each solution, the control strategy should and could be optimized at the same cost, so that it would not be relevant in terms of Trade-off decisions.

With respect to the Trade-off activities originally planned, the evaluation of Vehicle Fabrication Energy has shown that additional progress in preliminary design development is required before assessments could be made with an acceptable expected accuracy. The same applies to the Evaluation of Energy Domestic Consumption changes.

On Evaluation of Alternatives Flexibility to perform other Missions it was realized that a key role on this capability would be played by the control strategy and therefore, while the flexibility would ultimately exist for all alternatives as a result of the intrinsic flexibility of the strategy itself, it would mainly be a matter of Trade-off in the only variable then available, that is fuel consumption.

Finally the analysis of Potential Market Penetration, being so dependent on the previous assessment, has also been included in the conclusive stage of Trade-off decisions.

3.2 DETAILED DESCRIPTION OF STUDY ACTIVITIES

3.2.1 Review of the Alternatives

As outlined in our proposal, a wide range of alternatives exist in selecting configurations, components and operational strategies of a propulsion system for a hybrid vehicle. To provide background information a summary description of such alternatives is presented in Appendix A.3-2.

In reviewing the alternatives to be analysed, it was decided to save the effort to quantitatively assess, as per our proposal, the series configuration performance; the propulsion system alternatives were accordingly reduced to two basic parallel configurations, with and without Continuously Variable Ratio Transmission (CVRT)(1), the first one including three possible variations:

a) CVRT handling both the ICE and electric motor powers,
b) CVRT handling the ICE power only,
c) same as b) with a clutch to disconnect the electric motor when "not operable".

As component alternatives to be analysed during Trade-off stage, the existing-technology, low-energy Lead-Acid and the advanced-technology, high-energy Sodium-Sulphur batteries were maintained to include the full spectrum of attainable performance. Preliminary data on these batteries are provided in Appendix A.3-3.

As control strategy alternatives it was initially assumed to include the analysis of trade-off in performance as a result of fixed point/line and/or continuous/on-off mode operation. Later on during the studies, it was concluded that the control strategy should play a role of "free variable", allowing the optimization of each configuration without practical limits in strategy sofistication at no extra cost(2).

The Review of the Alternatives was then specifically intended to only address the propulsion system alternatives which were already considered in our proposal; in defining the vehicle architecture as described in the following subsection, it appeared however that, in principle, a number of alternatives also existed in the vehicle characterization. While this topic was not addressed in our proposal, as being conditioned by the Mission Analysis results, the Trade-off studies could have included, if appropriate the evaluation of Vehicle Architecture alternatives as well.

Since however the Vehicle Architecture study has identified without uncertainties a

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(1) See References [2] through [6], Subsection 1.2

(2) See Ref. [7], Subsection 1.2

single optimal hybrid vehicle configuration which could best suit the identified Mission, the evaluation of alternatives during the Trade-off studies did not get beyond the boundaries of the propulsion systems.

3.2.2 Vehicle Architecture

Preliminary Mission Analysis results had shown that Vehicle Architecture should fit a general purpose six-passenger car with over 100- mile daily range capability and competitive performance/price characteristics with respect to conventional vehicles.

The most influencing element, in defining the architecture of a Hybrid Vehicle is represented by the traction battery, due to its relevant weight and size. The battery itself is not, on the other hand, significantly conditioned by the daily range requirement, as it would be in an electric vehicle, because by means of appropriate control strategies various battery discharge levels could be obtained for any driving range which would correspond to different values of achievable fuel economy.

The battery size would mainly depend on the required electric motor power which in turn depends on the total required vehicle power and on the ratio between thermal and electric power. However the total required vehicle power to provide the required vehicle performance depends on vehicle rolling resistance and aerodynamic drag which in turn are related to vehicle architecture dependent elements such as suspensions and body profile and frontal area.

The methodology used to define the Vehicle Architecture as well as the Propulsion System characteristics has necessarily used an iterative approach which, upon some assumptions, led to corresponding decisions or calculations and then to an assessment of adequacy to the assumptions themselves and to the required adjustments.

Before starting the actual Vehicle Architecture study a preliminary assessment of the aerodynamic drag and rolling resistance impact on vehicle power was made which led to a tentative selection of the corresponding coefficients and accordingly to a tentative identification of engine and electric motor power resulting in preliminary battery weight and size values. On such a basis the actual process of Vehicle Architecture definition was started and completed according to the step by step selection procedure shown on Figure 3.2-1. At each step the various possible choices were analyzed and evaluated to provide the best expected combination of functionality, efficiency, comfort, safety and fuel economy.

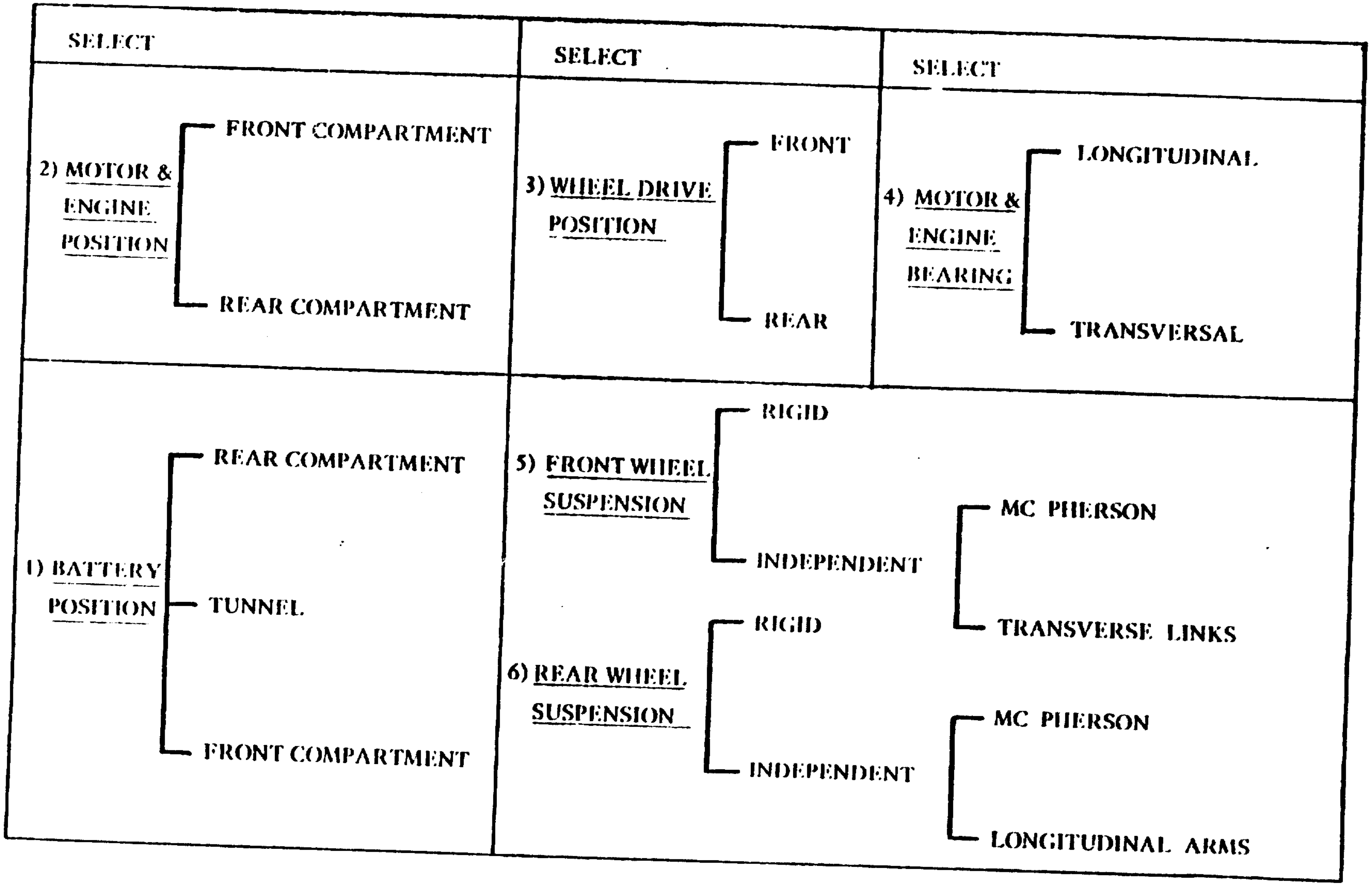

FIG. 3.2-1 — HYBRID VEHICLE LAYOUT AND SUSPENSIONS SELECTION TREE

At the end of such a procedure the resultant vehicle characteristics were verified with those of the existing models and a reference conventional vehicle was selected which, by appropriate adjustments, could best match the advanced vehicle characteristics so identified. Critical items were also identified which would require further developments to match the initial assumptions.

3.2.3 Evaluation of the Propulsion System Alternatives

3.2.3.1 Propulsion System Power and Transmission Ratios

On the basis of the vehicle aerodynamic drag and rolling resistance characteristics established at the Vehicle Architecture level, more accurate calculations of the Engine and Motor power were performed under the usual assumptions:

a) maximum vehicle speed obtained using thermal power only

b) electric power used as needed to meet the other performance specifications.

The corresponding battery power was then checked against previous estimates and detailed electrical models were obtained from B. Boveri and M. Marelli subcontractors (for Sodium-Sulphur and Lead-Acid batteries respectively)(1) which were added to the SPEC'78 data base (See Appendix A.3-1 "Mathematical Model for Performance, Emissions and Consumption Simulation of Conventional, Hybrid and Electric Vehicle Propulsion Systems").

Tentative transmission ratios were accordingly calculated for the various Alternatives under evaluation which were properly adjusted to meet (or slightly exceed) the various performance requirements.(2).

The effect of transmission ratio variations on the Power vs. speed plots is shown in qualitative terms for the thermal engine on Figure 3.2-2 and for electric motor on Figure 3.2-3 (2).

Due to the iterative approach that a complete simulation of the various components non-linearities had required, no effort was made to exactly match said specifications for every alternative as the overall goal of making trade-off assessments feasible and reliable as well, did not require such a waste of efforts.

Any gain in one vehicle performance parameter, due to some more favorable design parameter characteristics, would have been in fact compensated by some loss in another performance parameter and the two would have been averaged out in the final overall evaluation.

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(1) See References [1] through [6], Subsection 1.1

(2) See References [8] through [10], Subsection 1.2

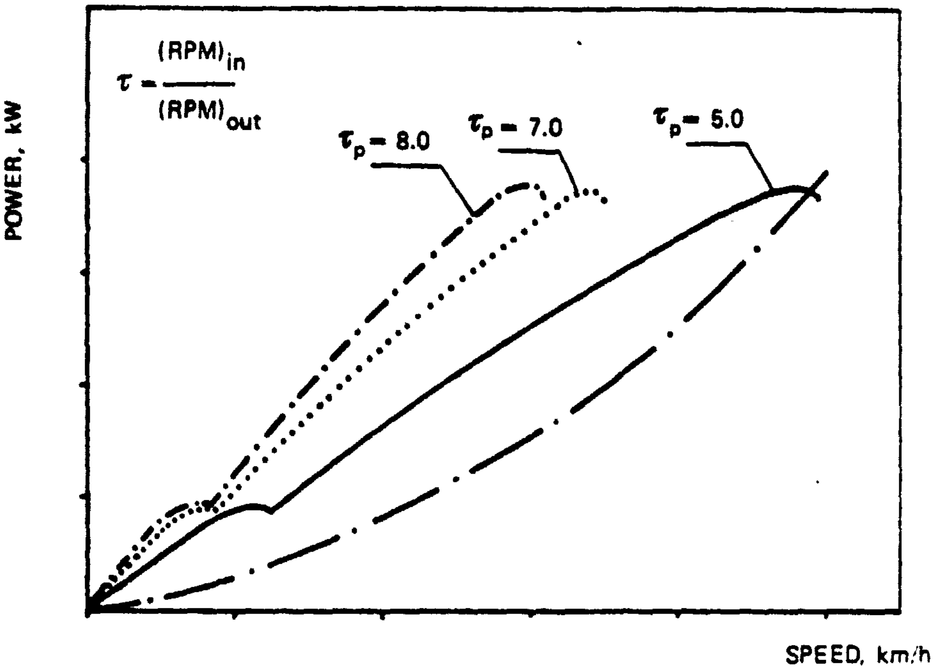

FIG. 3.2-2 – ENGINE POWER VS VEHICLE SPEED

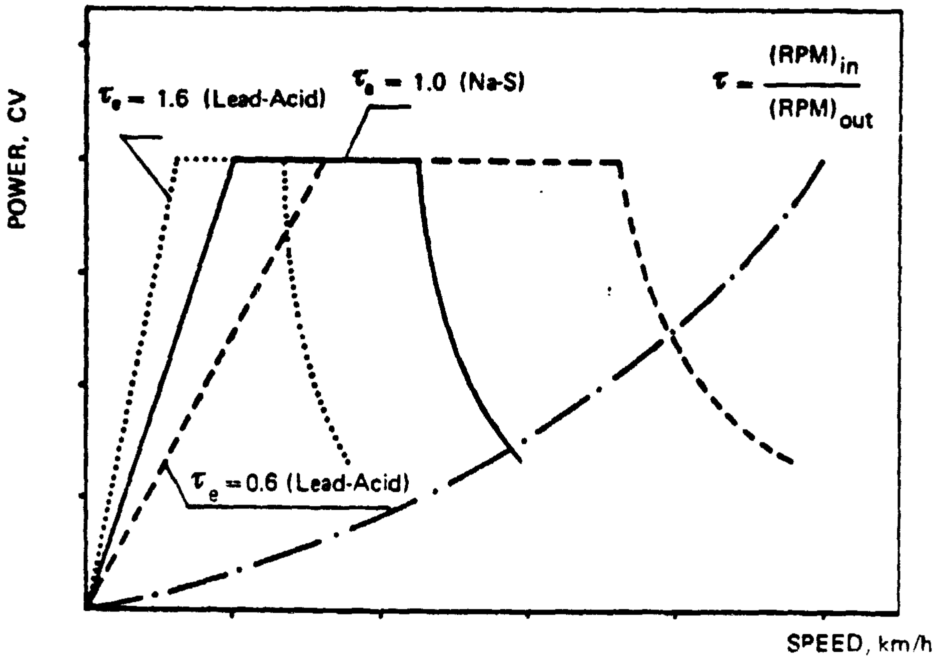

FIG. 3.2-3 – ELECTRIC MOTOR POWER VS VEHICLE SPEED

3.2.3.2 Vehicle Weight

The detailed Vehicle Weights were obtained starting from a detailed analysis of the current conventional vehicle selected as reference vehicle.

As a second step all the additional equipment that would be required on a 1985 conventional U.S. passenger car were added or substituted, as appropriate and appropriate addition and/or substitution were then made to convert the conventional propulsion system into an adequate hybrid propulsion system, assuming that current components and/or technologies were used as practical.

As a third and final step, for each component and/or subsystem, assessments were made to identify the weight reductions which could be expected as a result of the Advanced Technologies and Components which, upon validation during the H.V. Program's Phase II, should be made available and used for 1985 mass production of hybrid vehicles. The overall effort of vehicle weight estimating was, to a large extent, one side of a single analysis of vehicle composition also used, as outlined in the following section 3.2.3.4, to evaluate the vehicle production costs.

3.2.3.3 Vehicle consumption, emissions and performance

From the methodology stand point the above matters can be covered together as the corresponding parameters were evaluated using the same SPEC 78 simulation program described in Appendix A.3-1.

It is worth noting that, while based upon a given set of input design parameter data base (which included mathematical models, complete actual or scaled-down characteristics of the various components and a wide selection of control strategy options) the performance parameters were evaluated irrespective of the actual results (above or below performance specifications), fuel consumption and emission on each of the various standard cycles could only be obtained if the simulated vehicle were actually able to follow the accelerations required by the cycle itself.

The model would in fact first calculate for each cycle point (1 second duration) the required speed, torque and power values (vehicle, engine, motor) and then the corresponding consumption and emissions; should the simulated vehicle fail to satisfy the operating conditions on some of the cycle points, the simulation program would not calculate the resulting consumption and emission values, as it has been conceived mainly as a design tool and not as a test bed simulator.

The program itself can provide however a complete listing of the power values required to perform any of the standard vehicle cycles for a given set of all vehicle design parameters but those related to its propulsion system.

This specific feature was used to evaluate electric power requirements in connection with the pure electric driving capabilities of a hybrid vehicle as a result of a given battery power availability.

The available control strategy options were not fully exploited during the Trade-off studies, since to simply compare the consumption and emissions behaviour, a single control strategy was used (to saturate thermal power first, with RPM limitation to 2,000 RPM, when the CVRT was available, or otherwise to 5,000 RPM).

In any event the thermal engine was always assumed to run under optimal conditions (maximum power at each consumption level) as shown qualitatively on Figure 3.2-4.(1)

3.2.3.4 Production costs

The Hybrid Vehicle Production Costs analysis was accomplished as a result of a detailed investigation of the production cost of the individual parts and components identified to carry out the vehicle weight estimates previously described in Subsection 3.2.3.2.

While, however, parts' weight is almost independent of the production levels, the production costs heavily depend on the planned production quantities.

The CRF experience on such matters has been acquired with reference to production levels up to 2,000 model vehicles per day (as related to current FIAT manufacturing facilities and market penetration). This level can already be considered in the range of large production volumes and therefore the available know-how can provide reasonable assurance of adequate methodology availability to obtain reliable but competitive cost estimates.

On the other hand we think that, to comply with production levels expandable, for the U.S. market, up to 4,000 vehicles per day, appropriate large scale production methods, techniques and work organization should be considered as mandatory requirements in conjunction with adequate capabilities in forecasting and assessing the most suitable technologies and materials which would be available in the mid 80's.

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(1) See References [11] and [12] , Subsection 1.1

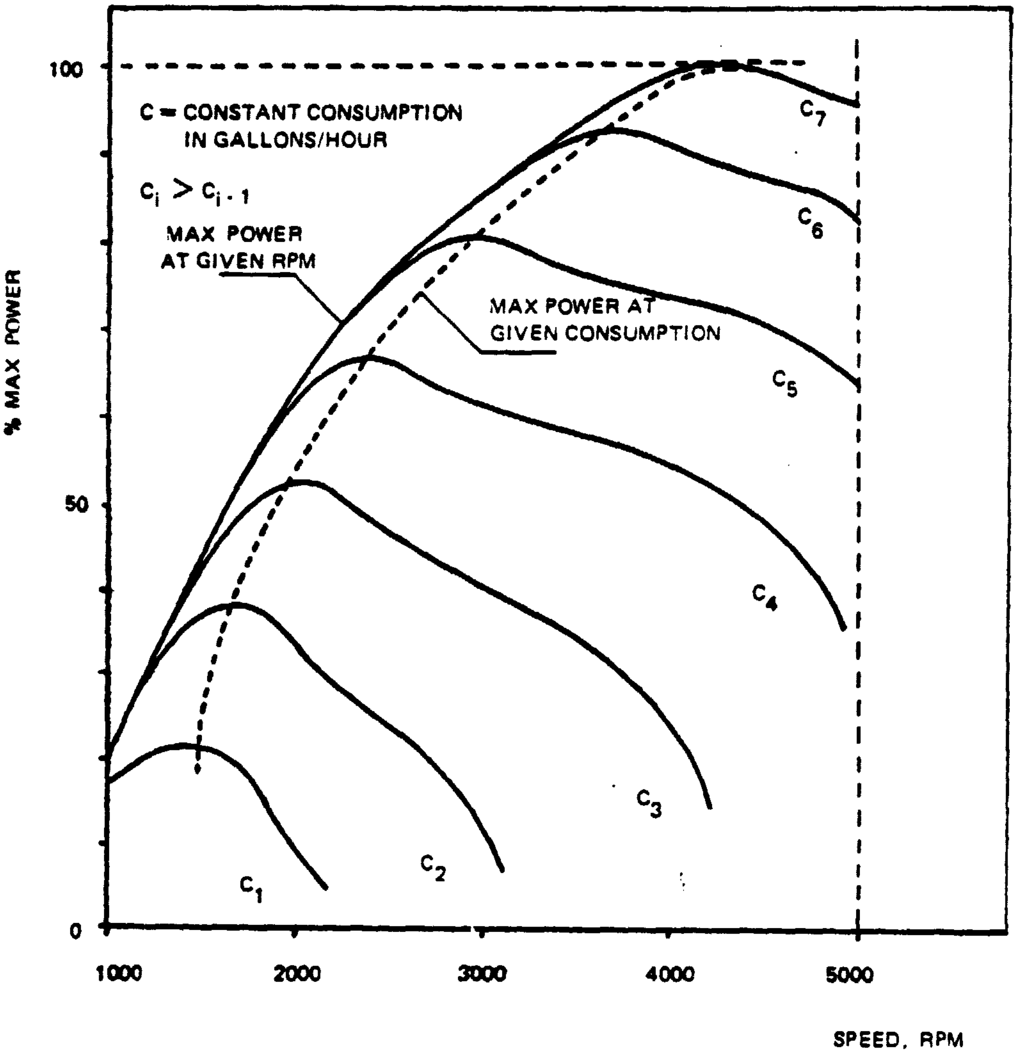

FIG. 3.2-4 – MAXIMUM ENGINE POWER VS. SPEED

The last issue would specifically apply to the new and advanced components not used in the conventional vehicles currently manufactured such as, traction batteries, microprocessor based control unit, Continuously Variable Ratio Transmission etc. The corresponding cost estimates have been made extrapolating the limited available data with specific support from the Subcontractors' expertise(1).

A final problem which had to be solved was the definition of the criteria to account for expected U.S. manufacturing costs, since all the analyses mentioned above were referred to the only available FIAT manufacturing costs in Italy.

The most appropriate procedure to obtain projected U.S. production costs was identified as follows:

1) Upon completion of the accurate cost analysis of the vehicle model in the FIAT fleet which could more closely satisfy the selected hybrid vehicle characteristics. the resulting cost should have been adjusted to project present small series FIAT production costs (as incurred today) and account for the appropriate U.S. mandatory equipment fitting as well as for the higher production volumes expected for the hybrid vehicles of the mid 80's.

   This projected FIAT production cost of a mass produced conventional K_5 large size (U.S. type) conventional vehicle can be referred to as X_1; its characteristics should compare with the corresponding K_5 vehicle identified during Task-1 "Mission Analysis and Performance Specification Studies".

2) The production cost X_1 should be adjusted to identify the production cost X_2 of the corresponding hybrid version under the same manufacturing conditions.

   This would define a cost (or price) ratio between hybrid and conventional vehicles of similar size/and performance characteristics.

$$C_2 = \frac{X_2}{X_1}$$

3) Defined as Y the U.S. manufacturing cost of the K_5 vehicle identified by the Mission Analysis the expected cost of an equivalent hybrid vehicle mass produced in U.S. factories should be given by:

$$X_3 = C_2 Y.$$

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(1) See Ref. [1] through [6], Subsection 1.1

In support of the estimates referred to FIAT manufacturing costs, it was felt appropriate to include in Appendix A.3-4 a summary of the FIAT Procedures and Regulations as used to assess expected production costs of actually manufactured models. These procedures were not obviously implemented in the hybrid vehicle cost estimates; they only represent the methodology applied to establish and update the exhaustive data base on the costs of each individual part and manufacturing step that has been used as a foundation of the production cost analysis actually performed during the Trade-off studies.

3.2.3.5 Reliability, Availability, Maintenability

Upon analysing the critical areas and corresponding objectives it was concluded that specific assessments could only be made as a result of a more detailed verification to be accomplished at the preliminary design level, taking also into account that the critical components lie in the area of non-conventional items (that is electronic controls, electric motor and battery) for which a trade-off decision was not expected during this task.

The methodology on this topic was therefore limited to the acquisition of existing operating life estimates on components included in the specific alternatives under evaluation which could lead to criteria for a trade-off assessment.

3.2.3.6 Life cycle cost

The life cycle cost methodology has necessarily followed the headlines of that used to estimate the life cycle cost of the reference ICE K5 vehicle as described in Volume I of the "Mission Analysis and Performance Specification Studies Report" (1) so that the two could be fully comparable.

Additional criteria, typical of the electric portion of the propulsion system, were used according to JPL guidelines.

Due to the uncertainties on the possible salvage value of the traction batteries it was decided to totally neglect such a value even when the limited use of the battery, under

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(1) See Ref. [13], Subsection 1.2

the assumed operating conditions, could result in a battery life beyond that of the vehicle itself. The fuel consumption was not adjusted to account for the estimated on-the-road MPG since such an adjustment had not been used in Task-1.

3.2.3.7 Operational Quality

Since the Vehicle Architecture definition has not identified significant alternatives which could lead to trade-off assessments in terms of Operational Quality, including Safety, the activity on this issue was limited to the identification of the most relevant hybrid vehicle characteristics in terms of Handling and Noise; in the area of Safety a possible exception was represented by the particular care which had to be given to the possible inclusion in the vehicle structure of a high temperature battery like the Sodium-Sulphur type.

To properly evaluate the Vehicle Frame Structure behaviour under normal operating as well as crash conditions, the vehicle structural elements were defined so that a preliminary stress analysis and subsequent definition of the element cross sections and materials by means of computer simulation mathematical models could be made.

This study was intended to identify possible criticalities at the design and/or manufacturing levels in a safetywise adequate structure. At the end of the trade-off task, however, the study itself (which would have not contributed in any event to trade-off assessments between safety related alternatives, as they did not materialize) has not provided yet complete interim results beyond the basic structure scheme used for stress analysis calculations (See: following Subsection 4.2, Vehicle Architecture). This matter will be therefore properly covered by the report on the "Preliminary Design Task".

3.2.4 List of related Appendices

The following Appendices related to Section 3. Methodology are included in Volume II of the "Trade-off Studies" Report:

Appendix A.3-1 : "SPEC 78" Computer Simulation Model
Appendix A.3-2 : Propulsion System Alternatives
Appendix A.3-3 : Lead-Acid and Na-S Traction Batteries
Appendix A.3-4 : FIAT Procedures and Regulation for mass production Cost estimates.

SECTION 4

INTERIM RESULTS

This Section deals with the results obtained in the process of defining the vehicle conceptual design (more specifically with respect to Vehicle Architecture) and the results of the various alternatives characterization (Configuration and Battery type combinations) which led to the identification of a selected configuration.

As mentioned on the Methodology description, since the optimization of the developed conceptual design will be completed during the following Task-3, Preliminary Design, parametric analyses have only been used to the extent actually needed to accomplish the proposed Task-2 objective.

The Interim Data are presented according to the Study Activities as described in the Methodology Section. All Design and Performance parameters identified or studied are therefore included in the appropriate subsections.

It has been already emphasized that our current design methodology is heavily influenced by the design tool we extensively use, namely the SPEC 78 Computer Simulation Model.

Being all the actual and detailed component characteristics duly accounted for by the model itself (from Engine Maps to Electric Motor Magnetization Curves) direct relationships between design and performance parameters could not be conveniently identified, the model correctness having been already validated through the verified agreement between calculated and measured values during the FIAT 131 Hybrid Vehicle development and testing (1).

The "relationship" table required by the JPL Data Requirement Description is therefore not included in this Report as not-applicable to the methodology that has actually been used.

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(1) See Ref. [1], Subsection 1.2

4.1 REVIEW AND SELECTION OF PROPULSION SYSTEM ALTERNATIVES

The propulsion system alternatives presented in our proposal were reviewed and discussed to define the actual configurations to be analyzed and compared during the trade-off studies. With respect to the schemes originally proposed, a lock-up torque converter has replaced the clutch originally shown to implement subsystem No. 1 (See Fig. 4.1-1/4.1-5). A hydraulic torque converter with lock-up provides in fact the following advantages, which improve the hybrid propulsion system efficiency and flexibility(1):

- Ease of starting-up the engine under load.
- Torsional vibrations not transmitted to the engine.
- Wear reduction of the engine mechanical components as a result of its "shock absorbing" action.
- Possibility of automatically varying the out-torque with respect to the in-torque, as required in the range $1 \leq \tau \leq 2.1$, being $\tau = T_{out} / T_{in}$. A lock-up clutch allows to lock up the converter when the ratio $\nu = \omega_{out}/\omega_{in}$ exceeds 0.86(2)

The composition of the updated schemes for the various configurations is shown in Table 4.1-1 and the corresponding block diagrams are shown in Figures 4.1-2/4.1-5.

It must again be pointed out that Configuration No. 4 only differs from No. 3 because of the clutch added to disconnect the electric motor when not in use (e.g. electric propulsion system out of service). It will then be analyzed only to evaluate fuel savings under such conditions.

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(1) See Ref. [14], Subsection 1.2

(2) See Ref. [15], Subsection 1.2

TABLE 4.1-1

HIGHER POTENTIAL PARALLEL CONFIGURATIONS

CONFIGURATION	SUBSYSTEM			COMPONENT
	I	II	III	
1	LOCK-UP TORQUE CONVERTER	FIXED RATIO	absent	Na-S/Lead-Acid
2	LOCK-UP TORQUE CONVERTER	FIXED RATIO	CVRT	Na-S/Lead-Acid
3	LOCK-UP TORQUE CONVERTER & CVRT	FIXED RATIO	absent	Na-S/Lead-Acid
4	LOCK-UP TORQUE CONVERTER & CVRT	FIXED RATIO & CLUTCH (between electric motor and drive line)	absent	Na-S/Lead-Acid

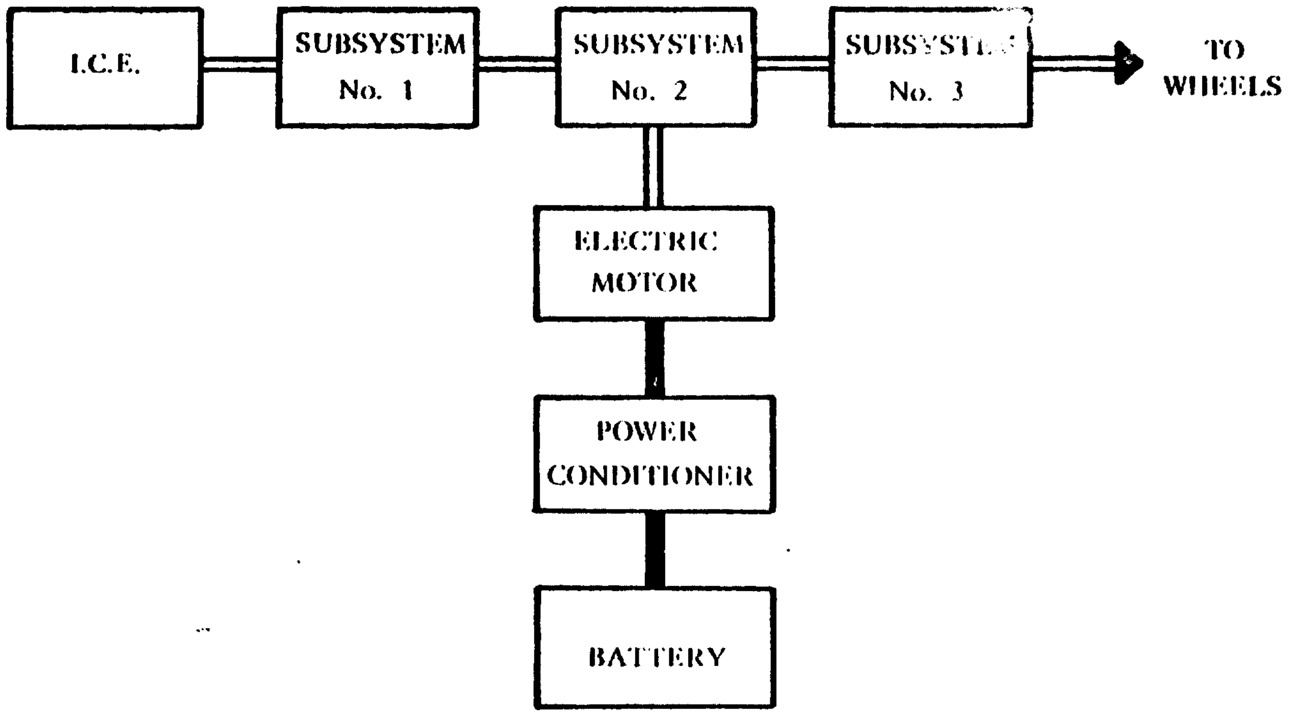

FIG. 4.1-1 – HYBRID VEHICLE POWERTRAIN: PARALLEL CONFIGURATION

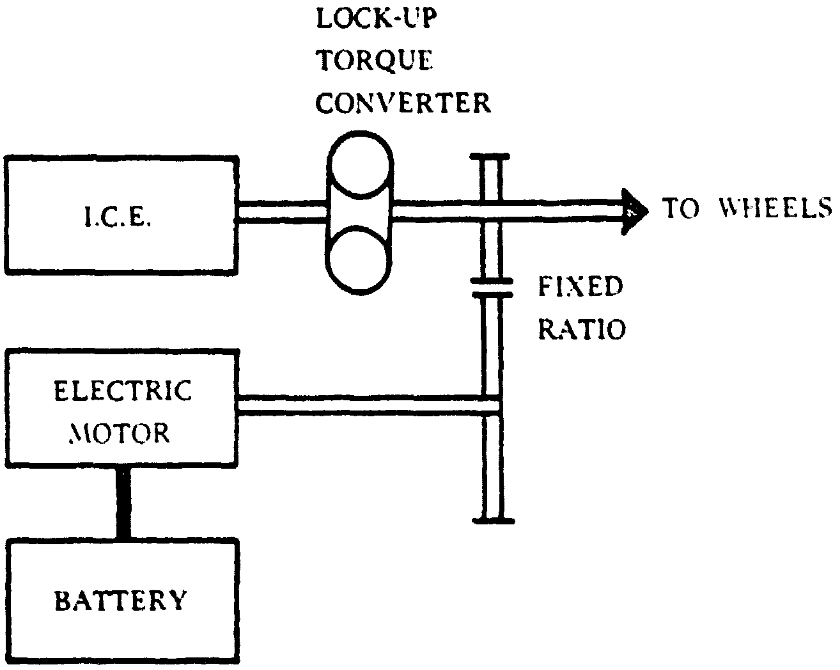

FIG. 4.1-2 – HYBRID VEHICLE: PARALLEL CONFIGURATION No. 1

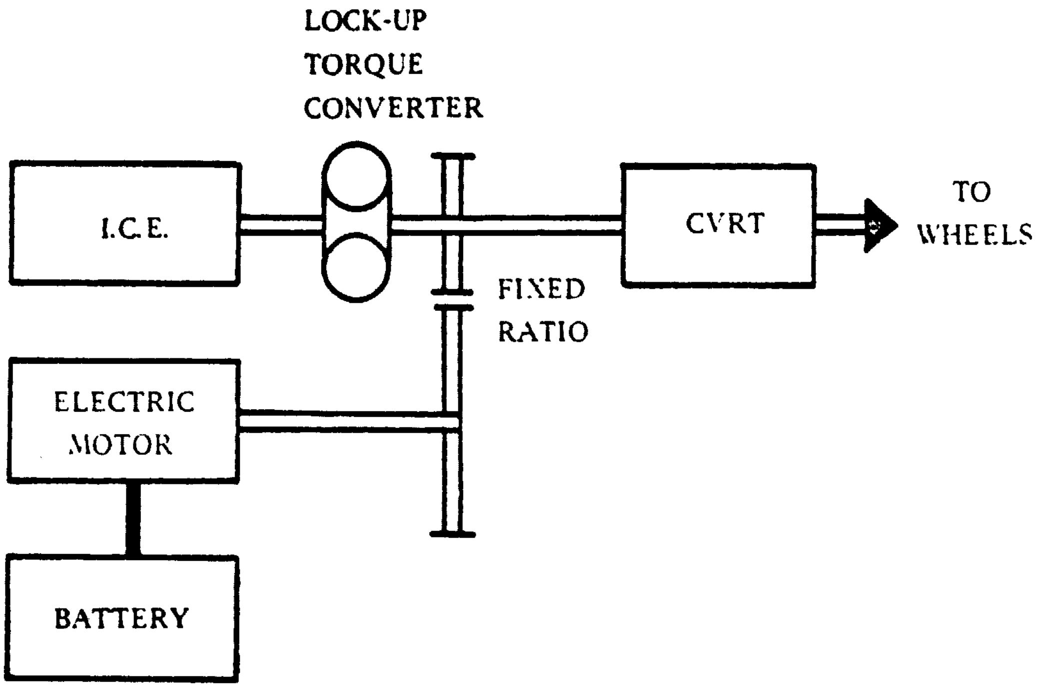

FIG. 4.1-3 – HYBRID VEHICLE: PARALLEL CONFIGURATION No. 2

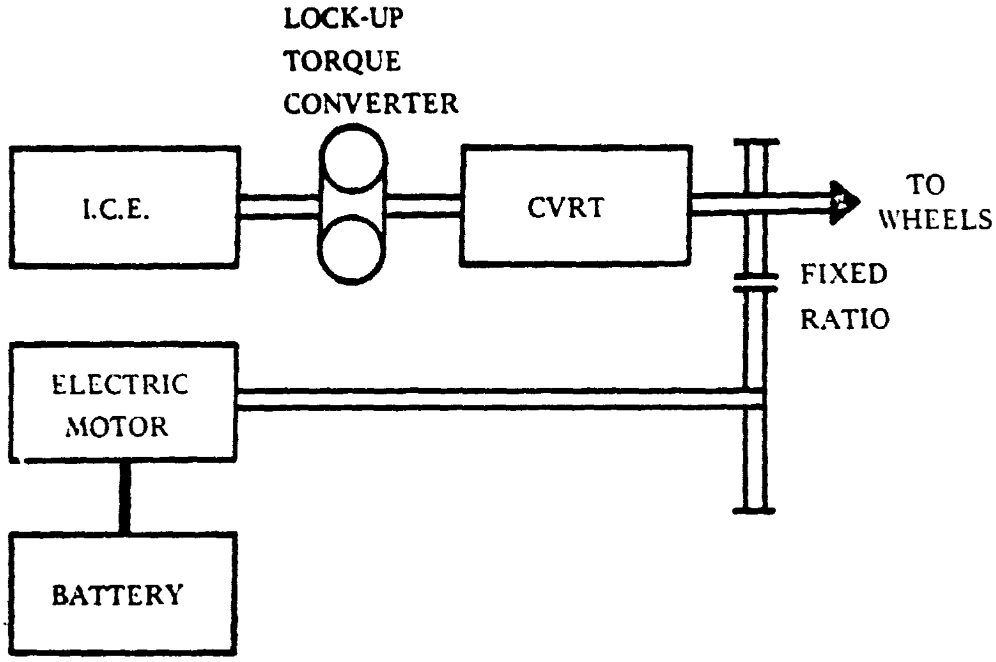

FIG. 4.1-4 – HYBRID VEHICLE: PARALLEL CONFIGURATION No. 3

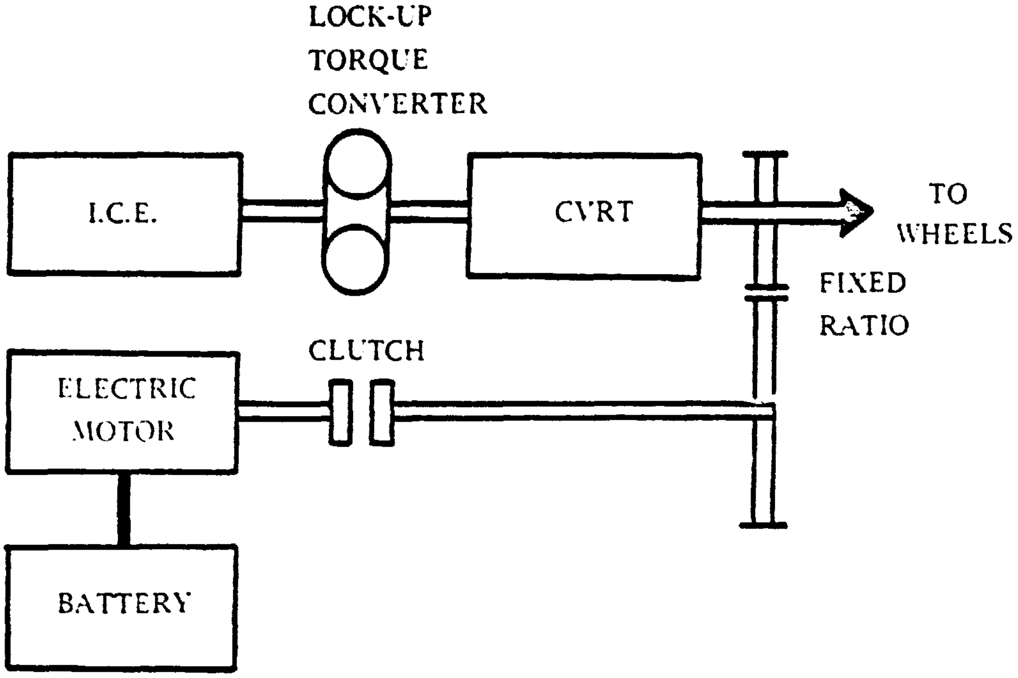

FIG. 4.1-5 – HYBRID VEHICLE: PARALLEL CONFIGURATION No. 4

4.2 VEHICLE ARCHITECTURE

4.2.1 Basic Hybrid Vehicle Characterization

During the Basic Hybrid Vehicle Characterization the following elements have been defined according to the methodology described in Section 3: battery, engine/motor, drive wheels positioning, front and rear suspension, body structure, materials and profile.

a) Battery positioning. The choice was restricted between a tunnel in the passenger compartment and the vehicle end compartments; while the first solution would make it easier to comply with passengers safety requirements (as in case of crash against a barrier the battery modules could collapse inside the tunnel without affecting in any event, the vital space of the passengers compartment), requirements of internal space relative to a six-passenger compartment and of space taken by the batteries should make the second solution mandatory. Battery fitting below the passenger compartment had to be discarded in principle because of the resulting excessive vehicle height . As battery positioning in the front end compartment would make the wheels steering much too difficult, batteries could only be positioned in the rear end compartment; in the case of a Na/S type battery a sealed container is necessary for thermal insulation purposes: the function of such a container can also be fulfilled by the very structure of the vehicle (integrated battery); in the case of the Lead-Acid type battery, a cage frame appears to be adequate to secure the modules to the vehicle structure.

b) Engine/motor and drive wheels positioning. With the engine necessarily in the front end compartment the front wheel drive became an obvious choice. Another reason for choosing the front wheel drive was that the battery height would have made rather hard to fit the differential in the rear end. This arrangement allows to reduce the vehicle weight since it eliminates the transmission shaft. The unbalance in the weight distribution, typical of the conventional front wheel drive model, due to the greater weight on the front axle, is, in the case of the hybrid vehicle, noticeably reduced, because of the battery weight acting over the rear axle.

c) Front wheel suspension. The first choice was between a rigid and an independent wheel suspension. The previous choice of a front wheel drive automatically excluded the rigid type suspension which would have also resulted in the generation of unwanted gyroscopic steering torques, when a slope difference in the transversal road profile occurs. An independent wheel suspension was therefore adopted and, in particular, the Mc Pherson type was preferred to the transverse links type. In fact, because of the multiple attachment points (three), the Mc Pherson type suspension provides greater space availability due to the absence of top transverse links and the same reduction in the structure stresses as the transverse links type suspension with overall reduced weight.

d) Rear wheel suspension. For reasons of greater space availability both in width and in height, an independent wheel suspension has been preferred to the rigid axle type. In particular the longitudinal trailing arms type with torsion bar has appeared to be the most appropriate solution to conveniently fit the battery over the rear axle. It appears the only solution which makes an adequate trunk volume (about .5 m^3) available above the battery compartment and does not require an unreasonable extension of the vehicle length. The availability of a hybrid vehicle approach to save fuel consumption should not in fact deemphasize the generally accepted assumption that, by 1985, energy concerns should have already forced people's minds to accept the concept of measuring vehicle size by usable volume availability and not by mere overall dimensions and therefore weight.

e) Materials. By careful and innovative body structure design, it is possible to obtain reductions in weight in the order of 20% which are mandatory to partially compensate the overall weight increase due to the batteries. Among the possible solutions for achieving greater lightness, the realization of a conventional body made of special steel type HSLA had to be discarded since the weight saving involved would have been negligeable. The only viable solution to reach the required weight saving appears to be a bearing body in special steel type HSLA or in aluminum alloys to be covered by plastic type SMC-R panels. For the two kinds of materials, different manufacturing problems exist in addition to those relative to metal-plastic connections; this is in fact a relatively new technology that might involve reliability problems and should then be adequately validated.

f) Body profile and rolling resistance. While a lightened structure to compensate the battery weight would help in limiting the total power required to meet performance specifications but could have a limited impact on the fuel consumption of a general purpose vehicle, the aerodynamic drag coefficient will play a major role in defining the attainable fuel economy in conjunction with the tires rolling resistance. Typical power vs. speed plots are given in Figures 4.2-1/4.2-3 for various C_X coefficients and for conventional or advanced tires, which show the significant possible savings in engine/motor power and therefore weights.

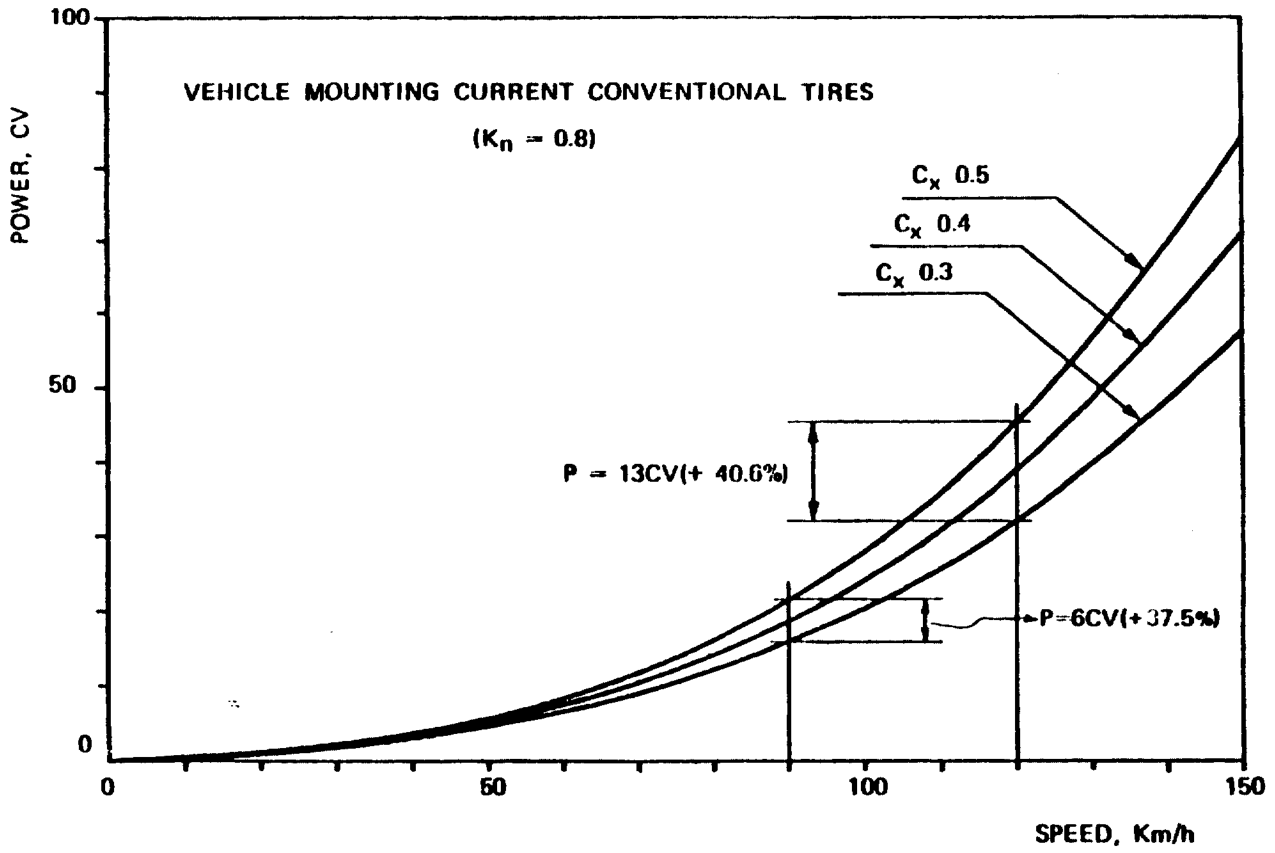

Fig. 4.2-1 – HORSEPOWER REQUIREMENTS AS FUNCTION OF VEHICLE SPEED

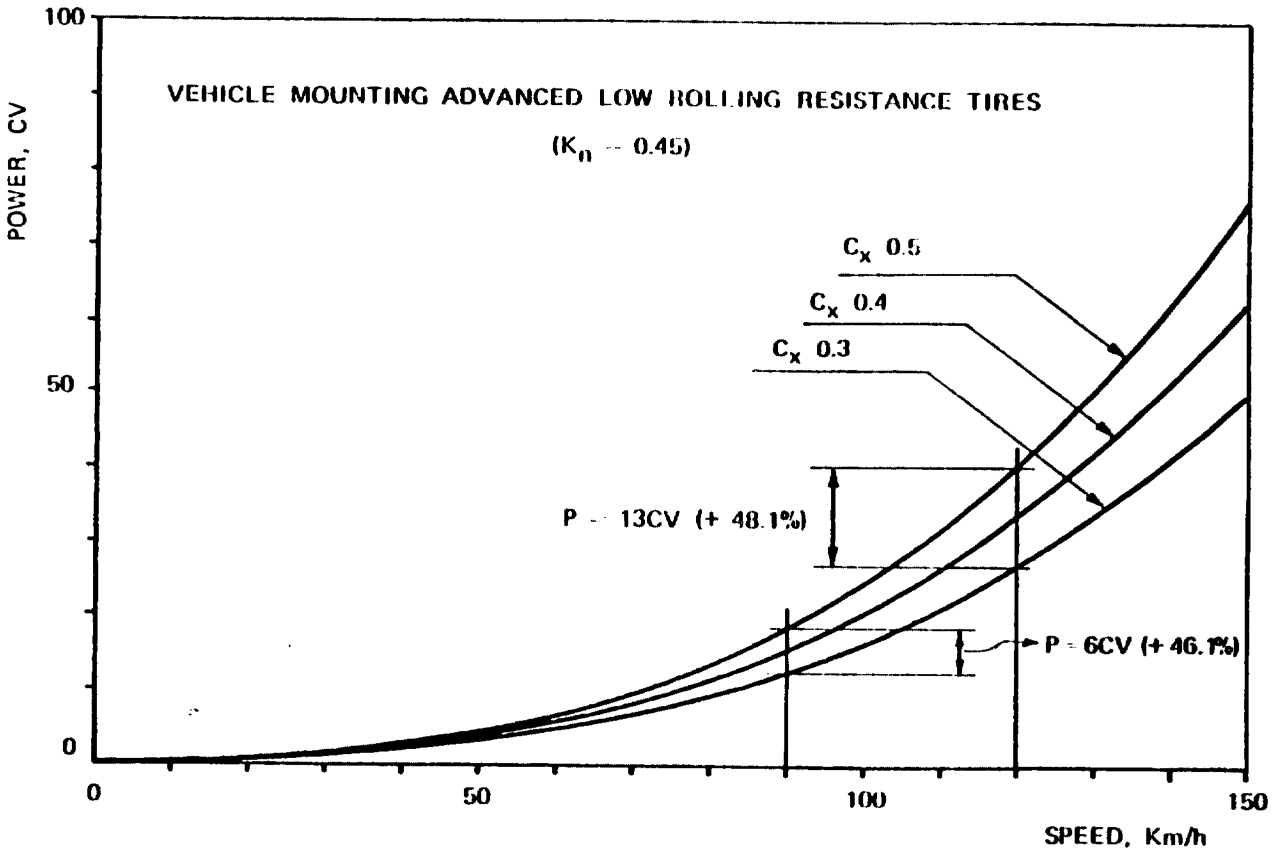

Fig. 4.2-2 -- HORSEPOWER REQUIREMENTS AS FUNCTION OF VEHICLE SPEED

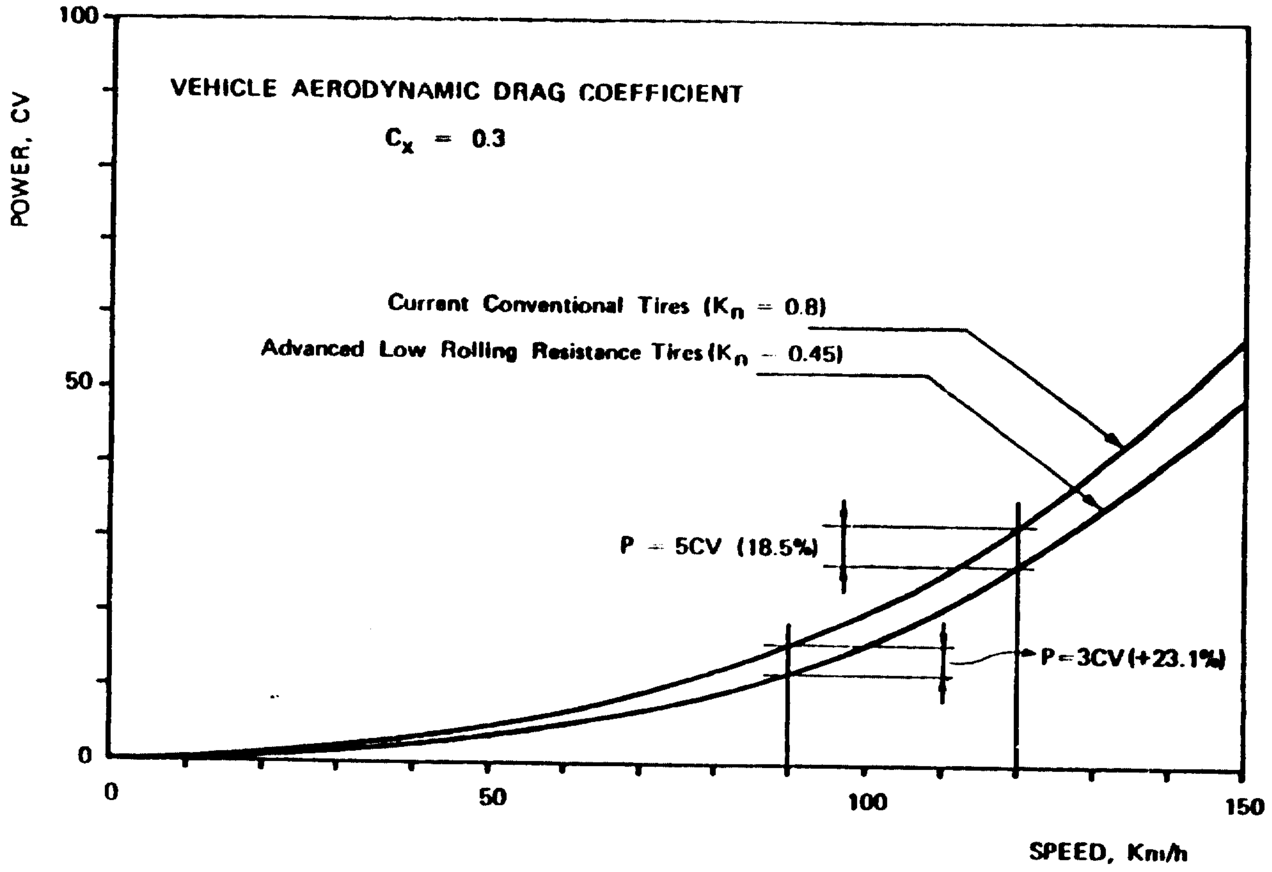

Fig. 4.2-3 — HORSEPOWER REQUIREMENTS AS FUNCTION OF VEHICLE SPEED

4.2.2 Vehicle Scheme Development

Having defined the basic vehicle architecture characteristics and requirements, the existing models of comparable size and characteristics were analyzed to identify a conventional reference vehicle which could best match the hybrid vehicle architecture. The Lancia "GAMMA" was selected as being an advanced and newly designed vehicle, recently introduced on the market which will certainly not become obsolete by 1985.

Another choice conditioning element was the availability of complete design and manufacturing information. Based upon the Lancia "GAMMA" scheme size/volume adjustments were performed to fit 6 passengers and the hybrid propulsion system as shown in Fig. 4.2-4/4.2 9. Moving from such a preliminary scheme these additional design steps were performed:

1) A study of a compatible body profile was developed to provide optimum aerodynamic drag coefficient as related to the vehicle cost usage and manufacturing constraints. Based upon the results of a parametric study the C_X impact on vehicle fuel economy, presented in Table 4.2-1, a $C_X = 0.3$ value was considered appropriate and attainable.
2) Engine and passenger compartments were accordingly modified and various component fittings and attachment requirements were further defined.
3) On such a basis a model of the basic vehicle structural scheme was developed to be used for handling and crashworthiness calculation during the preliminary design stage.

These three steps are illustrated in Fig. 4.2-10/4.2-15 as intermediate results in the definition of a vehicle architecture design concept which meets the vehicle functional and technical requirements and provides a common ground to perform on a realistic basis the trade-off analysis among the various propulsion system alternatives.

To complete the analysis of the Vehicle Scheme Development, as presented in this Interim Results Section, the actual and projected characteristics of various large size vehicle are compared in Table 4.2.2.

Starting from the manufacturer's characteristics of the 1978 Chevrolet "IMPALA" (1978 K_5 Reference Conventional ICE Vehicle) and the projected characteristics of the 1985 K_5 Reference Conventional ICE Vehicle as obtained from the Task-1 Report and current projections of the specialized technical press on 1985 Automative Technologies, a comparison is made with the manufacture's characteristics of the 1978 Lancia "GAMMA", the top vehicle (on both size and performance) of the current FIAT's fleet.

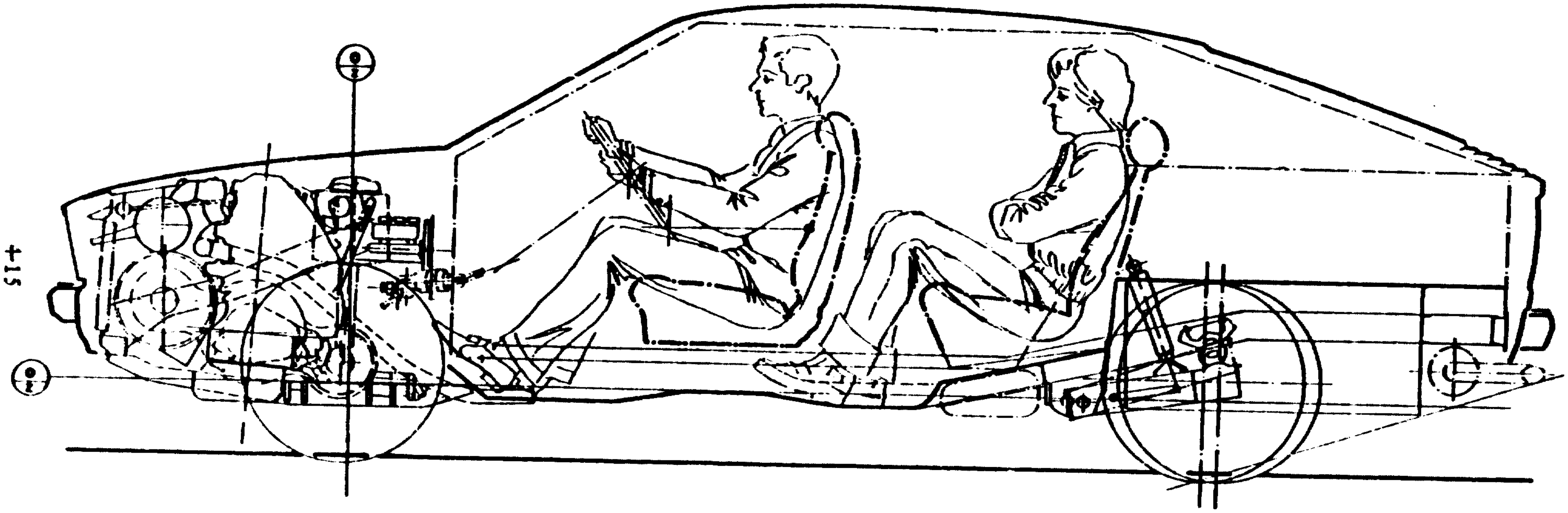

Fig. 4.2-4 — LANCIA "GAMMA" FITTED WITH MAXIMUM SIZE FRONT HYBRID PROPULSION SYSTEM AND REAR BATTERY COMPARTMENT. 1st SOLUTION: 5 PASSENGERS, WITHOUT BODY MODIFICATION.

SIDE VIEW

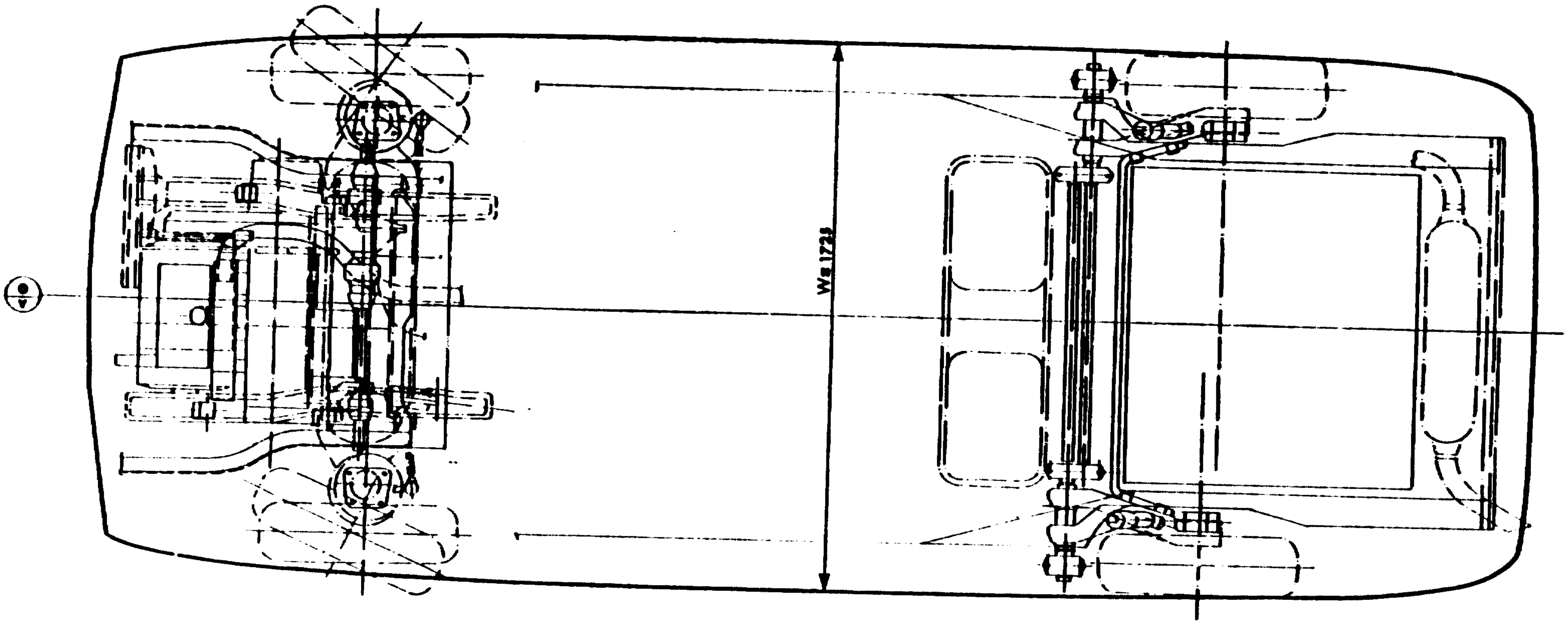

Fig. 4.2-5 — LANCIA "GAMMA" FITTED WITH MAXIMUM SIZE FRONT HYBRID PROPULSION SYSTEM AND REAR BATTERY COMPARTMENT. 1ST SOLUTION: 5 PASSENGERS, WITHOUT BODY MODIFICATION.

TOP VIEW

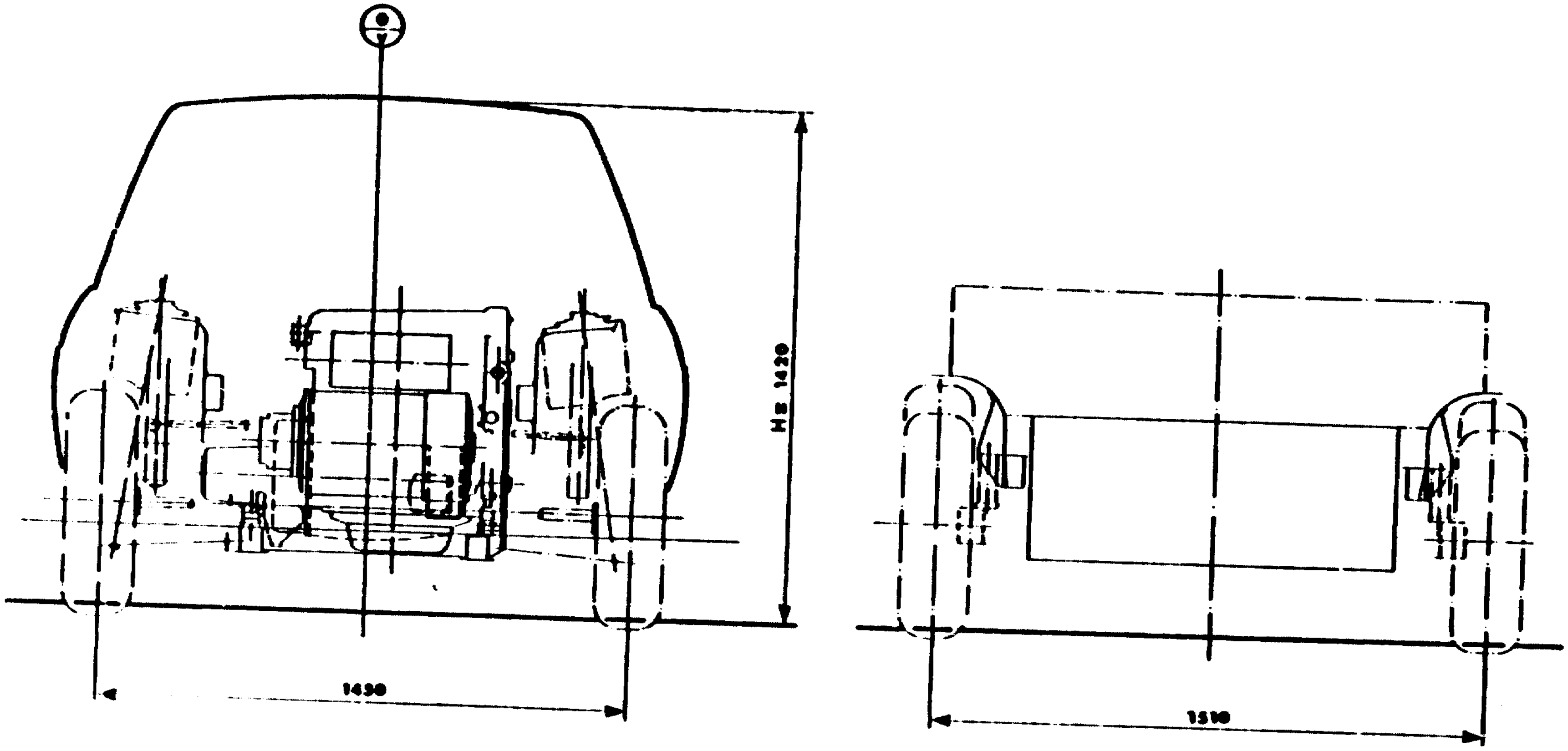

Fig. 4.2.6 LANCIA "GAMMA" FITTED WITH MAXIMUM SIZE FRONT HYBRID PROPULSION SYSTEM AND REAR BATTERY COMPARTMENT. 1st SOLUTION: 5 PASSENGERS, WITHOUT BODY MODIFICATION.

FRONT/REAR VIEW

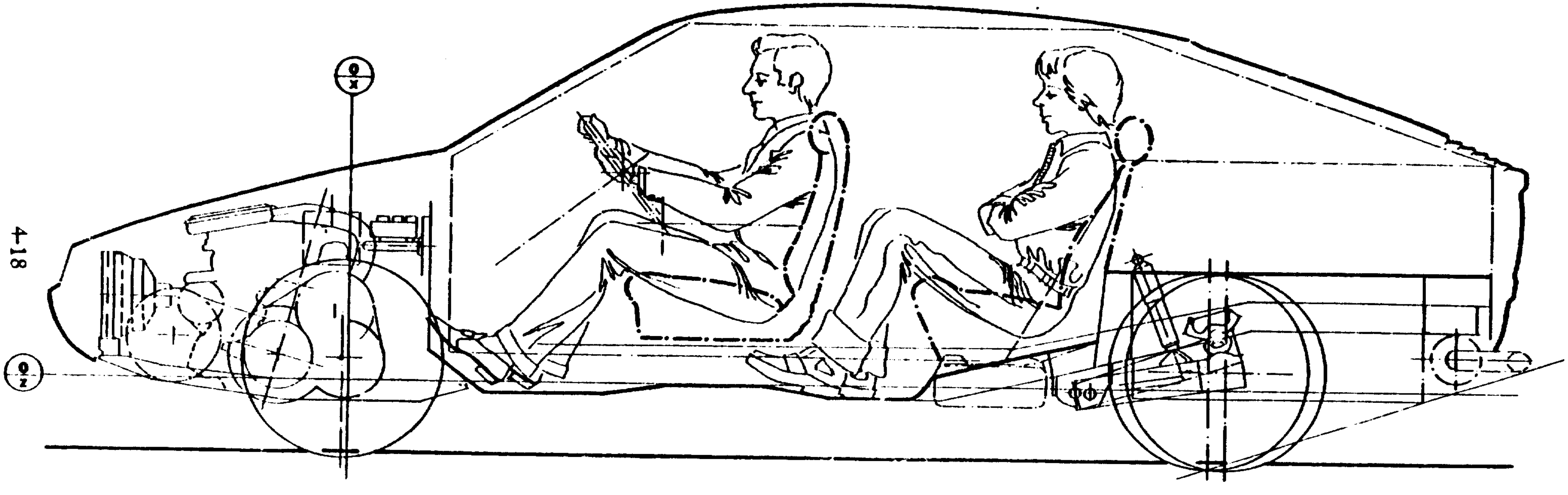

Fig. 4.2-7 – LANCIA "GAMMA" FITTED WITH COMPACTED FRONT HYBRID PROPULSION SYSTEM AND REAR BATTERY COMPARTMENT. 2nd SOLUTION: 6 PASSENGERS WITH IMPROVED HOOD PROFILE.

SIDE VIEW

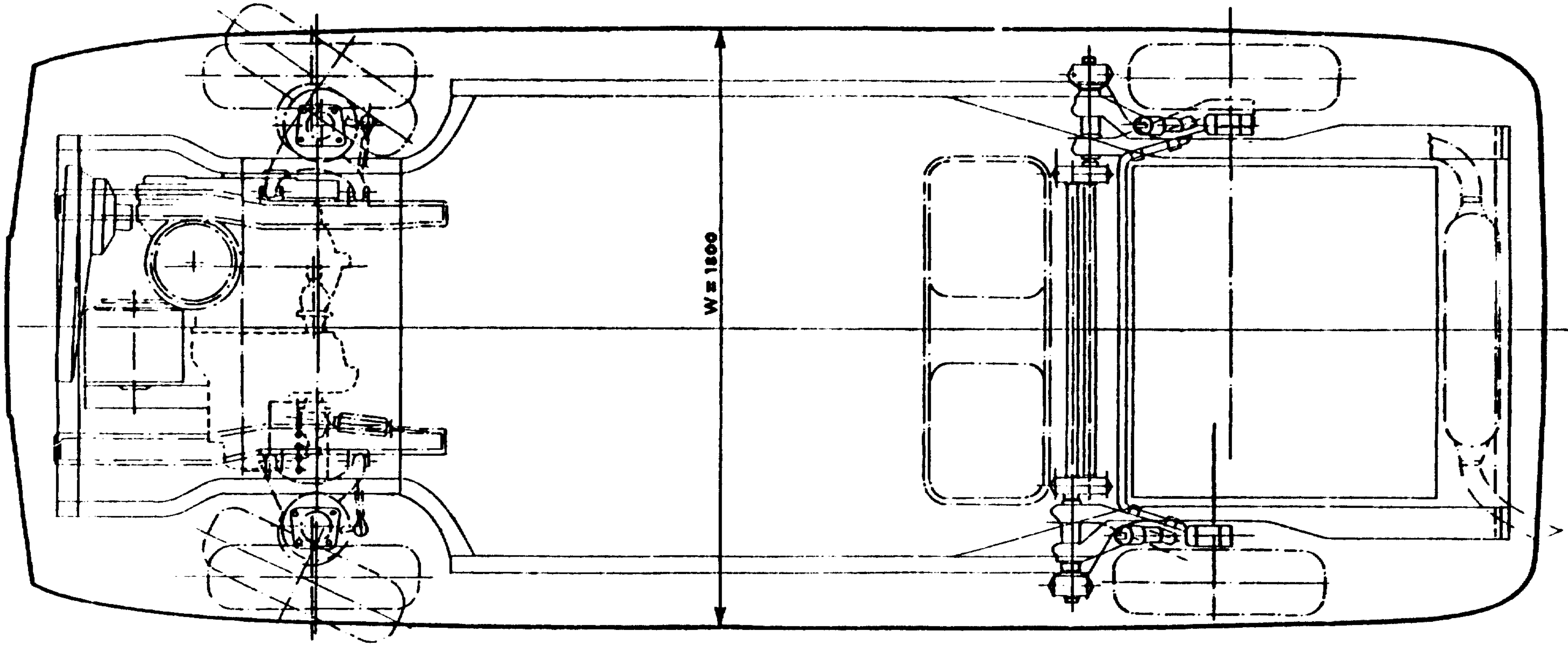

Fig. 4.2-8 — LANCIA "GAMMA" FITTED WITH COMPACTED FRONT HYBRID PROPULSION SYSTEM AND REAR BATTERY COMPARTMENT. 2nd SOLUTION: 6 PASSENGERS WITH IMPROVED HOOD PROFILE.

TOP VIEW

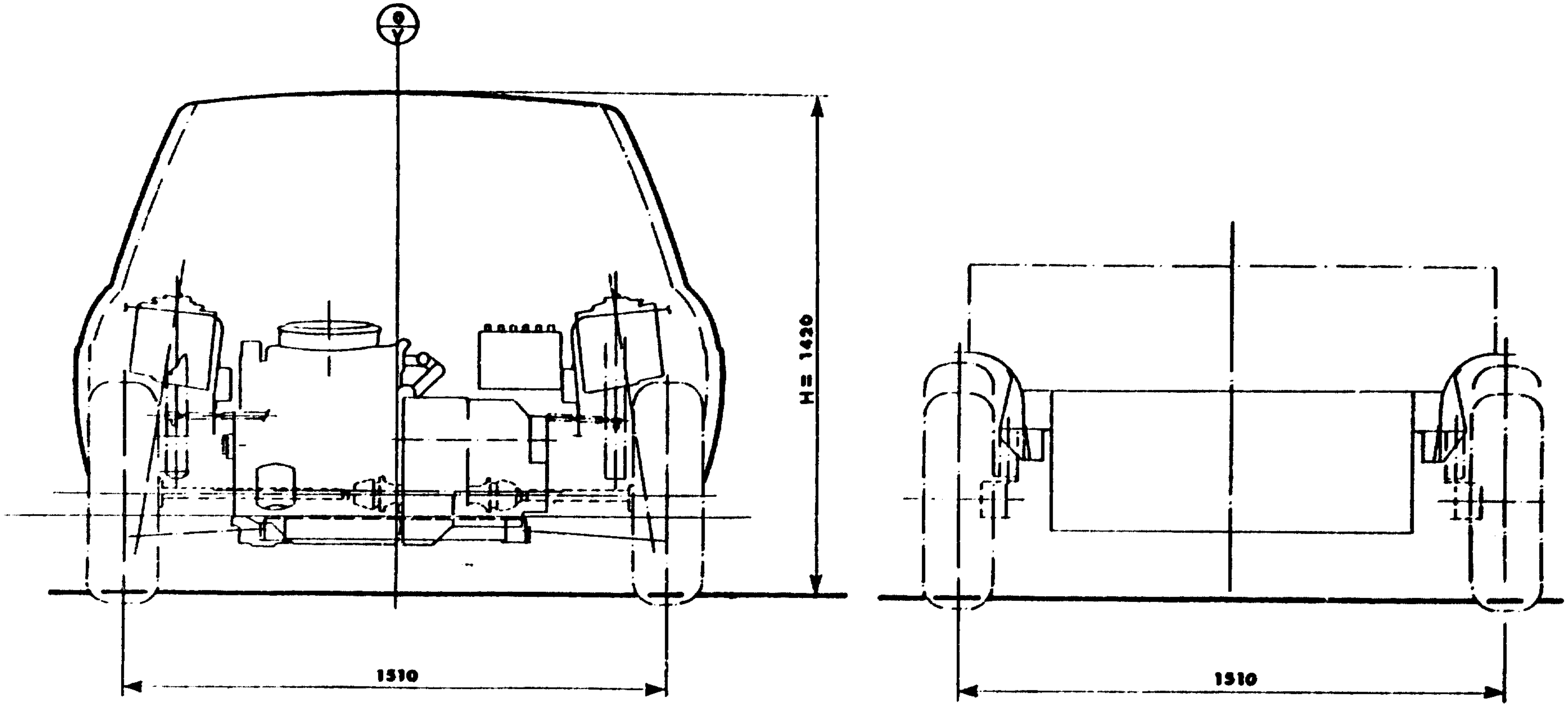

Fig. 4.2-9 -- LANCIA "GAMMA" FITTED WITH COMPACTED FRONT HYBRID PROPULSION SYSTEM AND REAR BATTERY COMPARTMENT. 2nd SOLUTION: 6 PASSENGERS WITH IMPROVED HOOD PROFILE.

FRONT/REAR VIEW

TABLE 4.2-1

TYPICAL(1) FUEL CONSUMPTION AS A FUNCTION OF VEHICLE C_x (GASOLINE ENGINE)

STD. CYCLE	% FUEL CONSUMPTION AT C_x		
	0.40	0.35	0.30
FHDC	100	96	92
COMBINED	100	96.5	94
FUDC	100	97.2	95.3

(1) CONSUMPTION SPREAD DUE TO ENGINE TYPE/SIZE IS WITHIN ± 1 PERCENT.

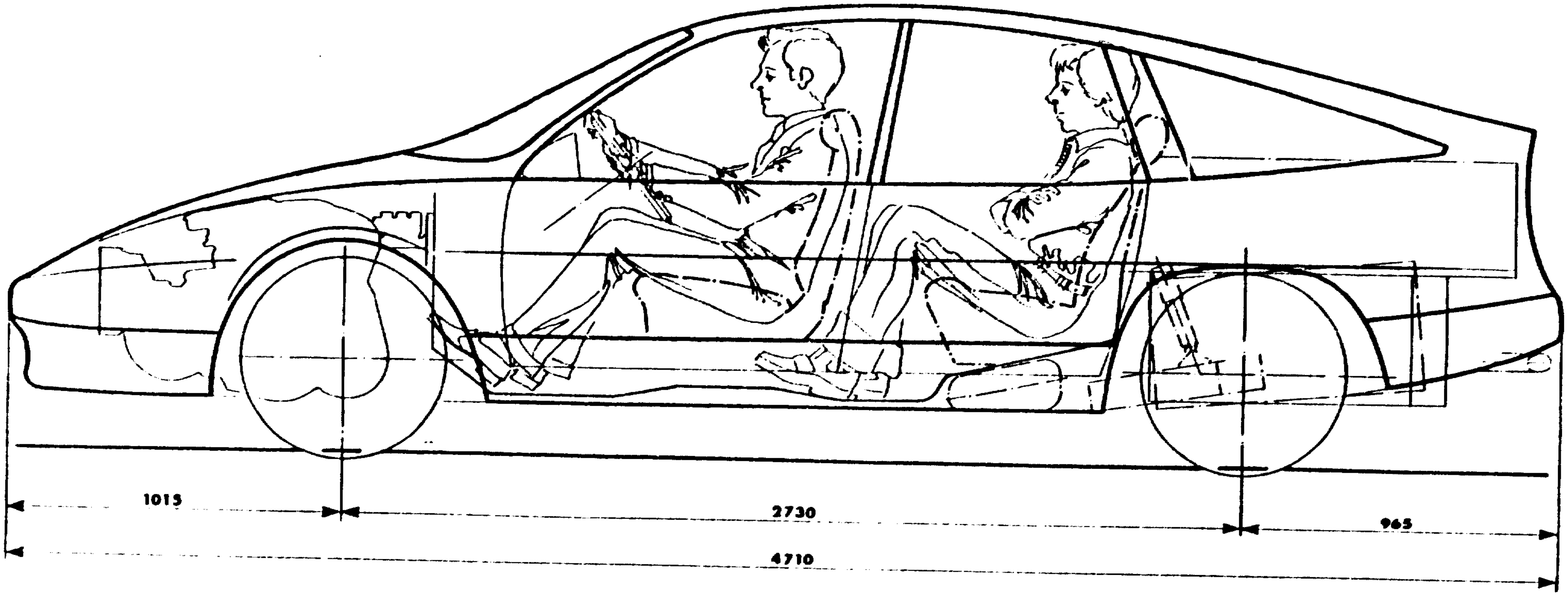

Fig. 4.2-10 – HYBRID VEHICLE BASIC SCHEME

SIDE VIEW

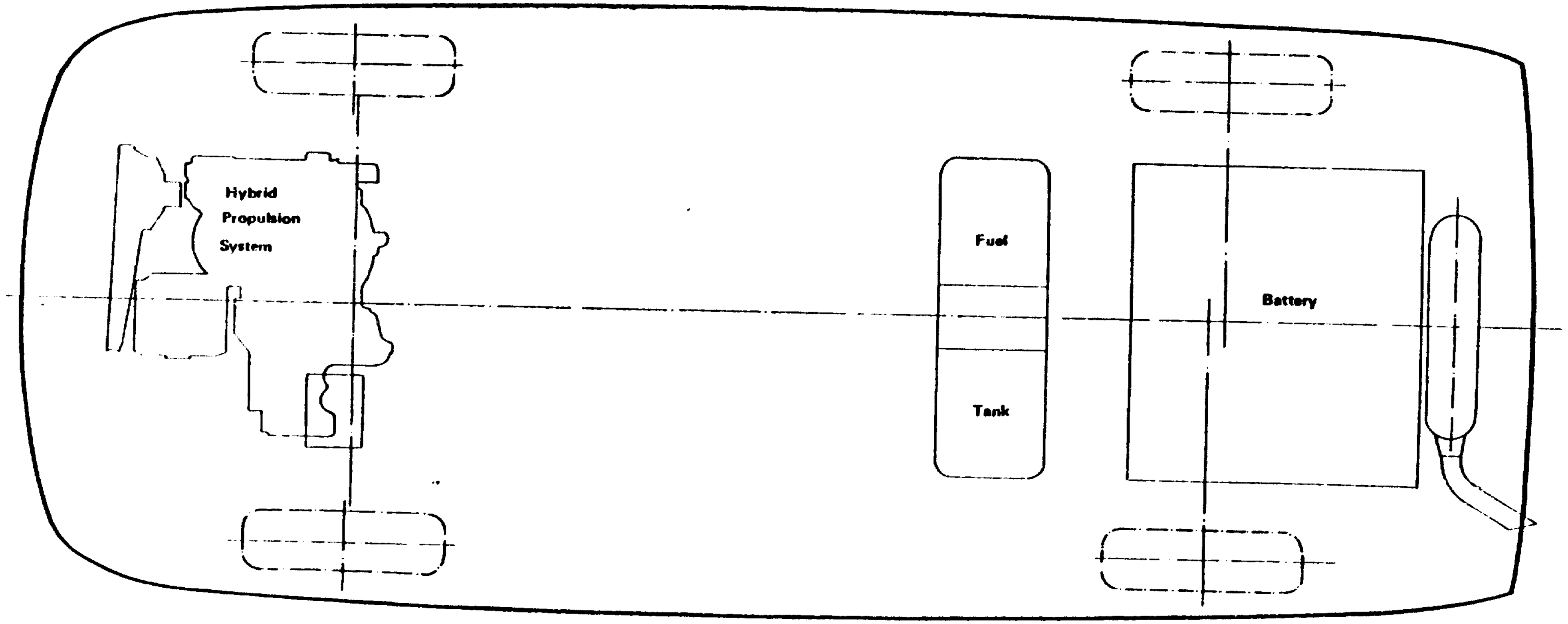

Fig. 4.2-11 – HYBRID VEHICLE BASIC SCHEME

TOP VIEW

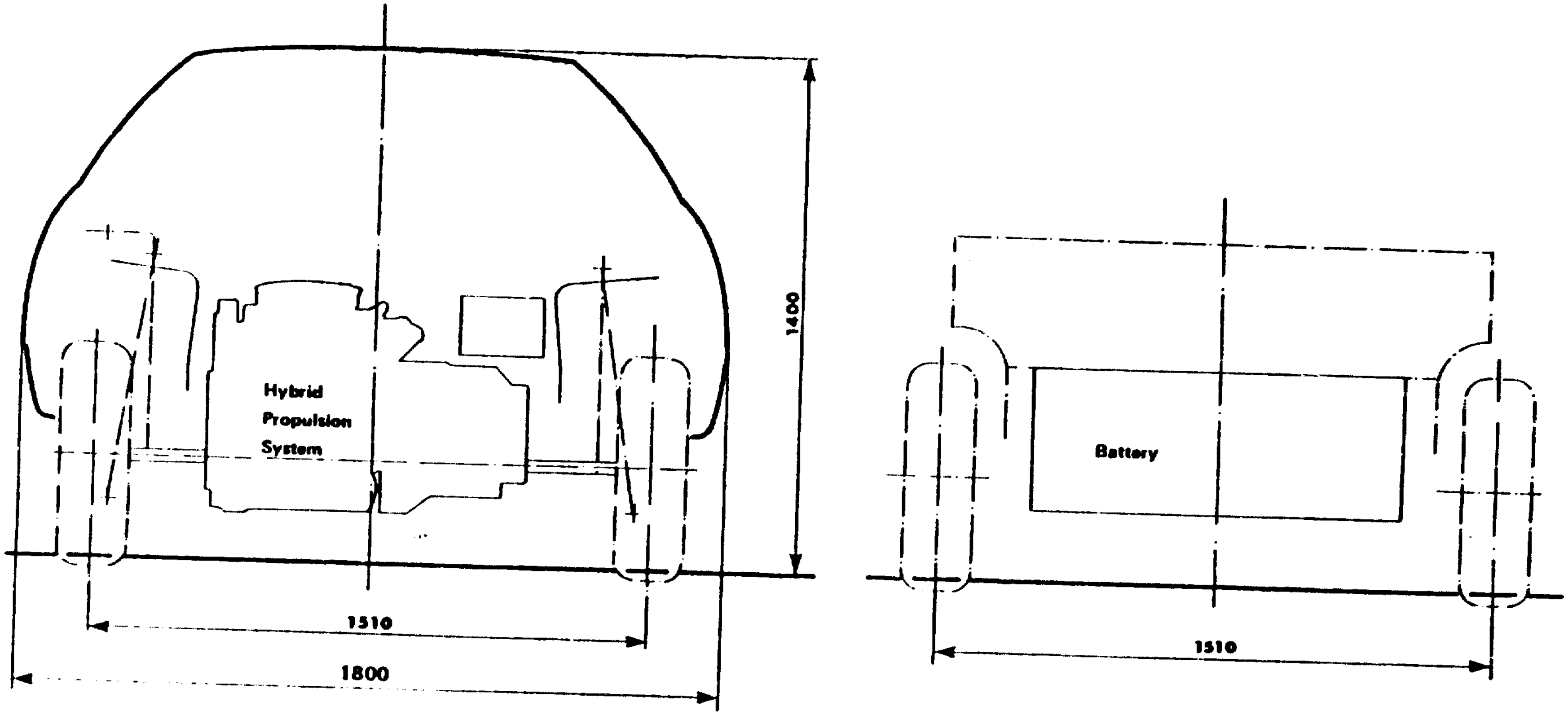

Fig. 4.2-12 — HYBRID VEHICLE BASIC SCHEME

FRONT/REAR VIEW

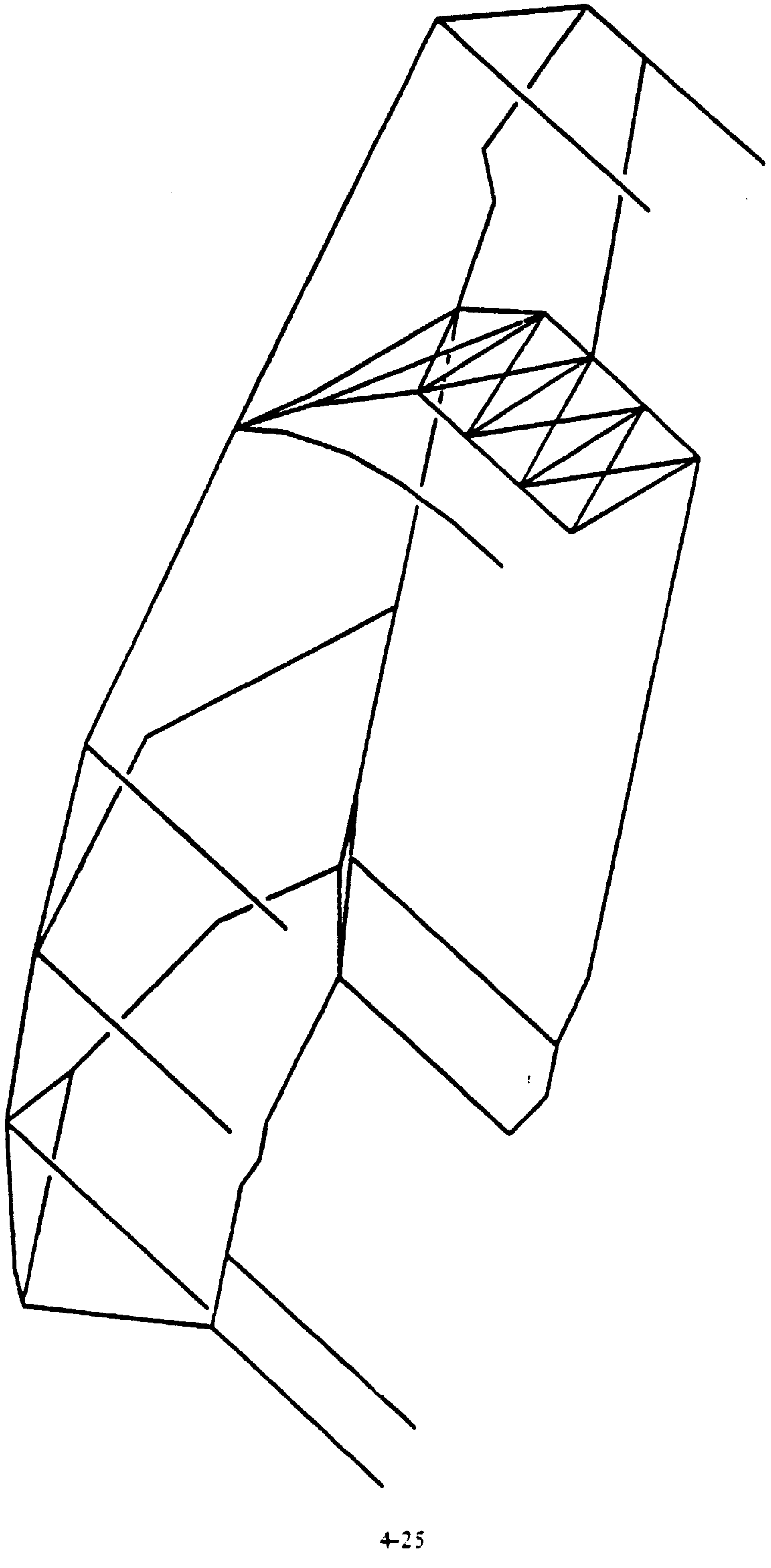

FIG. 4.2-13 — HYBRID VEHICLE — COMPUTER PLOT OF BASIC STRUCTURAL SCHEME

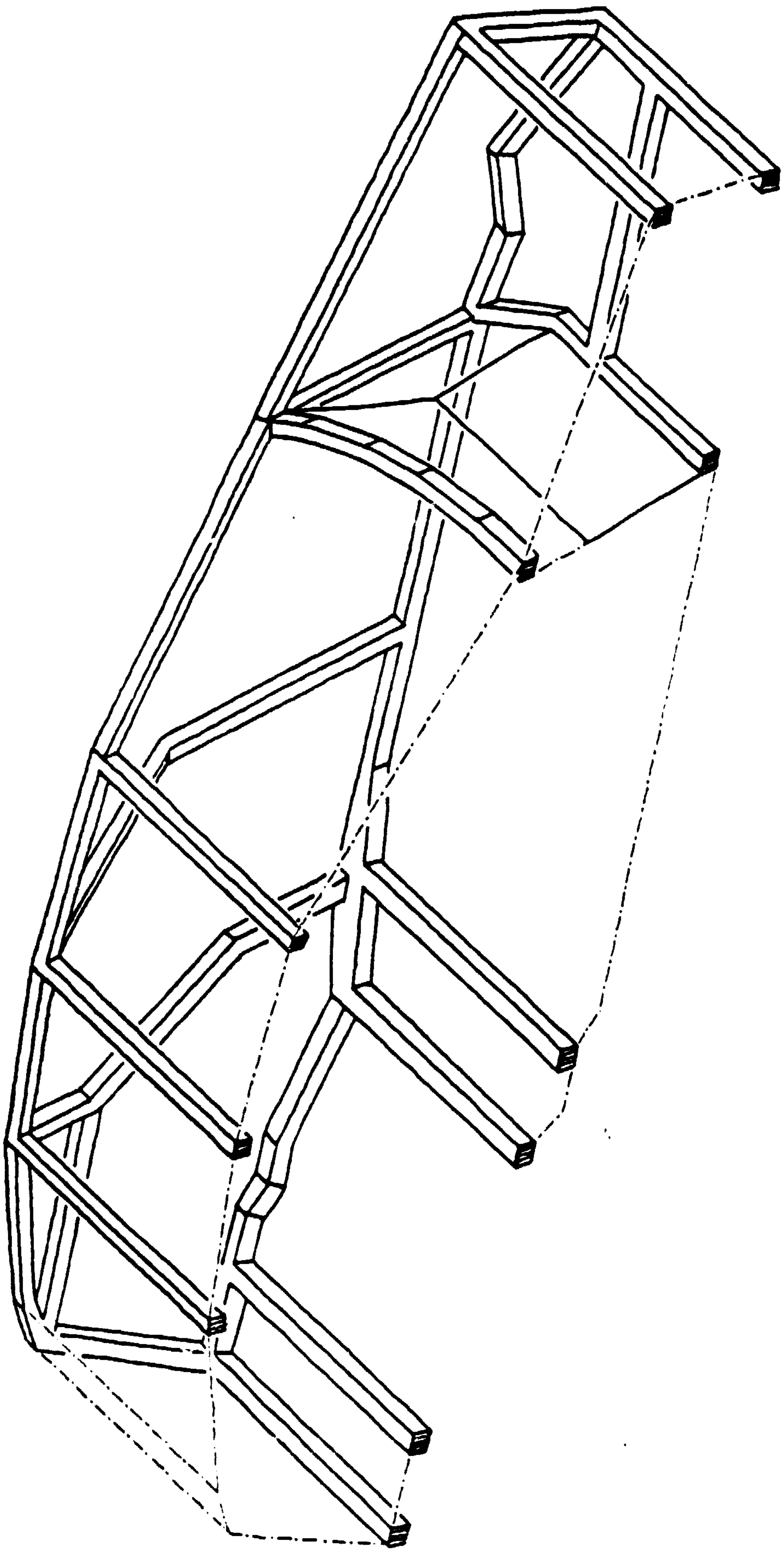

FIG. 4.2-14 — HYBRID VEHICLE — BASIC STRUCTURAL SCHEME MATERIALIZED

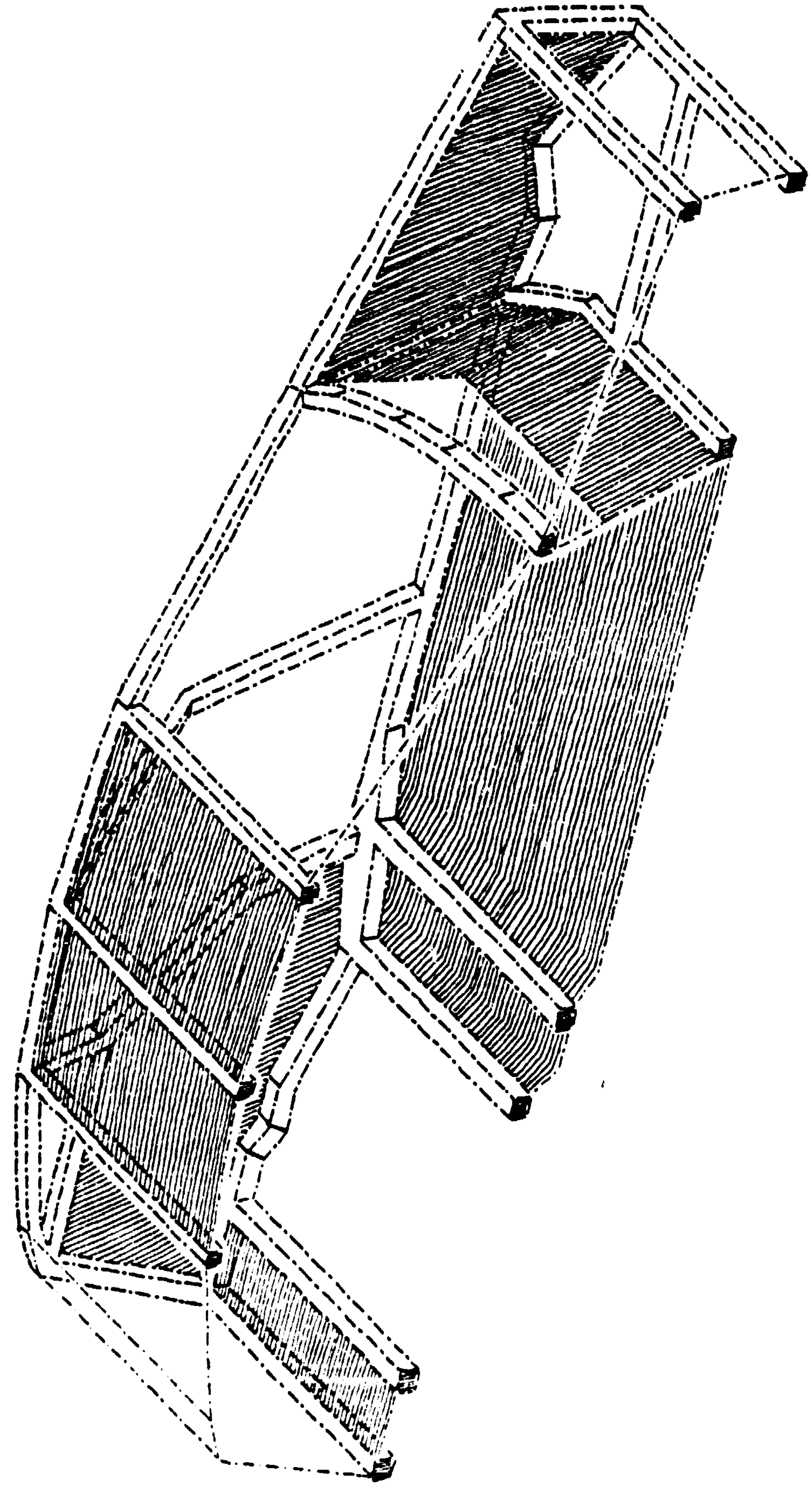

FIG. 4.2-15 — HYBRID VEHICLE STRUCTURE — SCHEMATIC VIEW OF WORKING PANELS

TABLE 4.2-2 a

ACTUAL AND PROJECTED CHARACTERISTICS OF LARGE SIZE CONVENTIONAL/HYBRID VEHICLES

ITEM		A '78 CHEVROLET IMPALA	B PROJECTED '85 CONV. VEHICLE	C '78 LANCIA GAMMA	D '85 HYBRID VEHICLE (1)	E '78 LANCIA GAMMA HYB. (US. VERSION)
PROPULS. ENGINE/ ELECTRIC MOTOR	TYPE	V 8 GASOLINE	V 6 GAS. TURBOCH. OR DIESEL	L (2 + 2) BOXER GASOLINE	L 4 GASOLINE	L 4 GASOLINE DC W/ FIELD CONTROL
	POSITION	FRONT LONGITUDINAL	FRONT TRANSVERSAL	FRONT TRANSVERSAL	FRONT TRANSVERSAL	FRONT TRANSVERSAL
	POWER	145 HP (SAE)	100 - 120 HP (SAE)	140 CV. (2) (DIN)	As appropriate	As appropriate
	DISPLAC, l	5.0	3.0 - 4.0	2.5	As appropriate	As appropriate
WHEEL DRIVE		REAR	FRONT	FRONT	FRONT	FRONT
TRANSMISSION		3 - SP TURBO HYDRA-MATIC	LOCK-UP TORQUE CON. & 4-SP AUTOM.	CLUTCH & 5-SP MAN. OR 3-SP AUTOM.	Dependent on configuration	Dependent on configuration
STEERING		DIRECT RATIO POWER	RACK AND PINION POWER	RACK AND PINION POWER	RACK AND PINION POWER	RACK AND PINION POWER
SUSPEN-SIONS	FRONT	UNEQUAL LENGTH A - ARMS	INDEPENDENT WHEEL	INDEPENDENT WHEEL	INDEPENDENT WHEEL	INDEPENDENT WHEEL
	REAR	LIVE AXLE	LIVE AXLE OR INDEPENDENT WHEEL	INDEPENDENT WHEEL	TRAILING ARMS	TRAILING ARMS
BRAKES	FRONT	DISC	DISC	DISC	DISC	DISC
	REAR	DRUM	DISC	DISC	DISC	DISC

(1) SAME OR COMPETITIVE WITH 1985 CONVENTIONAL ICE REFERENCE VEHICLE

(2) CV = METRIC HORSEPOWER: 1 CV = 0.98632 HP

TABLE 4.2-2 b

ACTUAL AND PROJECTED CHARACTERISTICS OF LARGE SIZE CONVENTIONAL/HYBRID VEHICLES

ITEM	A '78 CHEVROLET IMPALA	B PROJECTED '85 CONV. VEHICLE	C '78 LANCIA GAMMA	D '85 HYBRID VEHICLE	E '78 LANCIA GAMMA HYB. (U.S. VERSION)
BODY/FRAME TYPE	SEPARATE, PERIMETER FRAME	BEARING BODY	COMPOSITE SAFETY STRUCTURE	BEARING BODY	BEARING BODY
OVERALL LENGTH, m	5.39	4.80 - 5.00	4.58	Same as B	4.58
WIDTH, m	1.92	1.80 - 1.85	1.73	Same as B	1.80
HEIGHT, m	1.45	1.40 - 1.45	1.41	Same as B	1.42
WHEEL BASE, m	2.95	2.75 - 2.85	2.67	Same as B	2.73
FRONT TRACK, m	1.57	1.50 - 1.55	1.46	Same as B	1.51
REAR TRACK, m	1.54	1.50 - 1.55	1.44	Same as B	1.51
CARGO CAPACITY, m^3	0.570	0.570	0.500	Same as B	0.570
CURB WEIGHT, kg	1,700	1,500 - 1,600	1,320	As appropriate but comparable to B	1,900 (3)
FUEL CAPACITY, l	80	55 - 65	63	As appropriate	40
PASSENGERS CAPACITY	6	6	5	6	6

(3) INCLUDES APPROXIMATELY 500 kg FOR THE ELECTRIC PROPULSION SYSTEM AND ACCORDINGLY STRONGER BODY STRUCTURE

It shows that, besides the much higher specific horsepower characteristics of the "GAMMA" which account for its outstanding performance, this vehicle already uses many of the solutions nowadays expected to be included in the 1985 typical U.S. large size passenger car, the main differences being the standard 5-speed manual transmission (4 Speed Automatic optional is available), the lower weight, size and passenger capacity.

While, however, the overall length and width are only 6.5% and 5.5% less than on the mid-range 1985 U.S. large size car, the cargo volume, passenger capacity (in terms of passenger number) and vehicle weight are respectively lower by 13.3%, 17.3% and 14.8%. Considering the smaller difference in the width and length size and the somewhat higher difference in cargo volume it appears that, also thanks to its compact 4 cylinder boxer engine, the "GAMMA" has an unusually large volume availability for a 5 passenger compartment, as it can be seen from the picture shown on Fig. 4.2-16, which is even more relevant considering its lighter weight.

The Lancia "GAMMA" has appeared therefore a perfectly suited car to start from in tailoring the possible architecture of the advanced 1985 Vehicle.

The suitability is even more evidenced by a comparison with the Hybrid Vehicle characteristics previously defined in Subsection 4.2.1, considering also that the lighter weight already provided by the current body manufacturing technology would offer an excellent starting point to obtain by means of the advanced 1985 technology the amount of weight reduction to conveniently fit the extra weight of the electric propulsion system.

The further Vehicle Architecture development presented in the following Section 5 will show how easily passenger capacity and body profile adjustments could be made on the original "GAMMA" 's architecture to obtain the required improvements, so often contradicting, in passenger sitting capabilities and aerodynamic drag resistance which would not require an undue compromise between the car "general purposeness" and the attainable savings in fuel economy.

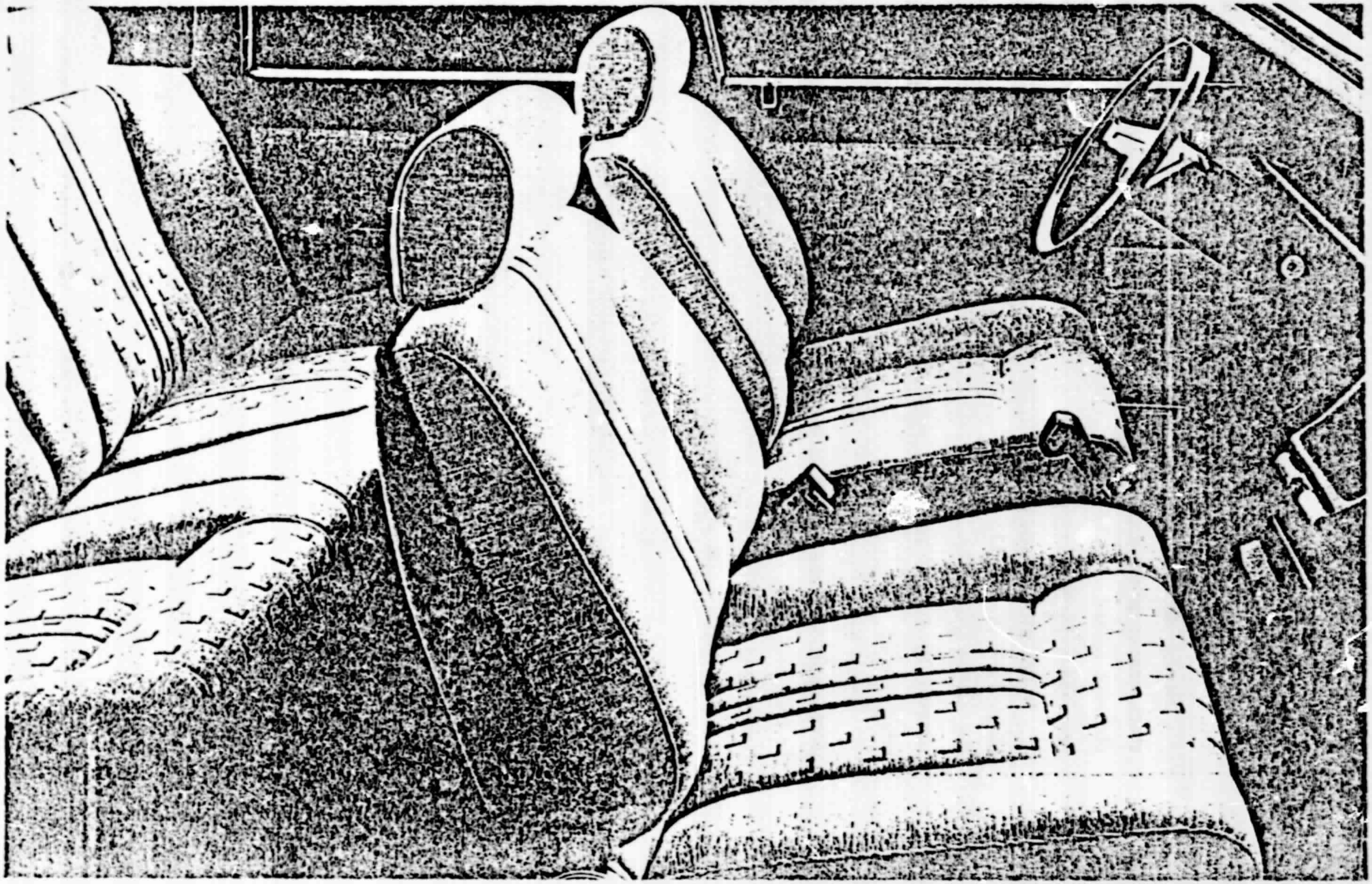

FIG. 4.2-16 – LANCIA "GAMMA" PASSENGERS COMPARTMENT VIEW

4.3. ANALYSIS AND EVALUATION OF THE ALTERNATIVES

Having defined the propulsion system alternatives to be analyzed and the characteristics of the basic vehicle architecture, the design and performance parameters obtained according to the methodology outlined in Section 3, are presented and described in this Subsection.

In line with the assumption that, to maximize the fuel saving potential, the vehicle should carry the maximum battery weight which would still make it competitive as far as size, weight and performance are concerned, a fixed battery weight of 300 Kg was assumed, to evaluate all the alternatives, which would conveniently fit the proposed vehicle layout.

Actual battery weight will be defined during the preliminary design task when the electric portion of the propulsion system will be optimized and other batteries will also be evaluated, which range in performance and characteristics between the two extremes (current and advanced technology) considered during the Trade-off studies.

4.3.1. Propulsion System Power and Transmission Ratios

The thermal power required to run the vehicle at its maximum speed without electric power contribution is 37 kW (approximately 50 CV). It can be obtained using a 1.1 - 1.3 liter engine at 5,500 RPM.

This allowed to calculate initial values of the total transmission ratio (5.0) and of the fixed ratio (subsystem II, $\tau_e = 1.0$) assuming to saturate thermal engine power and use electric power to satisfy peak power demands(1). This approach has not obviously optimized the fuel economies that could be obtained using the various solutions, but has allowed to calculate transmission ratios so that performance requirements (namely accelerations) could be met. The resulting fuel economies, yet to be optimized by means of more appropriate propulsion system control strategies, and the corresponding electricity consumption, would have therefore been used as measuring parameter values for alternatives' efficiency evaluation.

The values of the various subsystem ratios, as shown on Table 4.3-1 with reference to Figure 4.3-1 are obviously dependent on the presence and position of the

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(1) See References [8] and [9], Subsection 1.2

TABLE 4.3-1

RATING AND CHARACTERISTICS OF PROPULSION SYSTEM ALTERNATIVES

DESIGN PARAMETER	BATTERY TYPE		
	(Na-S)	(Both)	(Lead-Acid)
MAXIMUM ENGINE POWER, kW		37	
MAXIMUM MOTOR POWER, kW		40	
NOMINAL MOTOR POWER, kW		20	
BATTERY WEIGHT, kg		300	
MAX. BATTERY POWER (AT FULL CHARGE), kW	32		31
MAX. BATTERY POWER (AT % DISCHARGE),kW	32 (at 60%)		27 (at 50%)

COMPONENT/DESIGN PARAMETER		CONFIGURATION AND BATTERY TYPE					
		No. 1		No. 2		No. 3	
		(Na-S)	(Lead-Ac.)	(Na-S)	(Lead-Ac,)	(Na-S)	(Lead-Ac.)
SUBSYSTEM I	Torque Converter	8"1/2		8"1/2		8"1/2	
	CVRT τ_c (MIN/MAX)	–		–		0.5/2.0	
SUBSYSTEM II	Fixed Ratio τ_e	1.0	1.6	0.4	0.6	1.0	0.7
SUBSYSTEM III	CVRT τ_c (MIN/MAX)	–		0.5/2.0		–	
DIFFERENTIAL RATIO τ_μ		5.0		7.0		5.0	8.0
TOTAL RATIO τ_o		5.0	8.0	1.4/5.6	2.1/8.4	2.5/10.0	2.8/11.2

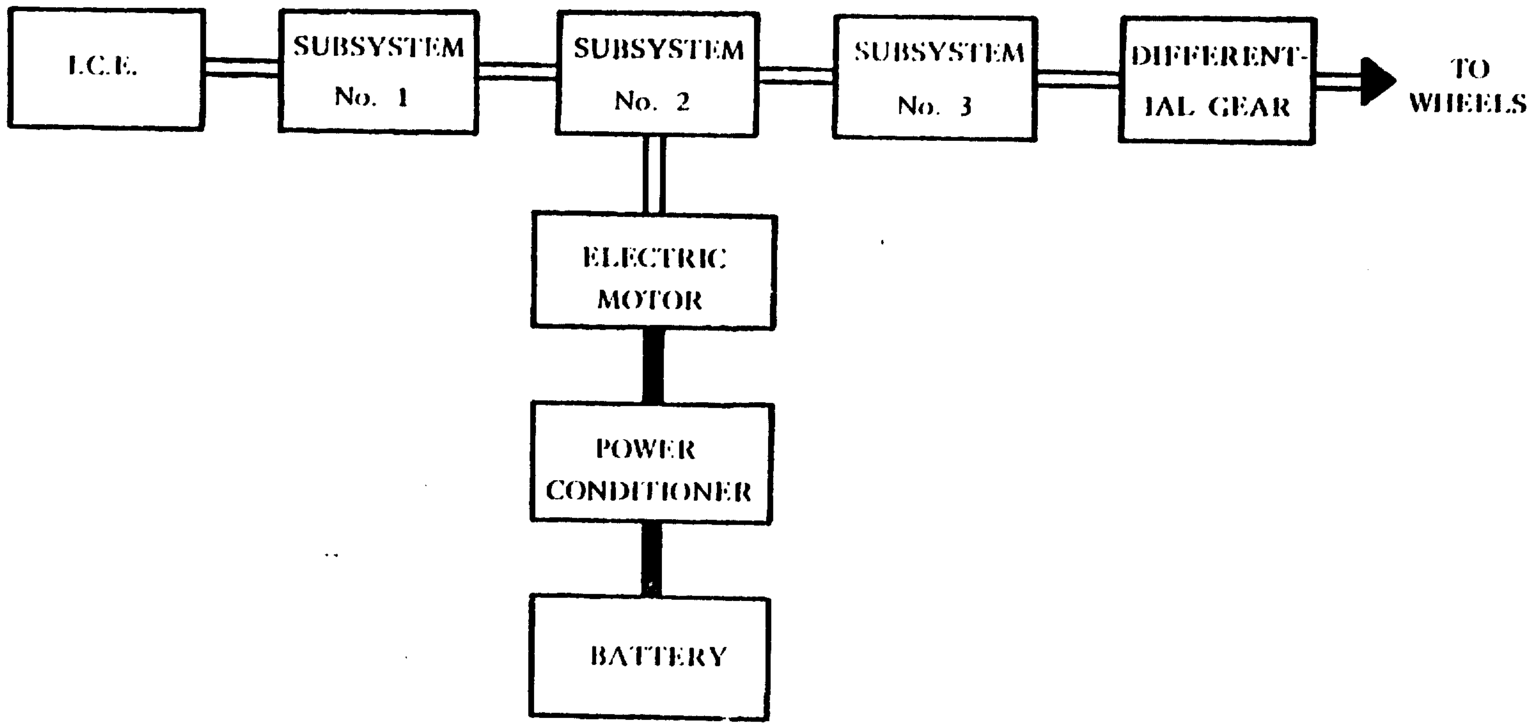

FIG. 4.3-1 — HYBRID VEHICLE POWERTRAIN: PARALLEL CONFIGURATION

Continuously Variable Ratio Transmission (CVRT) and on the available electric power as well.

Transmission ratios have been in fact adjusted to let the vehicle meet performance requirements during normal operation. However, since in the case of Lead-Acid battery the available battery power varies with the depth of discharge, if an operating range up to 50% discharge is assumed, a derated 27 kW power must be referred to instead of the maximum 31 kW power available at full charge.

The use of the CVRT allows the engine speed to be made independent of vehicle speed so that thermal power can be limited during accelerations at the value corresponding to a fixed RPM limit (in this case 2000 RPM). Thus more relevant contributions can be obtained from the electric motor with correspondingly better fuel economies.

On Configuration No. 1, without CVRT, using the Sodium-Sulphur battery the initial values of transmission ratios are shown, which would have not allowed the vehicle to meet performance specifications, since fuel consumption in the various cycles was already higher than in the other solutions and a change in the required direction could only make it worse. Using the Lead-Acid battery, because of the required derating of the operating power the fixed ratio had to be increased to $\tau_e = 1.6$ to provide adequate starting torque (overall ratio for the electric motor 8.0). However there was not enough power to satisfy standard cycles performance requirements (lower than performance specifications) and the solution had to be discarded.

On Configuration No. 2 the CVRT has allowed to limit engine speed to 2,000 RPM. Using the Na-S battery, to improve performance as needed in the high speed range, τ_e had to be decreased to .4 so that a correction at low speed was also needed, increasing τ_p to 7.0 (overall ratio for the electric motor 2.8 times the CVRT's actual ratio). Using the Lead-Acid battery the lower torque at low speeds required adjustment of τ_e at a somewhat higher value .6, the CVRT downstream with respect to the fixed ratio taking care of torque requirements at higher speeds (overall ratio for the electric motor 4.2 times the CVRT actual ratio).

Finally on Configuration No. 3 (same speed limitation as No. 2), using the Na-S battery, the initial transmission ratios have been adequate to satisfy all performance requirements. Using the Lead-Acid battery, being the CVRT upstream with respect to the fixed ratio, to compensate for reduced battery power at higher speed, performance had to be improved by decreasing τ_e to .7 only, but a larger compensation was required on τ_p which had to be increased up to 8.0 (overall ratio for the electric motor 5.6).

In conclusion only solution No. 3 with Na-S battery could satisfy performance requirements with the transmission ratio values initially calculated. The overall increase of the total ratio (including the effect of the CVRT) to satisfy performance would indicate that higher consumptions should be expected as a result of the higher engine speeds corresponding to a given vehicle speed. This effect will be analysed in quantitative detail in Subsection 4.3. 3.

4.3.2 Vehicle Weight

The weights of the chassis and propulsion system components of the hybrid vehicle are shown on Table 4.3-2.

The Current-Technology Weights column refers to a hybrid vehicle manufactured in mass production volumes according to the technology presently used to manufacture the Lancia "GAMMA" and using the additional electrical components as available nowadays. The Advanced Technology Weights column refers to a hybrid vehicle to be manufactured in 1985 mass production using the advanced technologies (to be validated at the prototype level during the Phase II timeframe) which could then be made available to reduce vehicle weight.

The weight figures shown can be attributed to all alternatives for the conventional section of the vehicle. Considering the electric portion of the propulsion system, the use of a Lead-Acid battery should result in a weight reduction of approximately 10 Kg with respect to the solution with Sodium-Sulphur battery to account for the lighter weight of the corresponding electric motor.

A summary of the curb weights and total vehicle weights with the prescribed 140 Kg test payload for the various configurations is shown for convenience on Table 4.3-3.

The load distribution between the front and rear axles, for configurations Nos. through 4, using Sodium-Sulphur batteries is as follows:

– empty weight

(total weight 1,580 (kg)

front axle load	(kg)	865
rear axle load	(kg)	715

TABLE 4.3-2

HYBRID VEHICLE WEIGHT BREAKDOWN

ITEM	CURRENT TECHNOL. WEIGHTS kg	ADVANCED TECHNOL. WEIGHTS kg
INTERNAL COMBUSTION ENGINE	157	118
CHASSIS AND AUXILIARY ELECTRIC SYSTEM	365	335
BODY/FRAME(1)	853	612
TRANSMISSION	65	65
ELECTRIC PROPULSION SYSTEM	190	150
POWER BATTERY	330	300
TOTAL WEIGHT	1,960	1,580

(1) BODY/FRAME INCLUDES: COMPLETE BODY, PAINTING, SEATS AND UP-HOLSTERY, WINDOWS, BUMPERS, TIRES AND WHEELS, OTHERS.

TABLE 4.3-3

VEHICLE WEIGHT

CONFIGURATION	WEIGHT WITH Na-S BATTERY		WEIGHT WITH LEAD-ACID BATTERY	
	CURB (kg)	W/TEST PAYLOAD, (kg)	CURB (kg)	W/TEST PAYLOAD, (kg)
No. 1	1,540	1,680	1,530	1,670
No. 2	1,580	1,720	1,570	1,710
No. 3	1,580	1,720	1,570	1,710
No. 4	1,580	1,720	1,570	1,710

- with test payload

(total weight 1,720 kg)		
front axle load	(kg)	915
rear axle load	(kg)	805

4.3.3 Vehicle Consumption and Emissions

4.3.3.1 Consumption

The vehicle consumption has been calculated for the various alternatives after the transmission ratios have been adjusted to provide the required performance as described in detail in Subsections 4.3.1 and 4.3.4.

As described, in Section 3.Methodology, the consumptions were evaluated assuming that the vehicle would use thermal power only up to a fixed maximum engine speed and the required additional power would then be supplied by the electric motor.

The electric power availability from the batteries was limited to the maximum power at the maximum operating discharge level (60% for Na-S and 50% for Lead-Acid batteries).

The RPM limit was originally set at 2,000 RPM and let increase to the maximum 5,000RPM when the required performance could not be met (alternative No. 1 without CVRT).

The complete results are shown on Table 4.3-4 together with the corresponding emissions.

On Configuration No. 1 consumption data are provided for the solution with Na/S battery only since the solution with Lead-Acid battery could not provide adequate peak power as required by several points of the FUDC and FHDC standard cycles even with transmission ratios adjusted to provide adequate low speed torque. The corresponding consumption could not be therefore calculated by the simulation model. However since consumption on the SAE cycle (which could be performed with the available power) was already higher than for any other solution, it was not considered worth to further modify the design parameters to match the performance specifications, as it would have resulted in a further increase of fuel consumption.

TABLE 4.3-4 – VEHICLE CONSUMPTION AND EMISSIONS

CONFIGURATION AND BATTERY TYPE		CONSUMPTION								EMISSIONS			
		SAE (1)		FUDC		FHDC		DAILY CYCLE (2)		EXHAUSTS	SAE	FUDC	FHDC
		MPG	ml/kWh	MPG	ml/kWh	MPG	ml/kWh	MPG	ml/hWh		gr/km	gr/km	gr/km
1[3]	Lead-Acid	23.5								HC CO NO_x	1.77 23.40 0.97		
	Na-S	23.95		31.60		41.50		38.10		HC CO NO_x	1.75 21.30 1.03	0.95 21.00 0.79	(0.38) (6.30) (0.87)
2[4]	Na-S	28.6		40.7	20.6	53.8	20.0	49.3	20.2	HC CO NO_x	1.65 20.90 0.65	0.85 9.80 1.00	(0.34) (3.53) (1.10)
	Lead-Acid	28.6		40.7	34.6[5]	53.8	23.8[5]	49.3	26.1	HC CO NO_x	1.67 20.70 0.66	0.85 9.80 1.00	(0.33) (3.53) (1.10)
3[4]	Na-S	28.2		42.0	29.5	57.4	23.8	51.9	25.2	HC CO NO_x	1.65 20.60 0.69	0.83 9.80 1.00	(0.33) (4.40) (1.00)
	Lead-Acid	27.9		39.6	38.5[5]	51.4	25.5[5]	47.3	28.2	HC CO NO_x	1.65 21.4 0.68	0.85 10.1 1.0	(0.34) (3.80) (1.0)

(1) SAE J227 (B) – (2) DAILY CYCLE = 4 FUDC + 10 FHDC (Sequence: H, U, 4H, 2U, 4H, U, H) – (3) ENGINE RANGE 1,000 - 5,000 RPM
(4) ENGINE RANGE 1,000 - 2,000 RPM – (5) MEAN FUEL ECONOMY ON URBAN AND HIGHWAY CYCLES OF THE DAILY CYCLE

Configuration No. 1 with Lead-Acid battery was therefore discarded; the data obtained for operation with Na-S battery show that, with unmodified transmission ratios, even if the electric motor is used to provide extra power when needed, no actual battery discharge occurred on any of the various cycles. Since, on the other hand, performance specifications could not be met with the existing ratios but on the SAE cycle, while the consumption was already higher than on any of the other alternatives under comparable conditions, is was estimated that the possible consumption improvements resulting from a better exploitation of the battery stored energy would have been largely offset by the consumption increase required to match the required performance. No further attempt was made therefore to improve both the efficiency and performance of this alternative by adjusting the transmission ratios, because of their opposing requirements.

On Configuration No. 2 it is worth noting that the lower operating power rating of the Lead-Acid battery does not affect fuel economy since the presence of the CVRT downstream the electric motor allows a better handling of the available electric torque/power capabilities by adjusting the electric motor overall ratio as required. This is reflected by a higher electric energy consumption of the Lead-Acid battery solution in the urban, highway and daily composite cycle (M_3 mission). The CVRT is also, on the other hand, responsible for the fuel economy improvement with respect to Configuration No. 1, as it allows the engine speed to be limited at 2,000 RPM letting the required additional power to be supplied by the battery through the electric motor.

Finally on Configuration No. 3 it can be observed that, with respect to Configuration No. 2 using a Na-S battery, somewhat higher fuel economies result, associated with a higher consumption of electric energy. This however is also counterbalanced by the better performance that the transmission ratios adjustment has given to the said Configuration No. 2.

Comparing the solution with Lead-Acid battery, lower fuel and electricity economies can be noted than for the solution with Na-S battery, compensated by a slightly better performance. However, due to a better compensation of battery power derating by means of transmission ratio adjustments, both energy (fuel and electricity) economy values and performance values are worse than on Configuration No. 2 with Lead-Acid battery as a result of the unavailability of the CVRT function to optimize battery power exploitation at any vehicle speed.

The analysis of the consumption results emphasize therefore the higher flexibility provided by the use of a CVRT on a parallel hybrid configuration: while the engine is operated along a minimum specific fuel consumption curve as discussed in Section 3, Methodology, the CVRT availability allows a reduction of the thermal energy contribution to the total power requirements by extending to the whole vehicle speed range the initial portion of the power vs. engine speed curve, corresponding to the lowest specific consumption values, and therefore requesting higher power and energy contributions from the electric motor. The electric power can of course be more efficiently matched to the required vehicle speed if it also can be handled by the CVRT as on Configuration No. 2.

In conclusion from the standpoint of fuel consumption, Configuration No. 3 can be used advantageously with respect to Configuration No. 2 at the expense of a higher electricity consumption if the available electric energy is not critical (as with Na-S battery), the advantage being that the CVRT would only handle the engine torque. CVRT sizing does not involve therefore development of products beyond the ratings of the presently available technology.

Should the power/energy availability be critical in connection with a maximum allowable battery weight, then a trade-off must be made against the risk of conditioning a more efficient use of the electric energy as well, to the development of a higher rating CVRT than presently available.

For a more convenient comparison among the fuel economies provided by the various alternatives, the results on Table 4.3-4 are also shown on Fig. 4.3-2 using a bar graph presentation.

As previously stated Configuration No. 4 had to be evaluated in terms of the possible consumption savings which could be obtained by disconnecting the electric motor, through a clutch when not in use (e.g. emergency conditions, for main electric propulsion system failure).

The consumption data presented on Table 4.3-5 show that fuel savings with respect to Configuration No. 3 are not sufficient to justify the addition of a component which should only be used under abnormal conditions.

The extended range capabilities provided by most of the configurations using the described control strategy, led to the conclusion that, to meet the maximum fuel savings objective, the battery energy should have been more properly exploited: as a limit it appeared appropriate to evaluate the pure electric driving capabilities of hybrid vehicle.

An analysis of the urban cycle requirements revealed that, by calculating the average power required to provide the average accelerations imposed on each second of the about 1,870 s cycle, only 6 points (1 s intervals) existed where, for the vehicle being analyzed, a

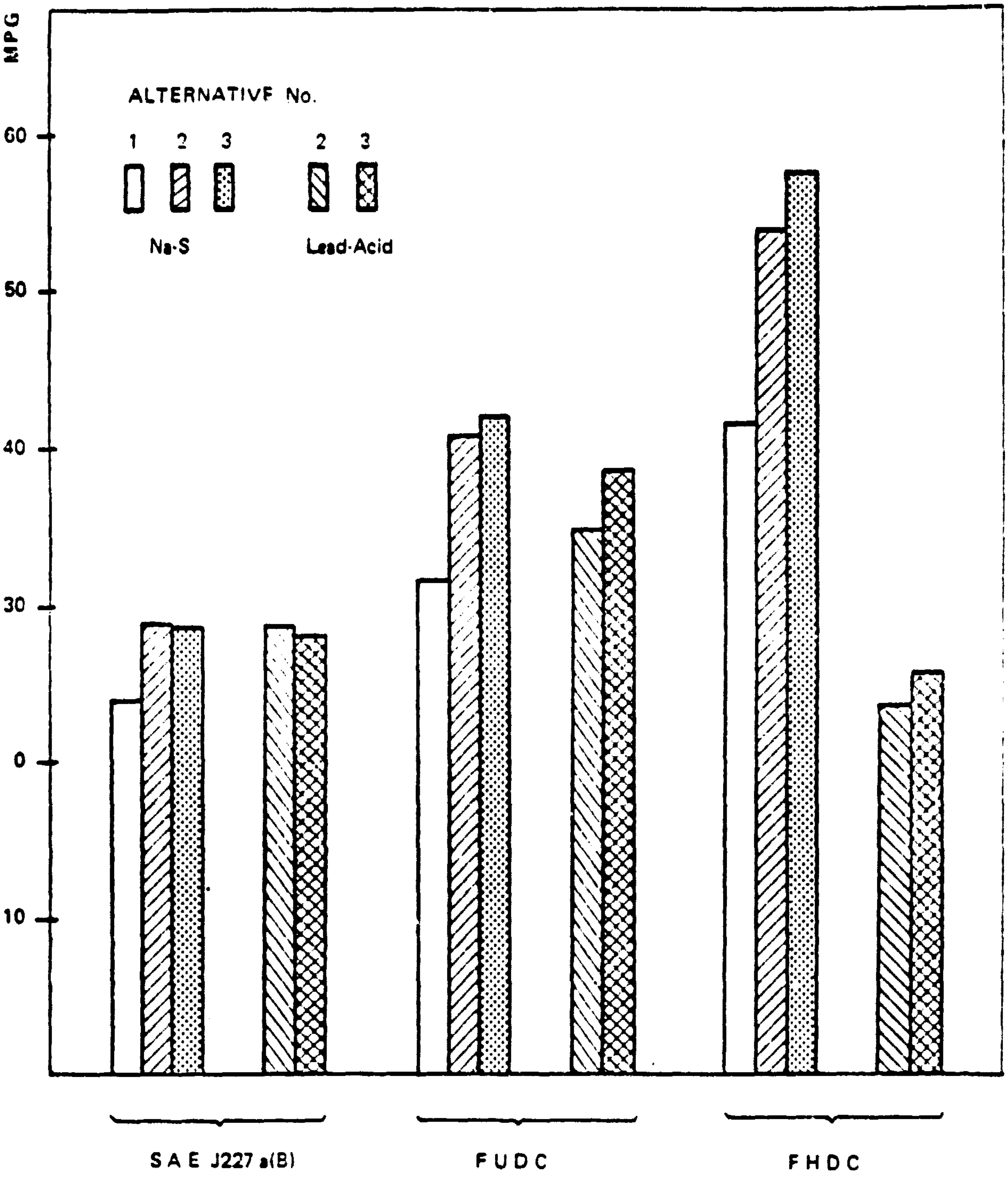

FIG. 4.3-2 – FUEL CONSUMPTION OF THE VARIOUS ALTERNATIVES ON THE STANDARD DRIVING CYCLES

TABLE 4.3-5

FUEL ECONOMY ON ELECTRIC POWER SHUTDOWN(1) (MPG)

CONFIGURAT.	SAE J227 a(B)	FUDC	FHDC
No. 3	28.1	34.6	46.2
No. 4	28.4	35	46.4
% VARIATION	+ 1.0%	+ 1.15%	+ 0.43%

(1) REFERS TO Na-S BATTERY ONLY

mechanical power above 40CV was required on the wheels and that the number of points where the corresponding power was between 36 and 40CV was only 12.

Taking into account the various power train components efficiencies it resulted that, while a 50 kW battery would be required to cover the maximum accelerating power required by an urban cycle, a 36 kW battery would cover all but 18 seconds of the cycle itself (i.e. more than 99% of its duration).

Electricity consumption and driving ranges were accordingly calculated as it had initially appeared that,by proper engineering of Na-S battery packaging,the overall weight could be kept close to 300 kg. The corresponding results are shown on Table 4.3-6.

Subsequent detailed analysis of the matter revealed that,using the current Na-S cell technology,the actual battery weight should be close to 360 Kg and it was decided not to pursue this solution for the time being.These interim results provide on the other hand a preview of what a mature Na-S tecnology could offer to electric and hybrid vehicle in the second half of the 80's.

4.3.3.2 Emissions

The emissions shown on Table 4.3-4 have been calculated on the standard cycles and referred to a gasoline engine in the normal European setting to evaluate the type and size of the required emission limiting devices to be defined during the preliminary design.

Based upon FIAT experience in setting-up standard engines to comply with the U.S. Standard requirements, it appears that a 3-way catalytic muffler should be sufficient to handle the emission levels so obtained.

4.3.4 Vehicle Performance

Vehicle performance parameters are shown for the various alternatives on Table 4.3-7.

They have been obtained using the same thermal power, a fixed battery weight and the appropriate transmission ratios discussed in Subsection 4.3.1.

To evaluate the various alternatives it has been assumed that the control system would use all the available engine power in the range 1.000-5.500 RPM (with or without CVRT) and all the available electric power at the corresponding RPM's as set by the

TABLE 4.3-6

PURE ELECTRIC DRIVING CONSUMPTION USING A 36 kW Na-S BATTERY

CONFIGURATION	ELECTRICITY CONSUMPTION, kWh		
	SAE J227a(B)	FUDC	FHDC
No. 1	0.04	2.79	2.42
No. 2	0.056	3.34	2.91
No. 3	0.041	2.86	2.45

TABLE 4.3-7

HYBRID VEHICLE PERFORMANCE

CONFIGURATION AND BATTERY TYPE		ACCELERATION TIME			RANGE ON GRADES				MAX	NONREFUELED RANGE			CRUISE/TO
		0-50 Km/h	0-90 Km/h	40-90 Km/h	3% 90 Km/h	5% 72 Km/h	8% 56 Km/h	15% 25 Km/	GRADE	SAE (*)	FUDC	FHDC	SPEED
		(S)	(S)	(S)	(Km)	(Km)	(Km)	(Km)	(%)	(Km)	(Km)	(Km)	(Km/h)
1	Na-S	6.28	16.2	11.6	unlimit. (1)	unlimit. (1)	> 3.2	> 1.0	32	407 (2)	537 (2)	704 (2)	125/125
2	Na-S	5.00	13.16	9.43	. . . UNLIMITED . . . . . (1)				44	486 (2)	691 (2)	913 (2)	136/136
	Lead-Acid	5.30	13.90	9.81	. . . UNLIMITED . . . . (1)				45	486 (2)	360 (3)	248 (3)(4)	136/136
3	Na-S	5.70	14.57	10.30	. . . UNLIMITED . . . . . (1)				40	479 (2)	715 (2)	975 (2)	136/136
	Lead-Acid	5.57	14.40	10.10	. . . UNLIMITED . . . . . (1)				45	473 (2)	400 (3)	366 (3)(4)	136/136
MINIMUM REQUIREMENTS		6.0	15.0	12.0	1.0	-	50 Km/h 0.3 Km	0.2	-	-	-	-	90/-
PERFORMANCE SPECIFICATIONS		6.0	15.0	12.0	8.0	16	3.2	0.8	30	145	190	270	105/120

(*) SAE J 227 a (B)

(1) PERFORMANCE SPECIFICATIONS MAY BE SATIFIED USING THERMAL POWER ONLY

(2) LIMITED BY EMPTY TANK

(3) LIMITED BY DISCHARGED BATTERY

(4) RANGE LIMITATION IS ONLY REFERRED TO OPERATING CONDITIONS WHICH MANTAIN THE FUEL CONSUMPTION AND EMISSIONS VALVES SHOWN ON TABLE

actual values of the fixed ratio (See Subsection 4.3.1 above).

JPL Minimum Requirements and Performance Specifications provided by Task-1, Mission Analysis are also shown for convenience.

a) Acceleration

Configuration No. 1 with Na-S battery does not meet the minimum requirements; as previously stated on Subsection 4.3.1; this could have been corrected by appropriate ratio adjustments, but it was considered unnecessary in view of the already higher fuel consumption than in the other alternatives (see Subsection 4.3-3). While for Configuration No. 2 the transmission ratio adjustments to satisfy performance requirements have been made for both battery solutions, so that the one using Sodium-Sulphur battery still provides better acceleration characteristics due to the higher battery power capabilities, for Configuration No. 3 the initial transmission ratios already provided acceleration performance in excess of specifications, when using a Sodium-Sulphur battery. When instead a Lead-Acid battery is used, as a result of the actual transmission ratio adjustments,slightly better accelerations have been obtained.

b) Grade (Range at given speed)

On all grades,specified ranges are exceeded; in particular the 3% and 5% grades speed requirements can be met using thermal power only so that unlimited range capability is practically available. On the 8% and 15% grades electric power contributions are required but the specified ranges can be largely exceeded. Better fuel economy on the various grades can of course be obtained, depending on actual availability of stored energy, than under thermal power saturation by using more efficient power control strategies as appropriate.

The maximum allowed grades shown for the various alternatives, which exceed by far the minimum requirement (20%),prove the excellent capabilities of the hybrid vehicle in terms of available torque at low speeds notwithstanding the extra 300 kg of the batteries!

c) Nonrefueled Range

All the alternatives exceed Performance Specifications but Configurations No.2 and 3 using Lead-Acid battery on the Highway Cycle; range limits however are due, with the control strategy previously indicated, to different operating conditions as specified by the notes on Table 4.3-7. In particular, it can be noted that (within the battery normal operating discharge range) the range limitation is due to battery discharge for Configuration No. 2 and 3 using Lead-Acid batteries on both the

FUDC and FHDC.

Among the Configurations using Na-S battery, only Configuration No. 2 has a range limitation due to the battery discharge on the Highway Cycle, which however almost occurs simultaneously with the emptying of the tank.

In all the other cases the range limitation is due to complete fuel consumption.

While this would indicate that better fuel economies should extend the last range values by means of more appropriate power control strategies, it must be pointed out that both batteries would still be operating at the end of the nominal operating discharge range and that, using an appropriate control strategy, they could be operated indefinitely at such discharge level or even recharged if appropriate at the expense of higher fuel consumption, but would provide yet a better fuel economy than any equivalent conventional ICE vehicle.

As a result, the operating conditions below the Non-refueled Range Performance Specifications do not correspond to an actual lack of absolute range capabilities, but indicate a performance limitation when related to the possibility of achieving the fuel economy characteristics specified for the vehicle operating conditions assumed on the Highway Cycle. The range values shown are therefore mainly relevant in terms of Trade-off evaluation between the various alternatives rather than in terms of actual Non-refueled Range capabilities.

d) Cruise and Top Speed

All the alternatives exceed both the Minimum Requirements and Performance Specifications: a single value is presented for either speed since no assumptions were made on engine/speed power limitation by the control logic so that top speed can be indefinitely maintained as cruise speed using thermal power only. Configuration No. 1 shows a lower value of top speed which goes along with its worse acceleration characteristics. It must be emphasized the role played by the advanced vehicle characteristics in terms of aerodynamic drag and rolling resistance coefficients.

At a cruise speed of 90 Km/h only 12.5 CV would be needed on the drive wheels of a vehicle having $C_X = 0.3$ $Kn = 0.45$ (advanced tire design): both Configurations No. 2 and No. 3, using the CVRT to match engine/wheels power and speed requirements,would provide close to 15 CV at only 2,000 RPM. If on the other hand a vehicle with current today's characteristics ($C_X = 0.45$ and $Kn = 0.8$) is considered, 20.5 CV would be needed on the vehicle wheels to keep the vehicle at 90 Km/h with a power increase (and corresponding mechanical energy waste) of 64%! The fuel consumption ratio would be even higher because of the higher specific consumption required to obtain a higher power from the same engine.

At 120 Km/h the corresponding power requirements on the drive wheels would be 27 and 43 CV respectively with a power increase reduced to 59%. These results have been obtained by using the parametric curves shown on Fig. 4.3-3/4.3-5.

With reference to the maximum 40 CV power available on the drive wheels, using the engine being considered during alternative evaluation, both Configurations No. 2 and No. 3 would provide the hybrid vehicle with the top speed of 136 Km/h shown on the table. Using the same 40 CV on a vehicle with the current today's characteristics considered above, the top speed would barely reach 115 Km/h (less than 85% of the previous one). These results confirm what has been clearly shown by the previous considerations on acceleration performance, that is a hybrid vehicle is characterized, because of the extra weight of the battery, by critical power requirements in terms of accelerations only and not in terms of maximum speed if advanced concepts to reduce power losses in aerodynamic and rolling resistance are used in vehicle design.

Adequate battery weight is on the other hand essential in maximizing, for each battery technology being considered, electric energy storage and therefore fuel saving capabilities.

e) Maximum Speed on Grades

The values shown on Table 4.3-8 can be conveniently compared with those shown in the Top Speed column (and they have been accordingly calculated in both absolute and relative terms), keeping in mind that on grades all the hybrid power is made available on the drive wheels.

Both Configurations No. 1 and No. 2 can reach 100% of Top speed (thermal power only on flat road) on a 3% grade, while Configuration No. 3, not being able to adjust the electric power characteristics by means of the CVRT, reaches its limit at 127 Km/h for both Lead-Acid and Sodium-Sulphur batteries.

Configuration No. 1, which starts with a worse performance at high speeds, shows significant relative improvements at intermediate speeds but then decays drastically at the low speed relative to the highest grade: this agrees with the lower % maximum grade capability than any other solution.

Both Configurations No. 2 and No. 3 show a better behaviour at the intermediate speeds with the Na-S battery; this goes along with the fact that the lower available power of the Lead-Acid battery has been compensated for low and high speeds, only to meet the performance requirements, by proper ratio adjustments, thus resulting

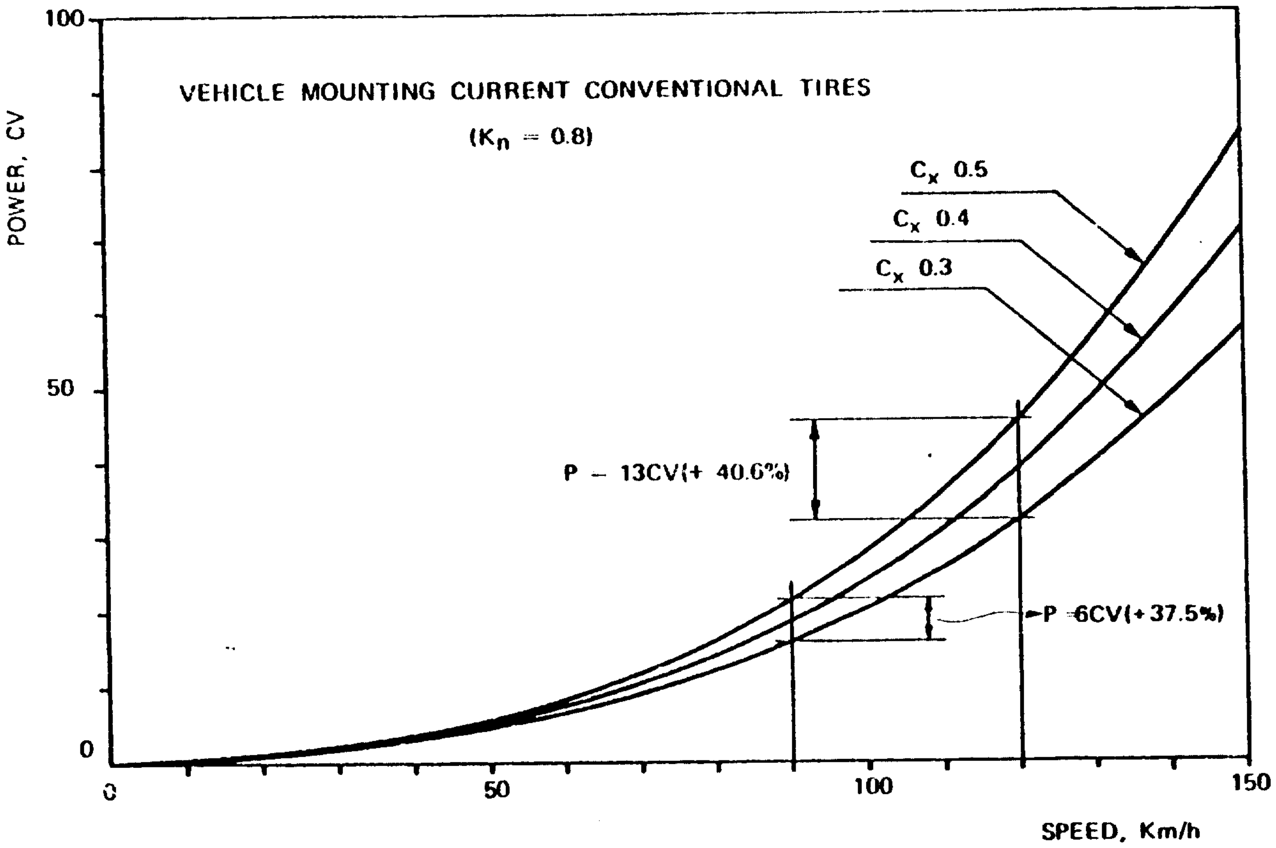

FIG. 4.3-3 – HORSEPOWER REQUIREMENTS AS FUNCTION OF VEHICLE SPEED

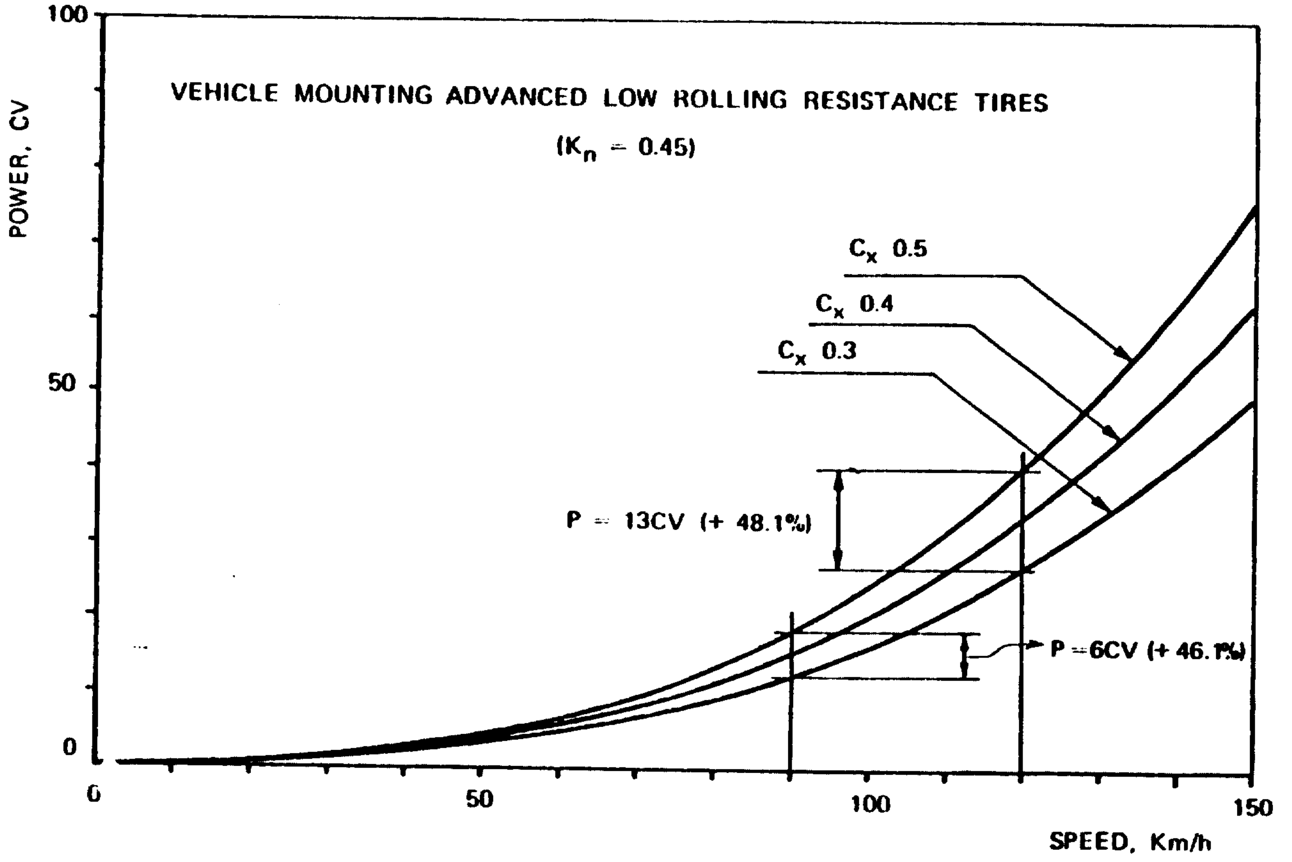

FIG. 4.3-4 — HORSEPOWER REQUIREMENTS AS FUNCTION OF VEHICLE SPEED

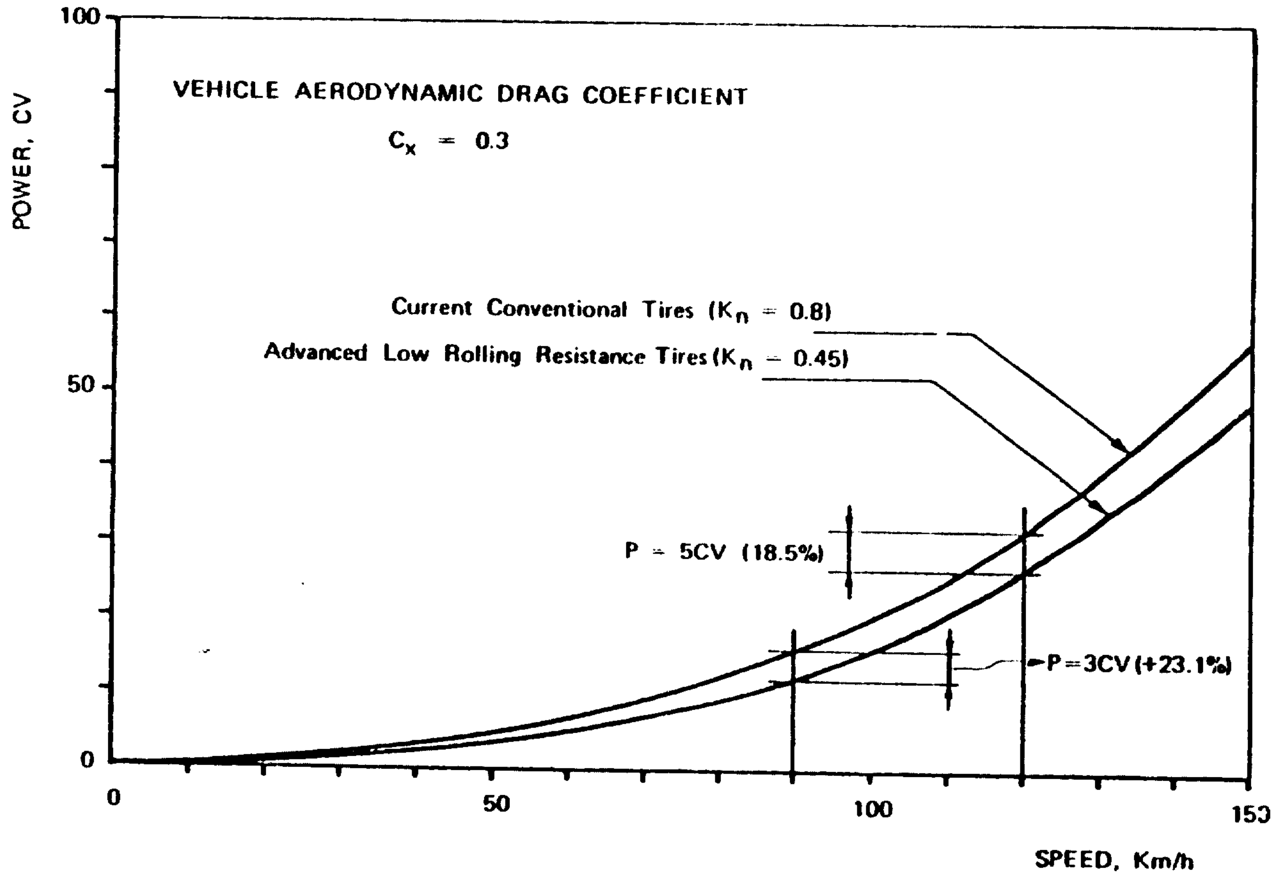

FIG. 4.3-5 – HORSEPOWER REQUIREMENTS AS FUNCTION OF VEHICLE SPEED

TABLE 4.3-8

VEHICLE PERFORMANCE (MAX. SPEED ON GRADES)

CONFIGURATION		MAXIMUM SPEED (1) ON FLAT ROAD		MAXIMUM SPEED ON GRADES (2)							
				3%		5%		8%		15%	
		Km/h	% Top Speed	Km/h	% Top Speed	Km/h	% Top Speed	Km/h	% Top Speed	Km/h	% Top Speed
No. 1	Na-S	125	100	125	100	121	97.0	99	79.3	54	43.2
No. 2	Na-S	136	100	136	100	126	92.7	103	75.7	68	50.0
	Lead-Acid	136	100	136	100	112	82.6	94	69.3	67	49.3
No. 3	Na-S	136	100	127	93.5	124	91.2	101	74.3	66	48.5
	Lead-Acid	136	100	127	93.5	111	81.7	94	69.3	66	48.5

(1) - FULL THERMAL POWER (No RPM LIMITATION)

(2) - FULL HYBRID POWER (FOR 1 MINUTE - No RPM LIMITATION)

in a not so brilliant performance in the intermediate range.

Again the values shown are only relevant to provide absolute and relative measuring means to fully evaluate the various solutions as some of their capabilities are not fully exploited in each of the operating conditions selected to compare the performance and/or efficiency they can provide.

All performance characteristics in excess of actual driving requirements can therefore be properly modified by appropriate optimization of the transmission ratios and/or the control strategy and turned into a higher fuel economy, in the same way as any performance deficiency could have been compensated for by appropriate optimization of the same design parameters or algorithms at the expense of a fuel economy degradation.(1).

As an example, assuming a Merit Figure MF = 100 for the best result obtained from one alternative for a given parameter, the remaining alternatives can be "ranked" with respect to such parameter in terms of percent of the optimum performance.

Giving therefore MF = 100 to the 0-50 km/h acceleration time of the alternative (No. 2, Na-S) the remaining merit figures would be:

(No. 2, Lead-Acid)	94.3
(No. 3, Lead-Acid)	90.0
(No. 3, Na-S)	87.9
(No. 1, Na-S)	79.7

Upon obtaining the MF's for the other acceleration conditions an overall MF for the acceleration behaviour can be obtained for the various alternatives.

Using the same approach on another performance parameter, like for istance the Fuel Consumption on FUDC, the ranking of the alternatives would appear as follows:

(No. 3, Na-S)	100
(No. 2, Na-S)	97
(No. 2, Lead-Acid)	97
(No. 3, Lead-Acid)	94
(No. 1, Na-S)	75.3

Again, upon obtaining the MF's for the other consumption conditions, an overall MF for the fuel consumption behaviour can also be obtained for the various alternatives.

An exhaustive comparison among the various alternatives in terms of "normalized" ranking of all the performance/cost parameters will be presented in the following Subsection 4.4.

---

(1) See Ref. [7], Subsection 1.2

4.3.5 Production Cost Analysis

The vehicle cost breakdown in 1978 U.S. $, determined according to the methodology described in Section 3, is shown in Table 4.3-9 for the various alternatives. The individual costs are intended to represent an estimate of the U.S. manufacturing cost for mass production (> 1,500 units/day) of the Hybrid Vehicle components and/or subsystems.

The part lists for the various subsystems are given below. Production costs have been obtained for the conventional parts and components by projecting actual FIAT production costs of the LANCIA "GAMMA" to the expected 1985 production levels and technology. Labor costs for vehicle assembly have been attributed to the Chassis and Body/Frame Subsystems according to current FIAT methodology and data availability. Adjustments to account for U.S. manufacturing have been only made at the total cost level using the procedure previously described in Section 3.

Chassis Part List

- General assembly, organisation and workmanship
- Tank, fuel pipes and fasteners
- Transmission levers and tension rods
- Muffler, catalytic converter, pipes and fasteners
- Water tank, cooling liquid tank and pipes
- Steering knuckle, bearings, wheels, front and rear spacers
- Rear driving axle and bearings
- Propulsion system suspensions
- Front and rear suspensions: coil-springs, pins, track rods front and rear stabilizer bars
- Steering-wheel for power steering, steering box, steering arms and supports; oil tank, pipes and fittings
- Front and rear brakes
- Power brakes;box and fittings, pipes and controls and ancillary components
- Parking brake control and levers
- Hydraulic control system: pedal and supports, pump, brake fluid supply tank, pipes, fittings and anti-skid braking system
- Electrical equipment controls

TABLE 4.3-9

HYBRID VEHICLE PRODUCTION COST BREAKDOWN 1978 $ VALUE

ITEM	CONFIGURATION AND BATTERY TYPE				
	No.1	No.2		No.3	
	(Na-S)	(Na-S)	(Lead-Acid)	(Na-S)	(Lead-Acid)
INTERNAL COMBUSTION ENGINE	358	358	358	358	358
CHASSIS (1) (2)	1098	1098	1098	1098	1098
BODY / FRAME (1) (2)	1921	1921	1921	1921	1921
AUXILIARY ELECTRIC SYSTEM (1)	360	360	360	360	360
TRANSMISSION	162	288	288	225	225
ELECTRIC PROPULSION SYSTEM (1) (2)	700	700	632,5	700	632,5
POWER BATTERY	1350	1350	450	1350	450
TOTAL COST	5949	6075	5107,5	6012	5044,5

(1) SEE SPECIFIC PART LISTS

(2) AS PRODUCTION COSTS ARE OBTAINED BY EXTRAPOLATION FROM ACTUAL FIAT PRODUCTION COSTS OF THE LANCIA "GAMMA" LABOR COSTS FOR VEHICLE ASSEMBLY ARE ATTRIBUTED TO CHASSIS AND BODY FRAME SUBSYSTEMS ACCORDING TO CURRENT FIAT METHODOLOGY AND DATA AVAILABILITY. ADJUSTMENTS TO ACCOUNT FOR U.S. MANUFACTURING ARE ONLY MADE AT THE TOTAL COSTS LEVEL.

- Heater fan, pipes and controls
- Air Conditioner

Body-Frame Part List (includes Labor)

- Car assembly, mechanical drawings for type approval, mechanical parts locking drawings
- Body assembly and paint
- Front frame
- Lateral frame
- Roof panel frame
- Rear frame
- Inside panels
- External coating
- Floor
- Dashboard and relevant ancillary components
- Windshield and supporting components
- Side windows and ancillary components
- Rear window
- Front and rear doors and ancillary components
- Radiator
- Front and rear seats and ancillary components
- Battery supporting fixtures
- Vehicle lifting points
- Insulating panels
- Floor carpet and up-holstery
- Trunk lid and ancillary components
- Front and rear integral bumpers
- Spare wheel installation
- License plates installation
- Radio installation
- Jack and toolholder
- External mirrors and fuel pipe door

- Safety belts and gaskets
- Sealing, paint and enamel

Auxiliary Electric System Part List

- Electric generator, starting motor, spark plugs
- Voltage regulators
- ICE starting battery
- External and internal lights
- Instruments and switches
- Windshield wiper and ancillary components
- Horn and fuses
- Emergency lights
- Electronic ignition system

Electric Propulsion System Part List

- Electric Motor/generator
- Reversible Power Conditioner
- Control unit
- On-board charger

4.3.6 Reliability, Availability, Maintainability

While in the previous subsections quantitative results obtained under given conditions were presented and discussed, the R.A.M. characteristics of the components included in the various alternatives as well as of the selected vehicle structural approach will be now qualitatively addressed. While Configuration No. 1, which has a lower ranking in terms of performance and/or consumptions, is made of conventional components with established R.A.M. characteristics , Configuration No. 3 offers with respect to Configuration No. 2 the advantage of a lower maximum torque rating for the CVRT and therefore a lower chance to incur in manufacturing problems. While not extensively used nowadays, CVRT's ratings satisfying Configuration No. 3 requirements already correspond to a well established manufacturing technology . The feasibility of a higher rating CVRT has yet to be validated. Configuration No. 4 would have included, with respect to Configuration No. 3, an additional device, i .e. the clutch, and therefore would have a slightly higher probability of failures. In general, the advanced components and/or characteristics which are common to all the configurations being evaluated (body in higher specific resistance material, plastic panels, CVRT, electronic control system, tires with low rolling resistance coefficient, better aerodynamic drag coefficient C_X) should contribute to the reduction of mechanical failure probabilities and, within certain limits, of maintenance problems as a result of the reduced power losses and therefore friction wear.

In fact the plastic panels, as an example, besides contributing to reduce the weight and therefore the static load on the supporting structure do not present any of the paint and rust interrelated problems common to conventional car bodies. The electronic control system, by continuously monitoring the most important parameters of an operating hybrid vehicle, shall promptly warn the driver in case of failures of any kind.

It is on the other hand expected that most of these advanced components and/or technologies should also be introduced in the 1985 conventional U.S. vehicles to obtain fuel economy levels in line with the 1985 C.A.F.E. limits. Any characteristics that could adversely impact the R.A.M. behaviour of such newly developed components should then be common to the conventional vehicles as well. As far as the additional electric components specific of the hybrid vehicle propulsion system, such as the electric motor, the power conditioner and the batteries, they should not significantly impact the overall R.A.M. vehicle behaviour while improving the operating conditions of the conventional portion of the vehicle.

In fact the electric equipment, by actively contributing to the braking function, makes the decelerations smoother and reduces conventional brakes wear. The lower power rating of the ICE would reduce the vibrations induced in the body structure, while the engine life itself should be greatly extended by the limited range of operation, mantained under optimum conditions, most of the time with most of the acceleration power provided by the electric motor.

On the other hand, the electric motor itself, with no parts in alternative motion, has an excellent record of field proven operation. It should present therefore very few probabilities of failures and of maintenance problems; the possible choice of an advanced brushless electric motor, automatically switched by means of electronic devices could

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even further reduce maintenance requirements of the electric power system.

Finally the traction battery could actually represent a critical item in terms of R.A.M. as its reliability, or more simply its operating life shall be strictly related to the extent of discharge required by the mission range and the system control strategy. A hybrid vehicle could be in fact designed for operation with any level of battery discharge per day within the allowed range. Zero or light discharge would result in a long battery life and reduced fuel economy; deep discharge would result in a shorter battery life but maximized fuel economy. For a given battery weight and vehicle fuel economy/range operating condition, the Na-S battery should have several times the life of a Lead Acid battery. On the other hand the Na-S battery, due to its continuous high temperature conditions, is expected to show an absolute life limit of about 5 years, irrespective of the actual charge/discharge cycles.

The Lead Acid batteries do not present any problem as far as faulty elements replacement is concerned. Maintenance of the Lead-Acid batteries requires periodic checking of battery performance, and restoration of the electrolyte level with distilled water.For the Na-S batteries, the problems that might arise from the high number of elementary cells (above 400) and consequently from a higher probability of a single cell failure, is to be solved by means of an adequate quality control plan with a resulting impact on the battery price. It is expected that in terms of mean time to repair, the battery layout can be designed in such a way that faulty modules made of several cells can be easily identified and replaced with minor problems related to the handling of high temperature parts.

On the other hand since the most probable failure mode is represented by a short in a single cell, the high number of cells should have a favorable inpact on the overall module/battery availability. The parallel connection of multiple cell strings should in fact allow the battery to withstand even multiple cell failures without relevant performance degradation.

It should also be pointed out that, since the hybrid vehicle system consists of two different and independent types of motors, it presents a very low probability of failures in both motors at the same time and the driver, therefore, should always have a chance to get at least to the nearest garage.

4.3.7 Life Cycle Costs Analysis

The life cycle costs, in 1978 $ figures, are shown on Table 4.3-10,for configurations No. 2 and 3 with either type of battery. The Mission Analysis has indicated that the average K_5 vehicle travels on Mission M_3 an average of 13,300 miles per year and, since the vehicle life has been set,for the conventional vehicle, at 100,000 miles or ten years, whichever comes first, a nominal vehicle life of 7.5 years has been established for life cycle cost analysis at the trade-off level. The values shown on the table have been obtained following the same methodology used for the conventional ICE Reference Vehicle (1).

It must be emphasized that the resulting life cycle cost has been obtained using the vehicle operating data (fuel consumption, average daily discharge level) previously used to compare the various alternatives.

Since, as previously outlined, no effort was made to optimize the exploitation of the fuel saving potentials of the various solutions, these cost figures should be evaluated in the light of the following considerations:

a) better fuel consumptions could be obtained by simply optimizing the propulsion system control strategy; the expected improvement would be rather impressive for the Sodium-Sulphur Battery.

b) the fuel cost savings should be on the other hand somewhat offset by the battery replacement and repair cost which have not been considered due to the limited discharge which either battery would be subjected to by the control strategy actually used in the simulated operating conditions. In this respect the Sodium-Sulphyr battery, considering its higher purchase price, is penalized by a much lower degree of utilization during the vehicle life than the Lead-Acid battery. It was felt however more appropriate for the present level of battery definition, not to make any guessing on possible battery salvage value which has conservatively been neglected in all cases in line with the assumptions made for the conventional reference vehicle.

These life cycle cost data should be therefore considered as absolute maximum limits which should be worked on during the conclusive preliminary design effort, to identify minimum operating costs on the one side and maybe more appropriate cost estimating relationships and assumptions to be applied, for sake of comparison,to the conventional reference vehicle as well.

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(1) See Ref. [13], Subsection 1.2

TABLE 4.3-10
HYBRID VEHICLE LIFE CYCLE COSTS 1978 $ VALUE(1)

ITEM	CONFIGURATION AND BATTERY TYPE			
	No. 2		No. 3	
	(Na-S)	(Lead-Acid)	(Na-S)	(Lead-Acid)
PURCHASE PRICE (2)	12,180	10,218	12,024	10,089
SALES TAX (3)	607	511	601	504
INTEREST (4)	5,818	4,891	5,757	4,830
SALVAGE VALUE(5)	–	–	–	–
A – ACQUISITION COST	18,575	15,617	18,382	15,423
TIRES, REPAIRS AND ROUTINE MAINTENANCE	6,500	6,500	6,500	6,500
ANNUAL TAXES, LICENSE AND REGISTRATION (6)	240	240	240	240
INSURANCE (7)	1,540	1,419	1,530	1,413
FUEL (GASOLINE)	1,950	1,950	1,866	2,035
ELECTRICITY	228	181	187	167
BATTERY REPLACEMENT	–	–	–	–
SALES TAX ON BATTERY REPAIRS	–	–	–	–
INTERESTS ON BATTERY REPAIRS	–	–	–	–
B – OPERATING COSTS	10,458	10,290	10,323	10,355
C – LIFE CYCLE COST (A + B)	29,033	25,907	28,705	25,778
D – VEHICLE LIFE: 7.5 YEARS AND 100,000 MILES.				
COST/YEAR	3,861	3,445	3,817	3,428
COST/MILE	0.290	0.259	0.287	0.258
COST/KILOMETER	0.180	0.161	0.178	0.160
E – TOTAL FUEL AND ELECTRICITY CONSUMPTION ON VEHICLE LIFE				
GASOLINE, gal	2,030	2,030	1,932	2,120
ELECTRICITY, kWh	5,687	4,511	4,668	4,173

(1) DISCOUNT RATE FOR PRESENT VALUE CALCULATIONS: 2% PRIVATELY OWNED – (2) 2.0 X MANUFACTURING COST (3) 5% APPLIED TO PURCHASE PRICE – (4) 12% ANNUAL PERCENTAGE RATE (A.P.R.) FOR 4 YEARS APPLIES TO PURCHASE PRICE + SALES TAX – (5) THE ASSUMED LIFE MILEAGE OF 100,000 MILES ESTABLISHES A ZERO SALVAGE VALUE – (6) $ 33/YEAR – (7) $ 125 + 0.01 X PURCHASE PRICE (FOR FIRST 5 YEARS AND $ 75 + 0.006 X PURCHASE PRICE SUBSEQUENTLY).

4.3.8 Operational Quality: Handling, Noise and Safety

Handling and noise considerations have not, so far, influenced the design characteristics of the vehicle architecture and the propulsion system alternatives. While the last ones have no significant impact on the vehicle handling quality, a different behaviour exists as a result of the differences between the hybrid and conventional vehicle architecture. The hybrid car is in fact a heavier vehicle because of the battery addition but, being its center of gravity closer to the vehicle center, load variations result in reduced excursions with respect to conventional vehicles equipped with front wheel drive. The yaw movement however could be more pronounced, because of the larger momentum of inertia, due to the batteries located in the rear compartment and should be adequately compensated for by proper rear suspension design.

The average noise and vibrations are largely reduced in a hybrid vehicle because of the lower power engine operating in optimal conditions and thanks to the smoother operation of the electric motor. The complete electric system shall be totally insulated to provide a high degree of safety during normal maintenance procedures as well as in case of accidents. A strong and efficient structure shall guarantee the safety of the passenger compartment according to the most advanced safety regulations. The batteries shall be adequately secured to the body structure to prevent them from affecting the passenger compartment integrity either in case of frontal crash or back bumping.

4.4 TRADE-OFF DATA REVIEW AND REFERENCE CONFIGURATION SELECTION

In the previous Subsections the various design and performance parameters have been presented and compared in absolute terms and existing interdependences have been outlined.

As the task objective was set in terms of Trade-offs among technical alternatives rather than between conflicting performance parameters (consumption and accelerations, for istance) no optimized conditions for the various alternatives had to be defined.

The various design and performance parameters were therefore analyzed during the Trade-off Data Review to identify the alternative(s) having the higher potential of minimizing the Hybrid Vehicle fuel consumption.

Among the design parameters which varied among the analyzed alternatives, only the vehicle weight and production cost appeared to have some impact on Trade-off considerations; the lower operating power rating (for a given weight) of the Lead-Acid battery with respect to the Sodium-Sulphur battery, being already accounted for by the performance behaviour, should not be overemphasized by a specific Trade-off assessment.

The performance parameters which were used to assess the alternatives are:

- Consumption on standard cycles and daily (mission) cycle.
- Emissions on Standard Cycles.
- Accelerations.
- Nonrefueled Ranges on Standard Cycles.
- Top Speed.
- Maximum speeds on Grades.
- Life Cycle Cost.
- Gasoline Consumption on Vehicle Life.
- Electricity Consumption on Vehicle Life.

For each selected parameter (design or performance) a Merit Figure MF was calculated using the same criteria described on Subsection 4.3.4. and the results are shown for all the alternatives on Table 4.4-1.

Following the first parameter column (Vehicle Weight), two MF values are given for each parameter: the "a" column corresponding to the actual parameters' MF and the "b" column corresponding to the cumulative MF (average with all the previous parameter MF's). While applying different weights to the various parameters appeared quite reasonable, it was felt more appropriate not to include in this evaluation an element of

TABLE 4.4-1

ALTERNATIVES RANKING BY MERIT FIGURE "MF"

CONFIGURATION	BATTERY TYPE	PARAMETER																				
		1	2		3		4		5		6		7		8		9		10		11	
		VEHICLE WEIGHT	CONSUMPT. ON STD CYCLES		EMISSIONS ON STD CYCLES		ACCELERAT.		NON REFUEL RANGE ON STD CYCLES		TOP SPEED		MAX SPEED ON GRADES		PRODUCT. COST.		LIFE CYCLE COST		GASOLINE CONS. ON VEHICLE LIFE		ELECTRICITY CONSUMPT. ON VEHICLE LIFE	
			a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b
No. 1	Na-S	99.2	76.2	87.7	81.2	86.5	80.7	84.3	77.1	82.9	92	84.4	94.9	85.9	84.8	85.8	—	—	—	—	—	—
	Lead-Ac	100	(74.7)(*)	—	(79.3)(*)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
No. 2	Na-S	96.8	96.4	96.6	95.4	96.2	100	97.1	96.9	97.1	100	97.6	100	97.9	83.1	96.0	88.8	95.2	95.2	95.2	73.3	93.2
	Lead-Ac	97.4	96.4	96.9	95.5	96.4	95	96.0	58.7	88.6	100	90.6	94.8	91.1	98.8	92.1	99.5	92.9	95.2	93.1	92.5	93.1
No. 3	Na-S	96.8	99.6	98.2	93.4	96.6	89.9	94.9	99.5	95.8	100	96.5	96.8	96.6	83.8	95	89.8	94.4	100	95.0	89.4	94.5
	Lead-Ac	97.4	93.1	95.2	93.6	94.7	91.6	93.9	60.0	87.1	100	89.3	92.3	89.7	100	91.0	100	92.0	91.1	91.9	100	92.6

(*) SAE J 227 a (B) CYCLE ONLY

discretionality which could deteriorate the visibility of the actual results. Unit weights for all parameters were therefore used while our viewpoint is only added at the end in terms of qualitative comments and conclusions.

The alternative corresponding to Configuration No. 1 with Lead-Acid battery was discarded at the Consumption stage as it was already ranking last, while not satisfying acceleration requirements on FUDC and FHDC.

The alternative corresponding to Configuration No. 1 with Sodium-Sulphur battery was evaluated throughout the Production Cost: it was then discarded as ranking fifth, significantly below the fourth one (Configuration No. 3 with Lead-Acid battery).

It can be noted that, as expected from the considerations previously made on the more limited operating power available from a given weight of Lead-Acid battery, the two remaining alternatives with Sodium-Sulphur battery always ranked at the first two places.

Configuration No. 2, due to the transmission ratio adjustment which provided it with the best performance characteristics, ranked first from Parameter No. 3 (Emission) through No. 10 (Gasoline Consumption on Vehicle Life) thanks to its top rating in all vehicle performance parameters (No. 4, 6 and 7).

Configuration No. 3 which did not require transmission ratio adjustments to meet performance specifications (and should have had therefore better performance characteristics as well under similar conditions) maintains a higher margin in consumption ratio (i.e. corresponding relative MF's) with respect to Configuration No. 2 consumption parameters (No. 3, 5, 10, 11) which outpasses its worse behaviour (at those conditions) in performance parameters.

It should not be overlooked, that a certain amount of "preferential" weight has been actually given to the consumption parameters (which favour Configuration No. 3) in view of the higher number of such parameters included in the average. However it must be observed that the average of the consumption MF's are 90.5 for Configuration No. 2 and 97.1 for Configuration No. 3 while the average of the corresponding performance MF's are 100.0 and 95.6 respectively (Na-S battery only).

The composite Consumption/Performance MF would therefore always favour Configuration No. 3 96.3 to 95.2 in terms of MF average or 107.8 to 104.6 in terms of corresponding MF ratios.

Should one therefore consider the heavier emphasis to be placed on fuel consumption as well as the yet-to-be-proved availability during Phase II of a CVRT with higher torque ratings (which should further penalize Configuration No. 2 in terms of expected Reliability MF) it can be stated that Configuration No. 3 has proven to be the most appropriate to meet the program objective within the conceptual design alternatives that have been evaluated.

While this appears a clear-cut decision for the alternative with Na-S battery, the availability of the CVRT on the electric motor too would actually make Configuration No. 2 using Lead-Acid battery slightly better than Configuration No. 3 from the MF rating standpoint.

However the same considerations made above for the alternatives using Na-S batteries should make the margin less significant or even reverse it; considering furthermore that a Lead-Acid battery does not, after all, seem the most appropriate solution to obtain the results that could be expceted in 1985 from a hybrid vehicle as advanced as it should be, it appears that Configuration No. 3 is the most appropriate choice to complete during the Preliminary Design Task the Hybrid Vehicle conceptual design optimization using,among all the available battery types,the most suitable to do its job on a Hybrid Vehicle for which final assessments on mission M_3 range distributions, corresponding fleet mix and life cycle costs have been made.

SECTION 5

FINAL VEHICLE CONCEPTUAL DESIGN

5.1 HYBRID VEHICLE DESCRIPTION

The basic scheme of the Hybrid Vehicle is shown in Figures 5.1-1/5.1-3. It consists of a two-volume vehicle with a six-passenger capacity. The vehicle profile has been carefully studied to provide an aerodynamic drag coefficient $C_x = 0.3$ so that fuel economy can be maximized.

The energy absorbing front and rear bumpers are integral to the vehicle body which is of the self bearing type and consists of a metallic frame made of HSLA steel covered by plastic (SMC) panels. This solution provides excellent strength/weight ratio characteristics.

The vehicle overall dimensions are:

Length	4,710	mm
Width	1,800	mm
Height	1,400	mm
Wheelbase	2,730	mm
Track (front/rear)	1,510	mm

Complementing the advanced body design, relevant space and weight savings as well as convenient fitting of the traction battery in the rear compartment, under the trunk volume, are provided by the front wheel drive. The propulsion system is transversally mounted in the front end compartment and consists of two parallel units: a conventional Internal Combustion Engine connected to a Continuously Variable Ratio Transmission (CVRT) through a lock-up Torque Converter; a DC Electric Motor/Generator connected, by means of fixed ratio gear wheels and transmission chain, to the transmission output shaft, which drives the front wheels through the usual differential group.

The front end compartment also houses the cooling system, the electric motor power conditioner, the microprocessor based vehicle control system, the auxiliary electric system battery, the starting motor, the air conditioner and the spare tire.

The power steering box is located behind the propulsion group for safety reasons. Two Mc Pherson independent wheel front suspensions provide excellent space availability to conveniently fit the compact propulsion system under a low profile hood. The passenger compartment is unusually roomy and comfortable thanks to the absence of the drive shaft tunnel and is given excellent protection by the enclosing rigid and undeformable frame structure. The wide windshield and window surfaces allow good all

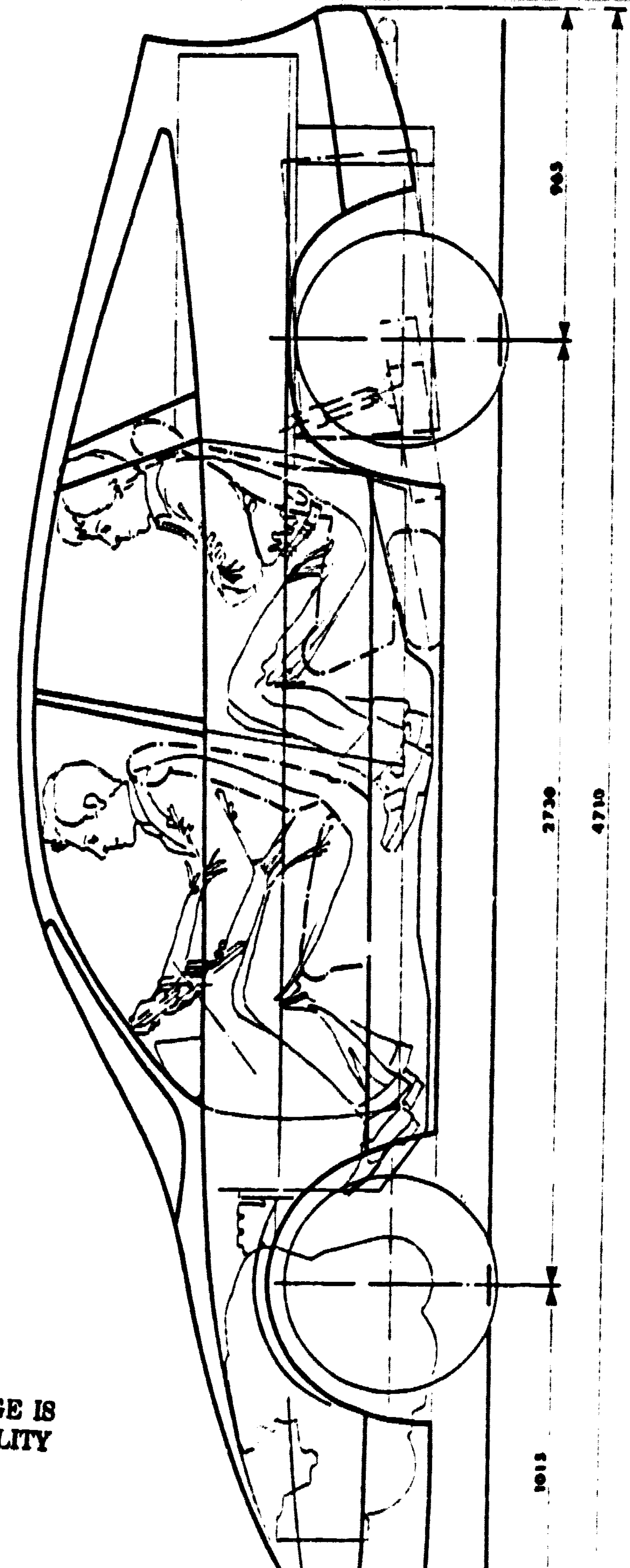

FIG. 5.1-1 — HYBRID VEHICLE — BASIC SCHEME

SIDE VIEW

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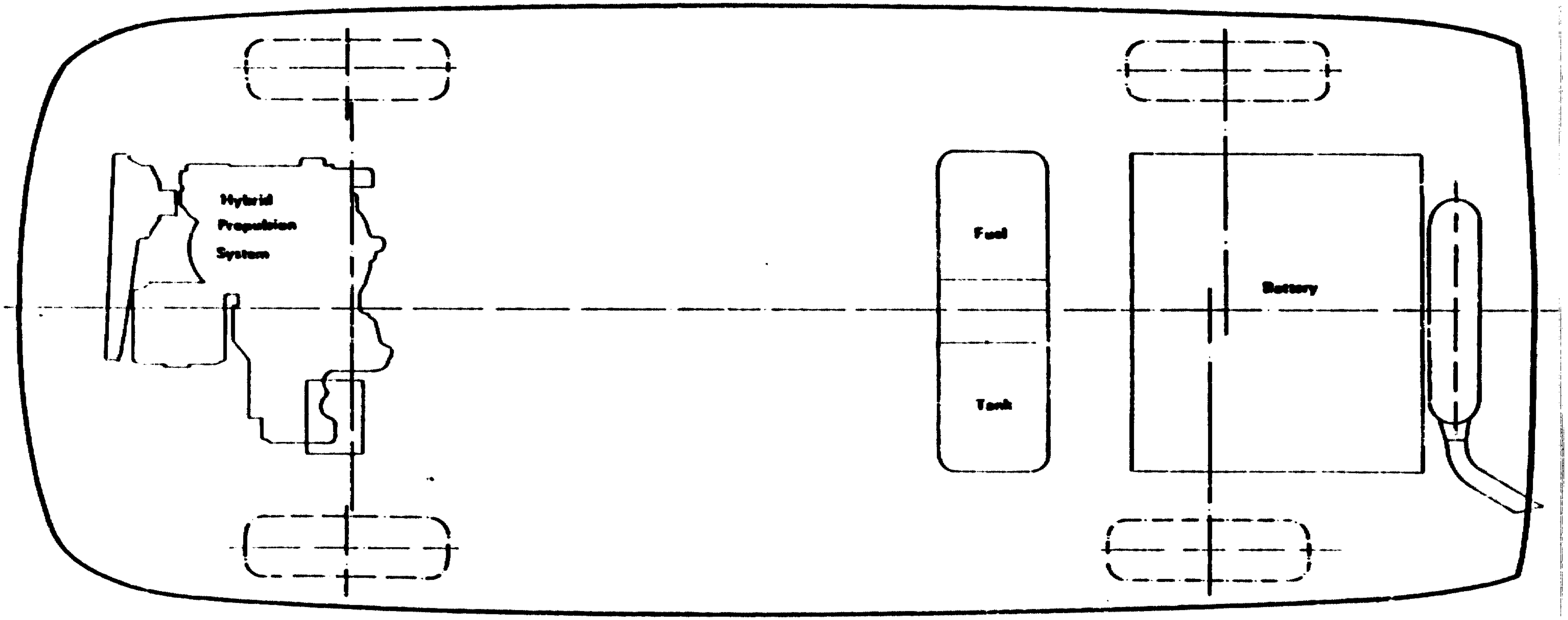

FIG. 5.1-2 — HYBRID VEHICLE — BASIC SCHEME

TOP VIEW

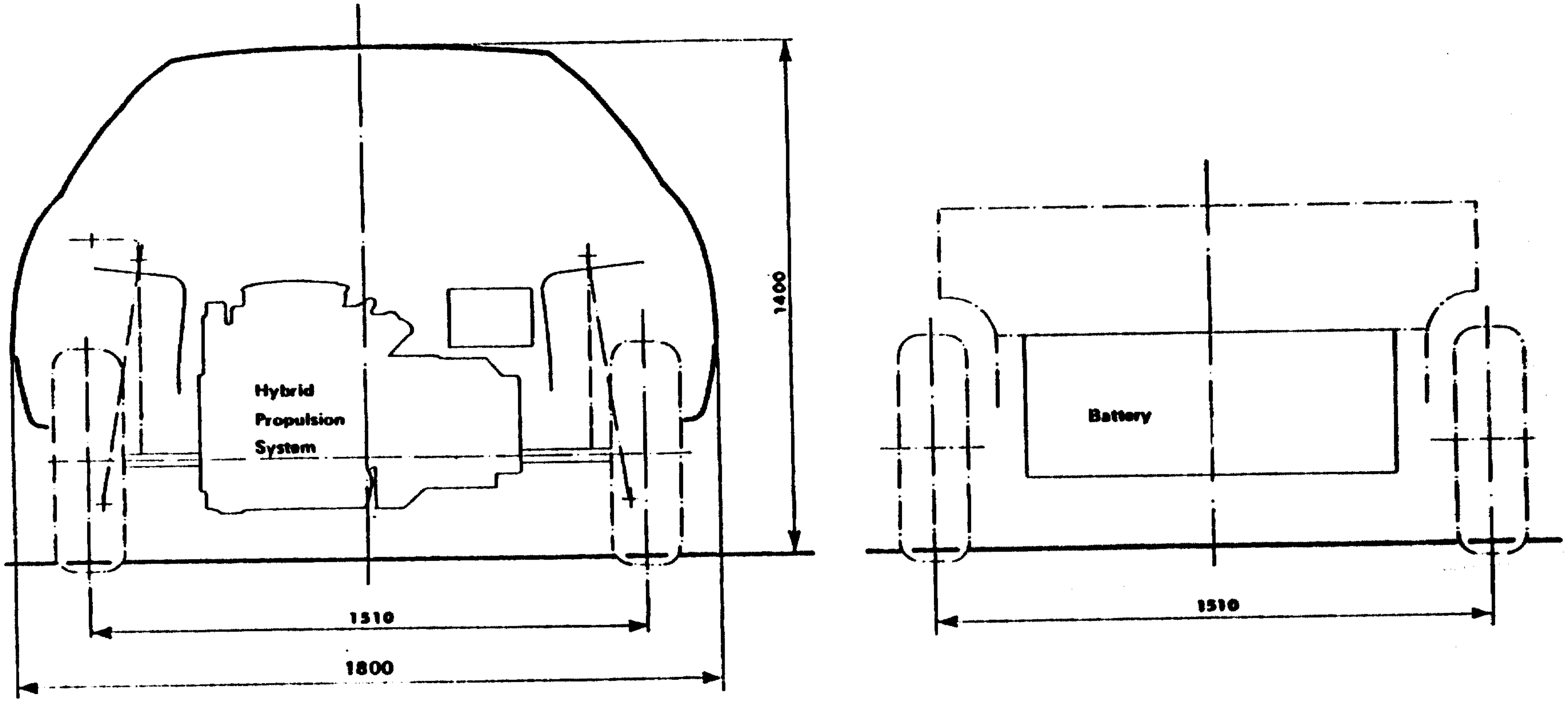

FIG. 5.1-3 — HYBRID VEHICLE — BASIC SCHEME

FRONT/REAR VIEW

around visibility. The fuel tank is in a protected position under the rear seat.

The rear independent wheel suspensions use torsion bar longitudinal trailing arms to allow the most convenient battery fitting between the wheels keeping the trunk floor at a surprisingly low level.

Exhaust emissions are kept within required limit tolerances by means of a simple three-way catalytic converter thanks to the engine low displacement.

It can be obseved that, without varying the general body structure, the rear end compartment was studied to allow the fitting of either type of battery being evaluated. Should the hybrid vehicle use a Na-S type battery (Figures 5.1-4 /5.1-6) the required sealed and thermally insulated container would be conveniently integrated within the body structure. The Lead-Acid battery (made of twelve elements) can be held in place using a simple cage frame as shown on Figures 5.1-7/5.1-9. Due to the smaller battery dimensions, the rear track can be reduced to 1,450 mm.

The above Figures 5.1-4/5.1-9 also show in greater layout detail the various components, which have been described, above.

The vehicle weights breakdown is as follows:

	Na-S	Lead-Acid
– Internal combustion engine, kg	128	
– Chassis and auxiliary electric system, kg	335	
– Body/frame, kg	602	
– Transmission, kg	65	
– Electric propulsion system, kg	150	140
– Traction battery, kg	300	
Total weight, kg	1580	1570

It can be observed that in spite of the extra weight of the battery the total weight figure is quite acceptable.

The body design approach (use of SMC type plastic panels on a special HSLA type steel frame structure) has significantly contributed to such a result.

The curb weight distribution on the two axles is a follows (heavier solution, Na-S battery):

front axle load	865	kg
rear axle load	715	kg

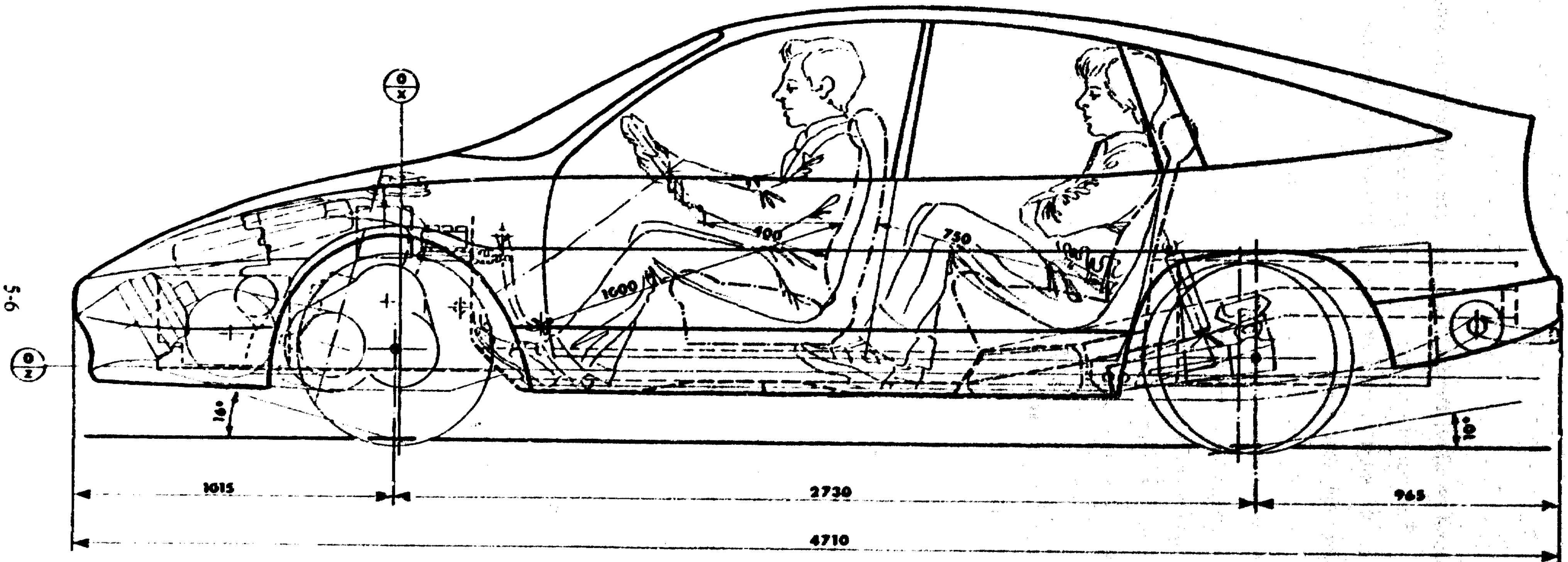

FIG. 5.1-4 — HYBRID VEHICLE, SODIUM-SULPHUR BATTERY VERSION

SIDE VIEW

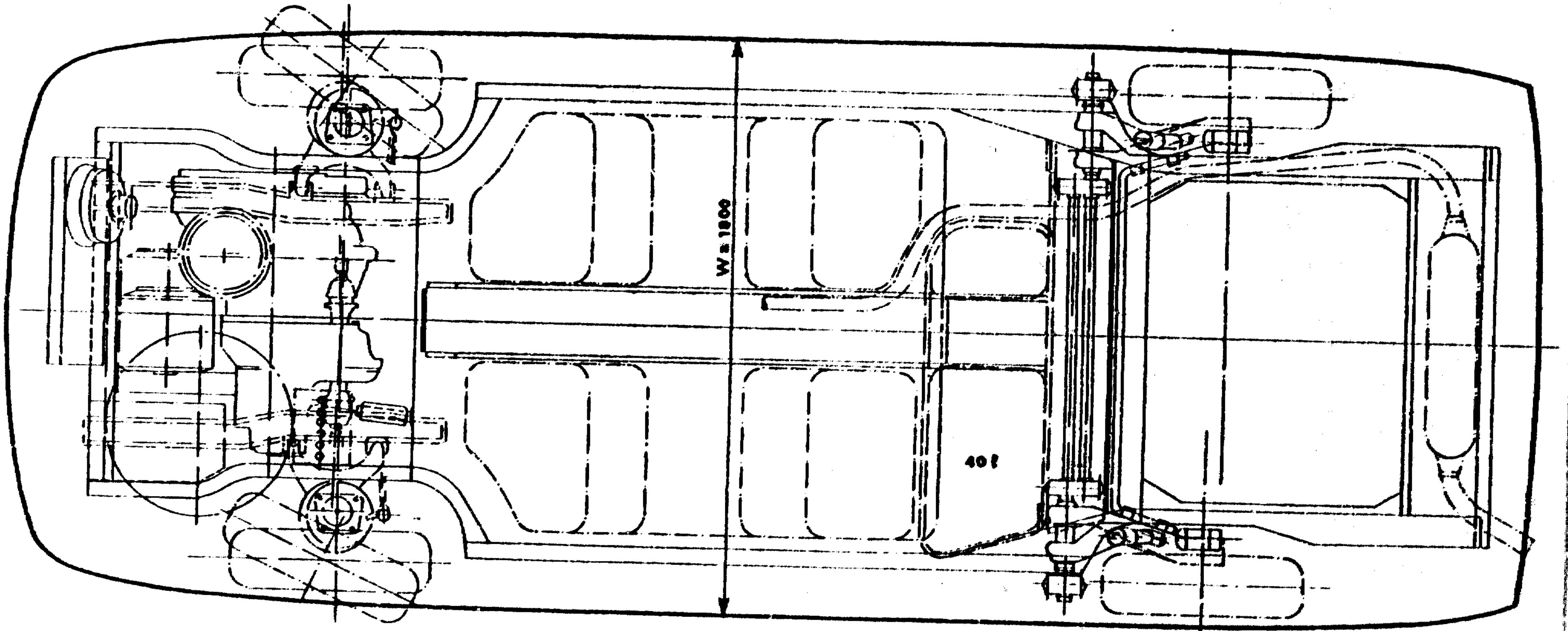

FIG. 5.1-5 – HYBRID VEHICLE, SODIUM-SULPHUR BATTERY VERSION

TOP VIEW

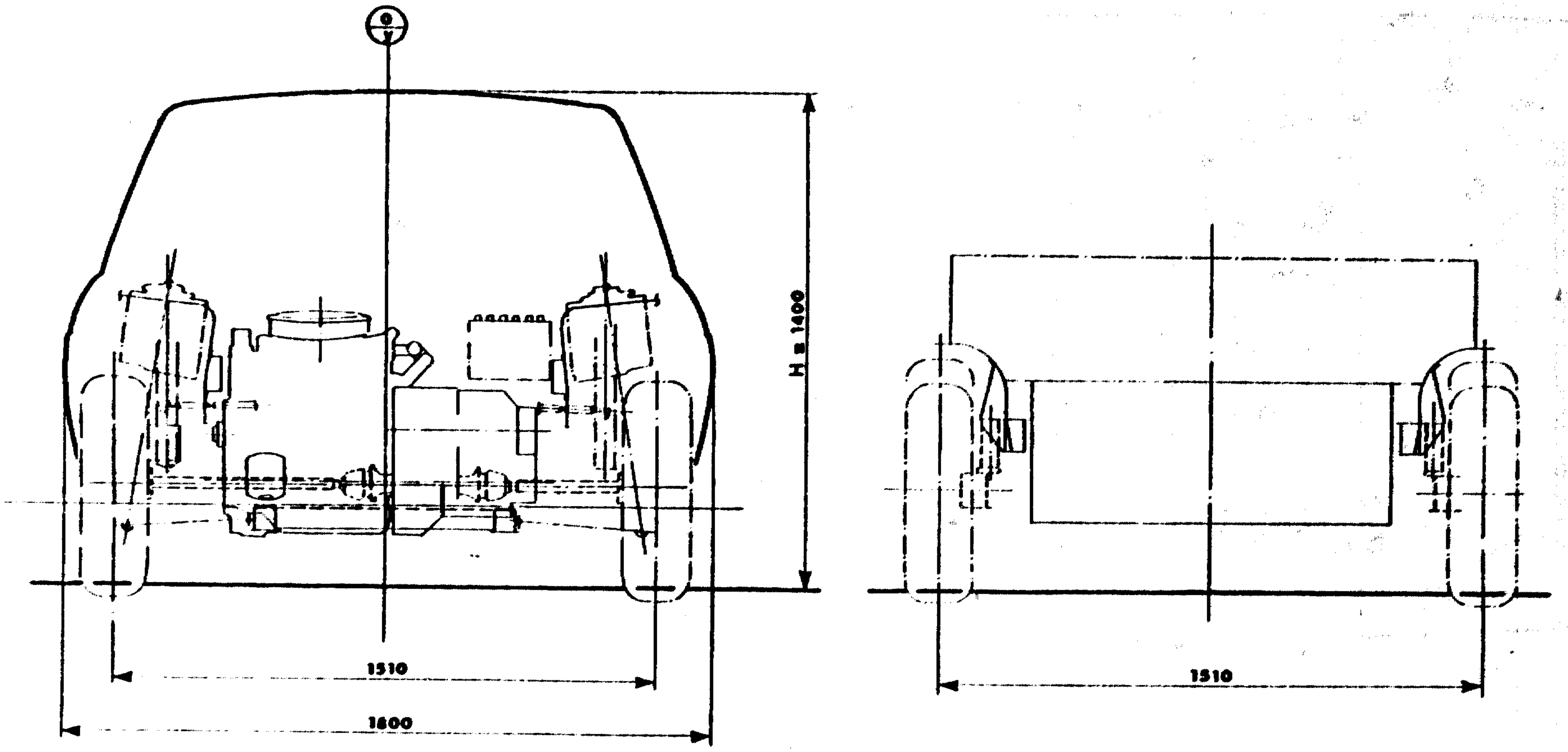

FIG. 5.1-6 — HYBRID VEHICLE, SODIUM-SULPHUR BATTERY VERSION

FRONT/REAR VIEW

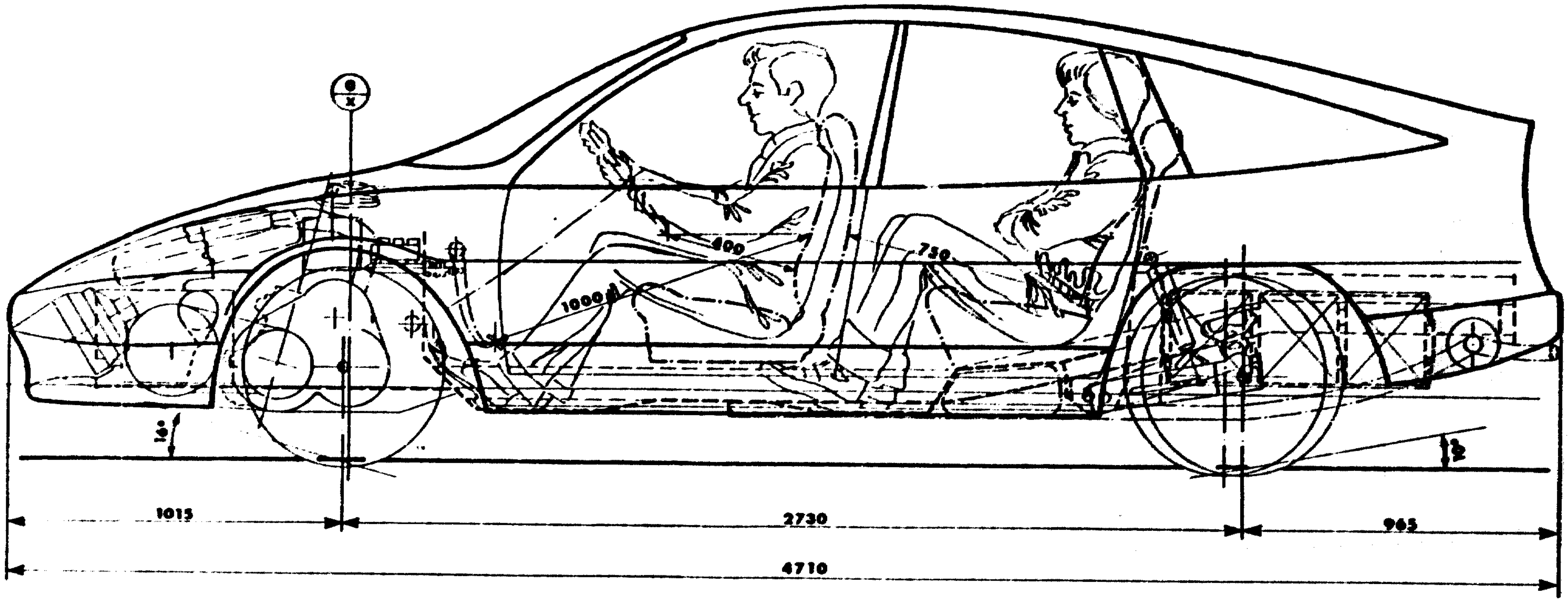

FIG. 5,1-7 – HYBRID VEHICLE, LEAD-ACID BATTERY VERSION

SIDE VIEW

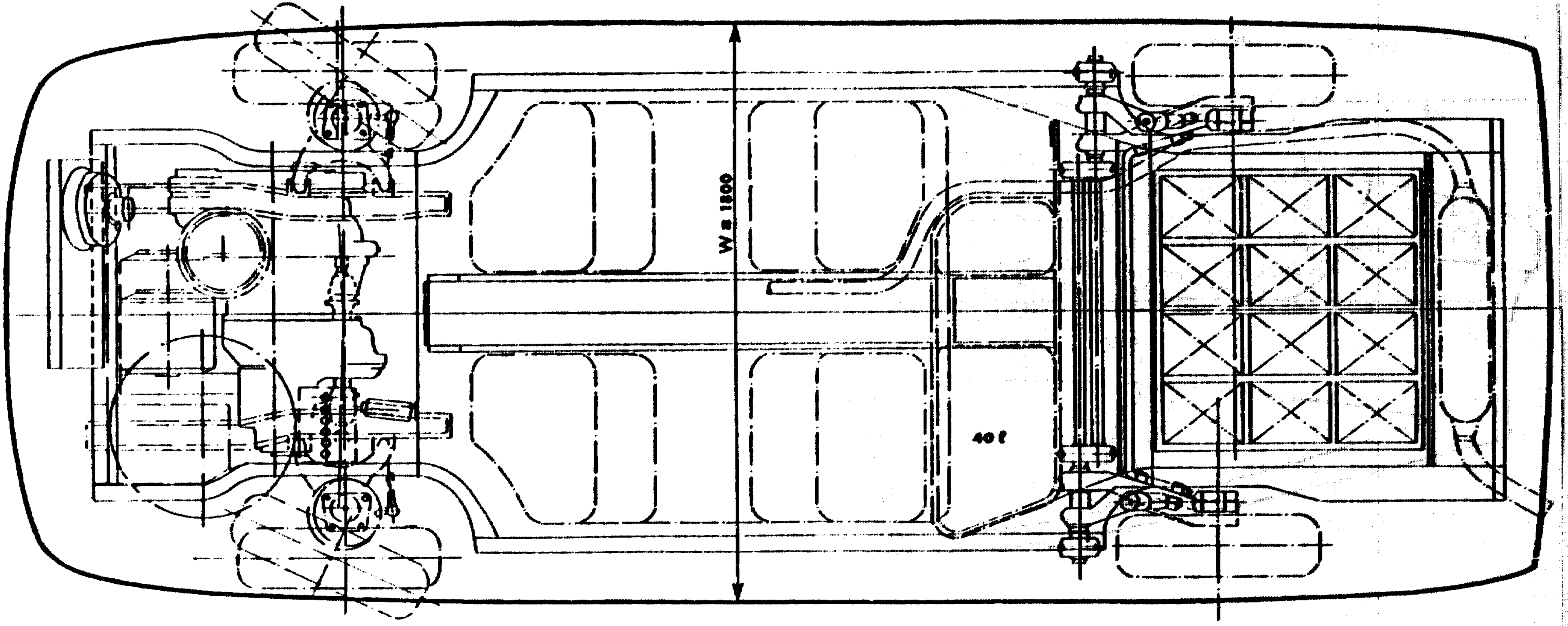

FIG. 5.1-8 — HYBRID VEHICLE, LEAD-ACID BATTERY VERSION

TOP VIEW

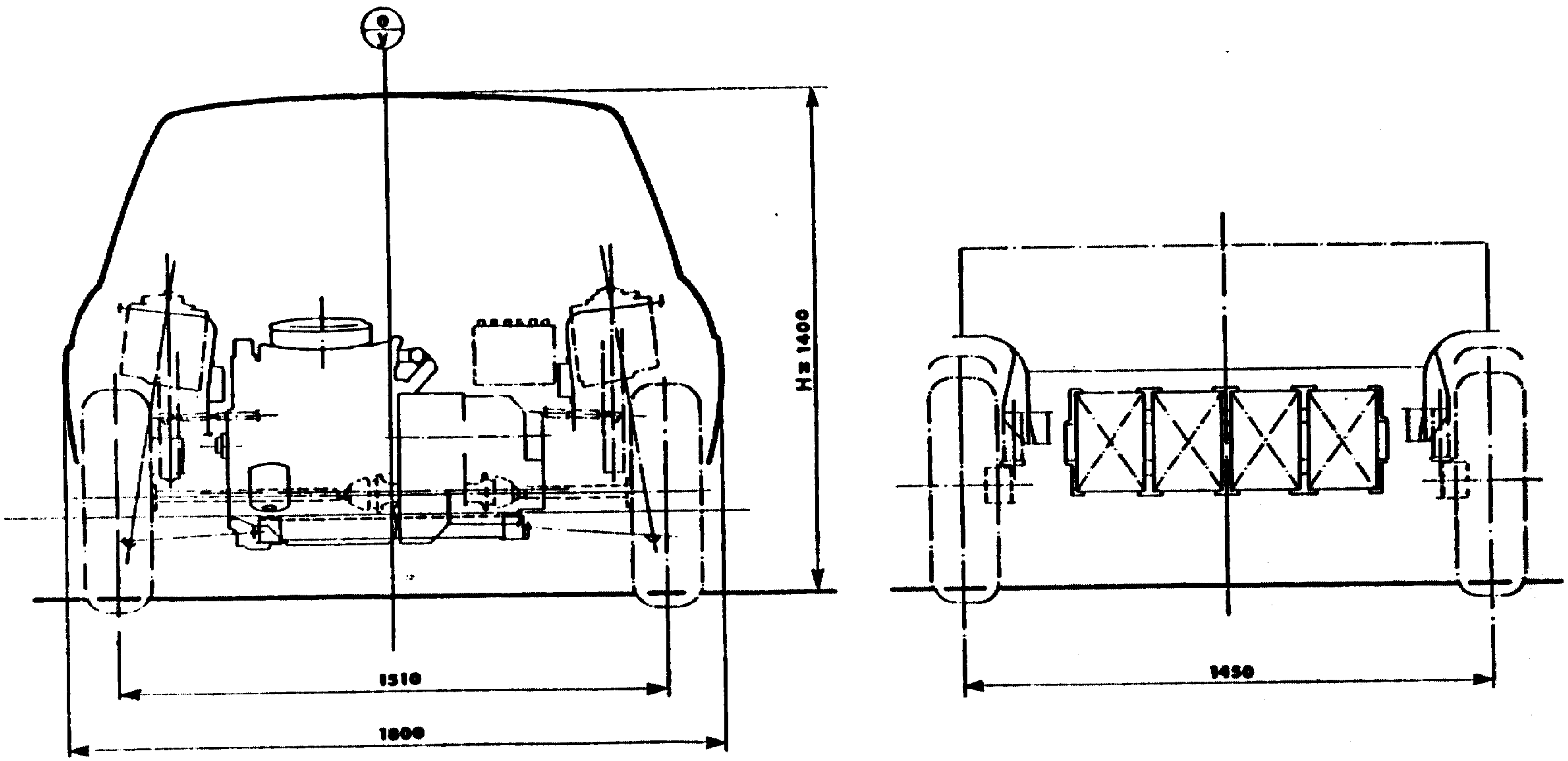

FIG. 5.1-9 – HYBRID VEHICLE, LEAD-ACID BATTERY VERSION

FRONT/REAR VIEW

5.2 CONCEPTUAL DESIGN DESCRIPTION

In the previous subsection the proposed Hybrid Vehicle characteristics have been addressed from the users' point of view which are related to its function of carrying a passenger and cargo payload on the assigned mission. This subsection deals with "under the hood" vehicle engineering aspects that are related to the vehicle interactions with the driver and the environment and to the interrelationship among the various subsystems and components. Tentative design specifications, at the component level are presented in Subsection 5.2.2.

5.2.1 Basic Vehicle Block Diagram

A basic system block diagram of the hybrid vehicle is shown on Figure 5.2-1. It synthesizes the vehicle conceptual design characteristics which will be analyzed with some detail in the following subsection 5.2.2.

The vehicle black-box is shown as a system which upon supply from external power sources (electric energy and fuel) or consumables (water, lubricants etc.) uses or opposes the environment (ambient air, road friction, earth gravity) to carry around a given payload. In the process the system mainly performs heat and fluids/particulates exchanges with the environment while acting as a noise source.

The power sources provide traction power to the drive wheels through the transmission which is the final element of the hybrid propulsion system including the thermal engine with its sensors and actuators on the one side and the electric motor/generator with its sensors on the other side. While the engine provides the usual conversion from fuel chemical energy to mechanical energy (plus heat, emissions and noise, partly recuperated or filtered out through heat exchangers and a catalytic muffler/converter), the electric power is supplied to the motor from the traction battery via the power conditioner. The battery energy is restored either through the charger (on-board or off-board) or through the motor (acting as a generator) and the reversible Power conditioner which, during the vehicle decelerations,recuperates,via the transmission, the excess vehicle kinetic energy thanks to the wheels/road pavement friction.

In case an advanced high-temperature battery is used, the battery heat exchange assumes a paramount relevance as it must be extremely limited during stand-by conditions (to prevent fast battery cool-down) and very active during the vehicle accelerations when heavy currents are drained from the battery resulting in significant

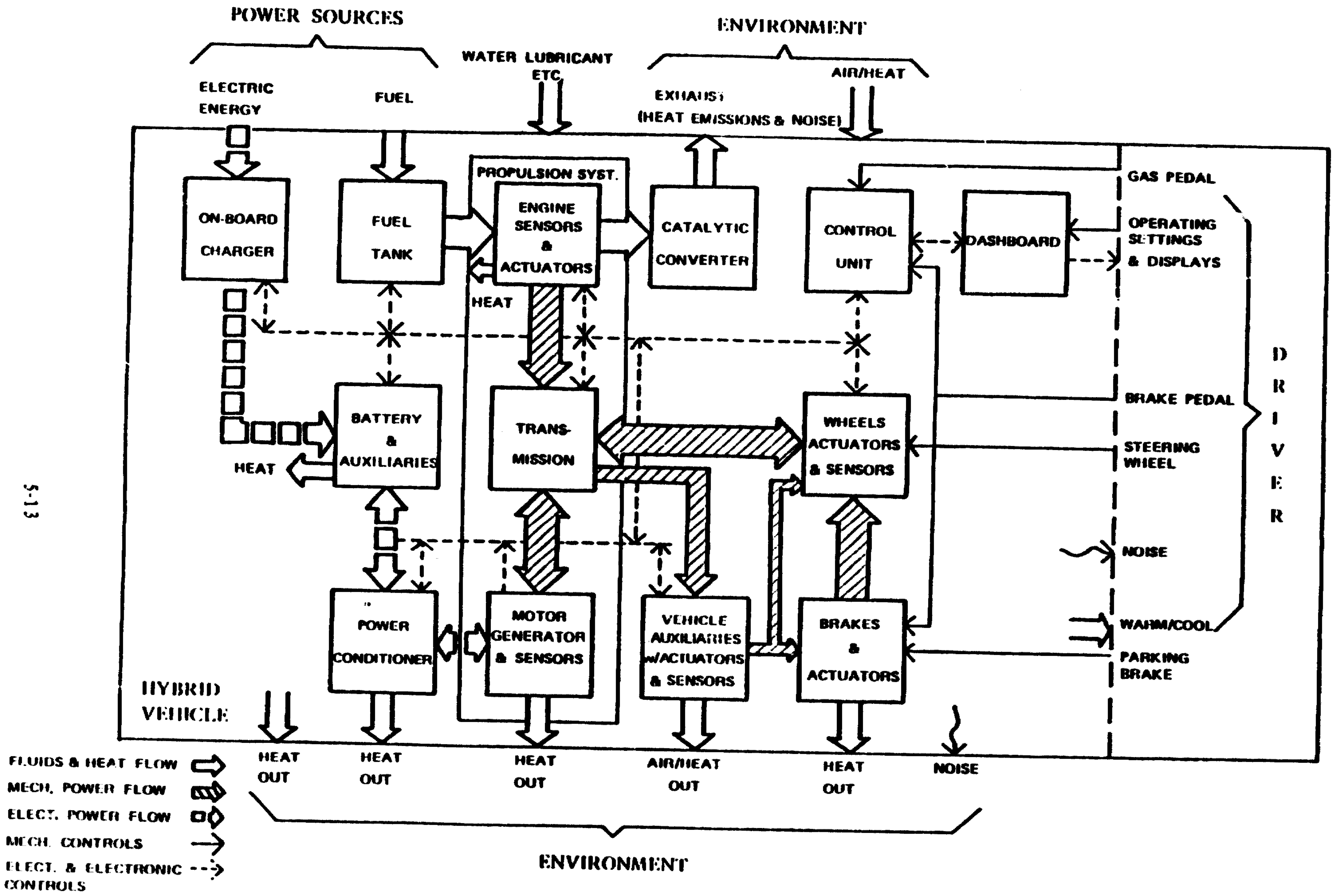

FIG. 5.2-1 - SYSTEM BLOCK DIAGRAM OF HYBRID VEHICLE

heat dissipation due to its internal resistance. This function shall be independently taken care of by means of the battery auxiliaries.

In addition to the regenerative braking action previously addressed, conventional brakes are also used to decelerate and bring the vehicle to a complete stop. While regenerative braking would mostly apply to downhill speed limiting or smooth vehicle slow downs at higher speeds,the conventional brakes action shall take care of the vehicle stops or slow speed slowdowns and of all the emergency situations.

Wheel braking as well as steering operation require appropriate power assist which is provided by equipment included in the vehicle auxiliaries together with the air conditioning heating and ventilation systems. It is expected that all the auxiliaries should operate in a hybrid mode and therefore the required auxiliary power should be obtained from the transmission output rather than from the engine or the battery themselves.

The final aspect of vehicle operation yet to be analyzed is the driver-vehicle interface. In addition to the conventional commands and controls, its expected that the hybrid vehicle, designed for use in the mid 80's by an energy-concerned drivers population, should grasp any advantage made available by state-of-the art technology. It has been therefore assumed that driver-vehicle interactions will play a major role in providing the optimum performance/cost combination.

The control unit will therefore supervise and direct most of the vehicle operation on the basis of optimized control strategies and properly interface the driver through a dashboard handling the various operating settings and display functions to acknowledge the driver's instructions and inform or warn him or her on the vehicle operating status in a simple and straightforward manner.

5.2.2 Vehicle Components and Characteristics

As a result of the Trade-off data review made to compare the interim results provided by the various alternatives, the configuration with Continuously Variable Ratio Transmission of engine power only was selected for the Hybrid Vehicle Propulsion System to be optimized during the Preliminary Design Task.

The various components characteristics used to define the conceptual design are presented here: both design parameter values which would result from the use of either battery(1) are shown where appropriate.

5.2.2.1 Internal Combustion Engine

A single engine type would be used for either solution. The main characteristics are:

- Four in-line cylinders
- Displacement 1.1-1.3 l
- Power rating 37 kW at 5,500 r.p.m.
- Max Torque 7.6 kgm at 4,000 r.p.m.
- Weight 128 kg
- Compression Ratio 8.9:1

5.2.2.2 Electric Motor/Generator(2)

Both solutions use a DC motor with separate excitation with different characteristics as follows:

	Na-S	Lead-Acid
– Nominal voltage (V)	144	
– Max field current (@ Nom. Voltage) (A)	3.7	
– RPM @ Nominal Power	2,500	5,000
– Nominal Power (kW)	20	

---

(1) During the Preliminary Design other advanced type batteries will be evaluated in addition to the two types considered during the Trade-off Studies. Preliminary Information on Na-S and Lead-Acid Batteries is provided in Appendix A.3-3.

(2) See Ref. [21], Subsection 1.2

	Na-S	Lead-Acid
– Peak power (kW)	40	
– Weight (kg)	90	85
– Dimensions (mm)	Ø 300x430	Ø 290x430

5.2.2.3 Traction Battery

The Sodium-Sulphur and Lead-Acid batteries mainly differ in terms of power, capacity, efficiency, operating temperature and initial cost. Their main characteristics(1) are:

	Na-S	Lead-Acid
– Nominal voltage (V)	144-72	144-110
– Capacity (Ah)	315	100
– Operating Discharge Limit	60%	50%
– Max Discharge Current (A)	450	250
– Specific Energy $(\frac{Wh}{kg})$	100	40
– Max Power		
at full charge (kW)	32	31
at end of operating discharge (kW)	32	27
– Number of elements	432	12
– Weight (kg)	300	300
– Dimensions (mm)	794 x 976 x 400	775 x 830 x 300
– Operating Temperature (°C)	300-350°C	Ambient Temperature

---

(1) A more detailed analysis of the batteries' characteristics is provided in Appendix A 3-3.

5.2.2.4 Power Conditioner

The main characteristics are:

	Na-S	Lead-Acid
Type	Double chopper	Double chopper
Max output current (A)	450	250
Weight (kg)	50	50
Size (mm)	400 x 250 x 300	400 x 280 x 300

5.2.2.5 On board battery charger

The main characteristics are:

	Na-S	Lead-Acid
Type	Constant current	Constant current
Input voltage (V)	120	120
Input current (A)	30	15
Output voltage (V)	144-180	144-190
Output current (A)	22	10

5.2.2.6 Transmission

The transmission is made of the components listed below mounted in this order and with the following main characteristics:

a) Lock-up Torque Converter:
External diameter (in) $8''{}^{1}/_{2}$
Transmission ratio: $\tau_T = 1 - 2,1$
The lock-up clutch operates at $(RPM)_{out}/(RPM)_{in}$ above $\nu_{min} = 0.86$

b) Continuously Variable Ratio Transmission (CVRT)

Transmission ratio $\tau_c =$ 0.5 – 2.0

Belt pulley drive

Max Torque (kgm) $\cong$ 12

c) Fixed ratio gears

	Na-S	Lead-Acid
$\tau_e =$	1.0	0.7

d) Differential gears

	Na-S	Lead-Acid
Ratio: $\tau_p =$	5.0	8.0

e) Overall ratio:

	Na-S	Lead-Acid
$\tau_o = \tau_c \cdot \tau_e \cdot \tau_p$	2.5 - 1.0	2.8 - 11.2

5.2.2.7 Brakes

Self-adjusting Power Disc (on the 4 wheels). Dual independent hydraulic system.

Regenerative braking by means of the electric system, in addition to the fuel economy improvements, significantly reduces conventional brakes wear.

Motor/generator inertia significantly contributes to prevent wheels lock-up under skidding conditions.

5.2.2.8 Tires

Advanced low-rolling resistance tires are used to improve the vehicle fuel economy without compromising on vehicle handling and safety.

The main characteristics are:

Type	Tubeless Steel-belted Radials	
Max Working Load (kg)	500	
Outer Diameter (mm)	625	
Inner (wheel) Diameter (mm)	406	(16")
Width (mm)	165	
Deflection (mm)	25.5	
Inflating Pressure (kg /cm^2)	2.2	(31.3 psi)
Weight (kg)	7.0	
Rolling Resistance Coefficient (K_n)	0.45	

5.2.2.9 Steering

Type	Rack and Pinion Power
Turning circle Diameter, (m)	11.25

5.2.2.10 Handling

The four independent suspensions and the well balanced weight distribution provide excellent stability with respect to conventional front wheel drive vehicles.

The electric motor provides quiet, smooth and quick responsive accelerations.

5.2.2.11 Noise and Vibration

Reduced engine power associated with optimized operating conditions provides unusually comfortable driving especially on accelerations which are mostly made on electric power.

5.2.2.12 Safety

The Vehicle design complies with all the expected 1985 U.S. Safety Regulations

Specific attention has been paid to the adequate fitting of the traction battery in the rear end compartment and to passenger compartment integrity under various crash conditions:

5.2.2.13 Reliability

- Notwithstanding the higher number of components than in a conventional vehicle, the hybrid vehicle provides the user with lower chances of breakdowns because of the two independent power systems.
- Optimized operating conditions significantly extend the engine life .
- Non-alternative electric motor operation minimize the fatigue effects of vibrations (particularly on accelerations and stop-and-go driving).
- Pure electric driving capability eliminates engine wear on traffic tied-ups.

5.2.2.14 Availability and Maintainability

The microprocessor based control system, while essential in satisfying all the vehicle operating requirements, provides a valuable tool in performing on-line diagnostic of various vehicle performance parameters, thus preventing some breakdown conditions and simplifying many failure identifications in addition to conventional testing procedures.

Ease of access to the traction battery is provided for either check-up or maintenance/replacement operations.

5.2.2.15 Control Unit and Panel Dashboard

The characteristics of these two systems will be analysed during the Preliminary Design Task only.

5.3. VEHICLE PERFORMANCE QUANTIFICATION

A summary of the Vehicle Performance parameters quantification is presented on Tables 5.3-1a and 5.3-1b.

The JPL Minimum Requirements and the Performance Specifications obtained from the "Mission Analysis and Performance Specification Studies" are listed for reference, where available, on the first two columns.

The Vehicle Characteristics, as shown on the third and fourth columns correspond to the two battery solutions evaluated in connection with Configuration No. 3, which was selected at the end of the Trade-off Data Review.

Appropriate comments are shown, where applicable, on the fifth column to indicate whether the two solutions meet Minimum Requirements and / or Performance Specifications.

The only parameters which do not meet Minimum Requirements are the Emissions and the Consumer Costs.

For the Emissions, as explained in the previous Subsection 4.3., the values shown are referred to those calculated at the engine exhaust, since it was felt more appropriate to evaluate the actual engine emissions than to include a possible catalytic converter model and calculate the expected vehicle emissions. As previously pointed out, the resulting engine emission level can be easily brought within the required limits by simply using a 3-way catalytic converter.

For the Consumer Costs, the higher cost of a Sodium-Sulphur battery significantly affects the resulting Life Cycle Cost due to the fact that its high energy storage capability is apparently not particularly suited to the "average" vehicle used on the "average" general-purpose mission.

Since the NPTS data show that among the purchased used cars about 15% are only 1-year old and about another 15% are only 2-years old, an in-depth analysis of this specific sector of the passenger vehicle fleet, which should correspond, on mission M_3 to the range of highest annual travel, could identify a more appropriate market and useage segment to fully exploit the fuel economy potential of the Sodium-Sulphur battery. The average Life Cycle Cost situation could improve on the other hand due to the Sensitivity Analysis results considering the much higher than expected rate of increase of the gasoline price.

In the last two columns of the table 5.3.1a (besides the Comments column)% margins

TAB. 5.3 - 1a — QUANTIFICATION OF PERFORMANCE, PARAMETERS —

PARAMETER		MINIMUM REQUIREMENTS		PERFORMANCE SPECIFICATIONS (*)		VEHICLE CHARACTERISTICS				MEETS OR EXCEEDS		%MARGIN OVER M.R./P.S.		COMMENTS
						Na-S		Lead-Acid		M.R.	P.S.	Na-S	Lead-Acid	
SPEED		km/h		km/h		km/h		km/h						
CRUISE SPEED		90		105		136		136		YES	YES	51.1/29.5	51.1/29.5	
MAXIMUM SPEED		–		120		136		136		NA	YES	NA/13.3	NA/13.3	
ACCELERATION		s		s		s		s						
0 - 50 km/h		6		6		5.70		5.57		YES	YES	5.3	7.7	
0 - 90 km/h		15		15		14.57		14.40		YES	YES	3.0	4.2	
40 - 90 km/h		12		12		10.30		10.10		YES	YES	16.5	18.8	
GRADE		km●	km/h	km●	km/h	km●	km/h	km●	km/h					
3%	RANGE ●	1.0		8.0		UNLIMIT.(2)		UNLIMIT.(2)		YES	YES	UNLIMIT.(2)	UNLIMIT.(2)	
	SPEED		90		90		90		90	NA	NA	NA	NA	
	MAX SPEED	–		–		–	127	–	127	YES	YES	UNLIMIT.(2)	UNLIMIT.(2)	(2) PERFORMANCE SPECIFICATIONS MAY BE SATISFIED USING THERMAL POWER ONLY.
5%	RANGE ●	–		16.0		UNLIMIT.(2)		UNLIMIT.(2)						
	SPEED		–		72		72		72	NA	NA	NA	NA	
	MAX SPEED	–	–	–	–	–	124	–	111	YES	YES	UNDEFIN.	UNDEFIN.	
8%	RANGE ●	0.3		3.2		UNLIMIT.(2)		UNLIMIT.(2)						
	SPEED		50		56		56		56	NA	NA	NA	NA	
	MAX SPEED	–		–	–	–	101	–	94	YES	YES	UNDEFIN.	UNDEFIN.	
15%	RANGE ●	0 2		0.8		UNLIMIT.(2)		UNLIMIT.(2)						
	SPEED		25		25		25			NA	NA	NA	NA	
	MAX SPEED	–	–	–	–	–	66	–	66	NA	YES	NA 100	NA 125	
MAX GRADE %		–		20		40		45						

(*) AS SHOWN ON TABLE 5-3 OF THE "MISSION ANALYSIS AND PERFORMANCE SPECIFICATION STUDIES" REPORT - VOLUME 1 PAGE 5-15

NA = NOT APPLICABLE

TABLE 5.3-1b – QUANTIFICATION OF PERFORMANCE, PARAMETERS

PARAMETER		MINIMUM REQUIREMENTS	PERFORMANCE SPECIFICATIONS (*)	VEHICLE CHARACTERISTICS Na-S		VEHICLE CHARACTERISTICS Lead-Acid		MEETS OR EXCEEDS M.R.	MEETS OR EXCEEDS P.S.	IMPROVEMENT POTENTIAL Na-S	IMPROVEMENT POTENTIAL Lead-Acid	COMMENTS
CONSUMPTION				MPG	ml/kWh	MPG	ml/kWh					
SAE J227a(B)		NONE	NONE	28.2	–	27.9	–	NA		(+++)	(+++)	(1) AVERAGE ELECTRICITY ECONOMY ON CORRESPONDING PORTIONS OF DAILY CYCLE
FUDC				42.0	29.5	39.5	38.5(1)			(+++)	(+++)	
FHDC				57.4	23.8	51.4	25.5(1)			(+++)	(+++)	
DAILY CYCLE				51.9	25.2	47.3	28.2			(+++)	(+)	
NONREFUELED RANGE			km	km		km						(2) LIMITED BY EMPTY TANK (3) LIMITED BY DISCHARGED BATTERY (4) Na-S BATTERY ONLY
SAE J227a(B)		NONE	145	479(2)		473(2)		NA	YES	(+++)	(+)	
FUDC			190	713(2)		400(3)		NA	YES	(+++)	NONE	
FHDC			270	975(2)		266(3)		NA	YES (4)	(+++)	NONE	
EMISSIONS		gr/km	gr/km	gr/km		gr/km						(5) MIN. REQUIR. & SPECIFICAT. REFERRED TO VEHICLE EMISSIONS (6) VEHICLE CHARACTER. REFERRED TO ENGINE EMISSIONS ONLY
SAE J227a(B)	HC	NONE	NONE	1.66		1.65		NA		(+++)	(+++)	
	CO			20.60(6)		21.40(6)						
	NO_x			0.69		0.68						
FUDC	HC	<0.255	<0.255 (5) (**)	0.83		0.85		NO(6)		(+++)	(+++)	
	CO	<2.11	<2.11	9.80(6)		10.10(6)						
	NO_x	<0.621	<0.621	1.00		1.00						
FHDC	HC	NONE	NONE	0.33		0.34		NA		(+++)	(+++)	
	CO			4.40(6)		3.80(6)						
	NO_x			1.00		1.00						
CONSUMER COST			1978$ \$/km	1978$	\$/km	1978$	\$/km					
CONSUMER PURCHASE PRICE		competitive with ... (***)	9,500	12,024		10,089		NO(7)		NA	NA	(7) PERF. SPEC. MAX LIMIT EXCEEDED BY 26.6% (Na-S), 6.2% (Lead-Acid)
CONSUMER LIFE CYCLE COST		same as average ... (***)	0.158		0.178		0.160	NO(8)		(++)	NONE	(8) 12.7% (Na-S) 1.3% (Lead-Acid)

(*) AS SHOWN ON TABLE 5-3 OF THE "MISSION ANALYSIS AND PERFORMANCE SPECIFICATION STUDIES" REPORT - VOLUME 1, PAGE 5 - 15

(**) REVISED WITH RESPECT TO VEHICLE PERF. SPECS, LISTED AS PS ON THE ABOVE TABLE, TO COMPLY WITH MIN. REQUIREMENTS

(***) REFERENCE CONVENTIONAL ICE VEHICLE NA=NOT APPLICABLE (+) FAIR (++) GOOD (+++) EXCELLENT

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over the Minimum Requirements and the Performance Specifications are shown where applicable, to identify an absolute merit figure, as compared to the relative merit figure used in Subsection 4.4 to establish a ranking of the various alternatives.

The data shown confirm that, thanks to the better transmission ratio adjustments, the solution with Lead-Acid battery has better performance characteristics than the second one at the expense of a higher fuel consumption.

This is pointed out by means of the Improvement Potential assessments made on the corresponding column of Table 5.3-1b.

While both solutions have excellent improvement potentials (by means of better control strategies) in the standard cycles Fuel Economy, thanks to the corresponding very limited range, the fuel economy improvement on the daily cycle range is only "fair" for the Lead-Acid battery solution but remains "excellent" for the Sodium-Sulphur battery.

The difference in the improvement potential is even more dramatically emphasized analysing the situation for the Nonrefueled Range characteristics taking also into account that a higher improvement potential in the range itself can always be turned into a corresponding improvement in fuel economy.

This leads to the conclusion that, on the basis of the considerations made above on the Life Cycle Costs, a good improvement potential should exist, on this parameter too, for the solution with Sodium-Sulphur battery even without taking into account all the peculiar characteristics of a hybrid vehicle which should ultimately provide it with longer operating life than the equivalent conventional vehicles.