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ABSTRACT

The objective of this paper is to develop a generalized loss management model to account for the usage of thermodynamic work potential in vehicles of any type. The key to accomplishing this is creation of a differential representation for vehicle loss as a function of operating condition. This differential model is then integrated through time to obtain an analytical estimate for total usage (and loss) of work potential consumed by each loss mechanism present during vehicle operation. The end result of this analysis is a better understanding of how the work potential initially present in the fuel, batteries, etc. is partitioned amongst all losses relevant to the vehicle's operation. The loss partitioning estimated from this loss management model can be used in conjunction with cost accounting systems to gain a better understanding of underlying drivers on vehicle manufacturing and operating costs. In addition, loss management models are useful for evaluation of technology models during the preliminary phases of design because they provide a common basis to measure the impact of disparate technologies.

INTRODUCTION

Economic cost is becoming an increasingly important consideration in the design, manufacture, and operation of vehicles of every type, class, function, and means of locomotion, due to the ever-present need to accomplish more with limited resources in a competitive environment. It should be obvious to even the pedestrian observer that the economic cost of building and operating a vehicle is strongly linked to the efficiency (or losses) inherent to operating the vehicle and its constituent components. This is due to several reasons: first, losses imply that a larger vehicle is needed to accomplish a given task, resulting in increased acquisition and operations costs. Second, inefficiency and loss imply increased operating cost through needless consumption of resources. Third, the previous two factors contribute to further indirect cost via environmental pollution. The confluence of these factors is a clear and present impetus that is driving vehicle manufacturers and operators to minimize the losses inherent to their products, within constraints dictated by operations in a competitive business environment.

From a purely thermodynamic standpoint, the job of the designer is to minimize losses in thermodynamic work potential incurred by the vehicle in performing its function (or mission). Typically, this means balancing the near-term cost of developing more efficient designs against the longer-term benefits garnered by reduced operating costs for the more efficient machine. A key tool used in finding the optimal balance between acquisition and operating cost is *cost accounting*, which is fundamentally nothing more than a bookkeeping scheme for tracking each individual contributor to cost. The end product of this process is cost accountability whereby responsibility for each incremental cost can be assigned to the appropriate source and tracked so that its impact on the total system is known. Cost accounting is an integral part of modern business practice, and it would be inconceivable today to attempt the construction and operation of a complex vehicle without having a detailed cost accounting system in place.

Since loss is strongly linked to cost, it follows that a necessary step in the construction of accurate cost accounting models is construction of some form of loss accounting model. However, no accurate means for *loss accounting* in vehicle design currently exists. Modern mission analysis models can estimate total loss (usually in the form of fuel consumption) with a relatively high degree of accuracy, but it is seldom possible to directly discern individual contributions to loss using these models. The best that can be done with state-of-the-art design methods today is to estimate the aggregate sum of all sources of loss. This is a fundamental shortcoming in the way vehicles are analyzed today, and is a primary motivation behind the work presented here.

A further motivation for development of vehicle loss management models is their ability to aid in understanding how specific concepts and technologies compare relative to one another. This is a subject of particular interest in preliminary design where it is common to evaluate a suite of technology concepts in a single advanced design. However, it can be difficult to ascertain the contribution of any individual technology to changes in overall system performance. Loss management models provide a means of explicitly evaluating the impact of each individual technology as well as their interactions by quantifying everything in terms of loss in thermodynamic work potential.

The objective of this work is to describe the basic architecture that will enable a detailed accounting of all sources of loss in work potential and also enable each individual source of loss to be quantified in terms of cost. This is a capability that does not currently exist, but is one that should go hand-in-hand with modern cost accounting systems. An accurate account of total loss facilitates accurate accounting of the contributors to direct operating costs.

The focus of this discussion will be confined to thermodynamic loss only, which is introduced in the context of a vehicle *loss management model*. A loss management model is defined here as a comprehensive, system-wide vehicle thermodynamic model that accounts for usage of work potential amongst all vehicle systems and processes. The basic motivation underlying the development of vehicle loss management models is the notion that, at the most fundamental level, the objectives of all vehicle designers is basically the same: to minimize the economic cost required to provide the service that their vehicle is designed to produce.

This paper will explain the theoretical basis for development of vehicle loss management models, with the initial focus being on development of the general model for vehicle loss accounting. The basic ideas will be developed in the most general form possible such that the results will be applicable to any form of automotive motion such as ships, cars, airplanes, rockets, submarines, etc. This model is then used as the centerpiece for a step-by-step development of a generalized loss management methodology applicable to any automotive system. Each step in the analysis process is explained in detail, and is demonstrated on the analysis of a lightweight fighter aircraft.

BACKGROUND

The foundation upon which the idea of vehicle loss management models is principally derived comes from two fields: exergy analysis (and derivatives thereof) and thermoeconomics. The primary body of work in the area of establishing accountability for loss in work potential is exergy (or availability) analysis. The focus of this field is to estimate the maximum work theoretically obtainable from a substance in a given environment. The principle measure of work potential is exergy, which is a thermodynamic quantity defined as:

$$Ex \equiv H - H_{amb} - T_{amb}\left(S - S_{amb}\right) + \left(\text{Additional Terms}\right) \quad (1)$$

where Ex is total exergy (work potential), H denotes total enthalpy, S is total entropy, T is temperature, and subscript “amb” denotes ambient conditions. The “additional terms” are used to denote exergy due to kinetic energy, potential energy, chemical potential, radiation, heat transfer, etc.[11] In addition to exergy, there are other loss figures of merit (FoMs) that are useful for vehicle analysis. Nichols[2] demonstrated the utility of “gas horsepower” as a measure of thermodynamic work potential in gas turbine combustors. Later, Curran and Craig[3] suggested the use of stream thrust as a measure of loss for jet-propulsive devices (which also includes propeller-driven applications). This work was further extended by Riggins, [4] who developed the concept of thrust work potential as a loss figure of merit. These various work potential figures of merit were later compared by Roth and Mavris, [5,6] with the conclusion that each is a valid thermodynamic figure of merit, the differences between each FoM being primarily in their definition of useful work potential. In addition, Bejan[7] recently considered the application of exergy analysis to aerospace vehicle design applications in which he applies exergy concepts to derive optimality laws for use of exergetic work potential in aircraft. Finally, it should be noted that many of the ideas discussed herein are treated with greater depth of detail by Roth (Ref.8).

In addition to exergy analysis, there is a very active and growing body of work that is closely related to exergy analysis. This field is known as thermoeconomics, defined by Bejan, Tsatsoronis, and Moran[9] as:

> *…the branch of engineering that combines exergy analysis and economic principles to provide the system designer or operator with information not available through conventional energy analysis and economic evaluations, but crucial to the design and operation of a cost-effective system. We can consider thermoeconomics as an exergy-aided cost minimization.*

The present discussion will borrow principles developed from thermoeconomics and apply them to the present problem, where applicable. However, the bulk of the work in thermoeconomics is focused on development of models appropriate for stationary power generation applications. Thus, the basic ideas developed for stationary power generation purposes will require modification in order to be suitable for the problems and idiosyncrasies specific to vehicle design. In this regard, the present work can be viewed as an extension of thermoeconomic principles to general vehicle design.

There are two primary differences between loss management models proposed herein and the more established thermodynamic loss estimation methods

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1. * The authors will assume henceforth that the reader has some degree of familiarity with the fundamentals of exergy analysis. Lacking this, the reader is referred to the excellent discussion on the fundamentals and applications of exergy methods given by Bejan in reference 1

used today: 1) the majority of current research is geared towards loss analysis at a single operating point, and 2) the reference condition for the dead state used in vehicular applications must be allowed to "float." The first point can be explained as follows: since stationary power generation equipment is typically operated at a single condition for long periods of time, their thermodynamic performance can usually be characterized by conducting a loss analysis on that single, steady-state operating condition. Thus, estimation of total loss is merely a matter of multiplying the loss rate by the time of operation. However, most vehicles are required to operate over a wide variety of conditions and throttle settings when performing their function. Thus, one must have knowledge of the instantaneous machine loss at every operating condition experienced during a nominal duty cycle[1] of the vehicle, and this instantaneous loss must be integrated over the entire duty cycle in order to obtain cumulative loss induced by each loss mechanism.

The second point relates to the fact that most vehicles experience a wide variation in ambient operating conditions as compared to that of a typical stationary power generation unit. Consequently, the maximum thermodynamic work potential that is available from a given quantity of fuel during one portion of the duty cycle may not be the same at a later time, due to changes in the ambient or "dead state" conditions. Consequently, the definition reference conditions must change to match the instantaneous conditions surrounding the vehicle. [2]

Finally, there is an active body of research in the field of total airframe thermal management that is germane to the topic of this paper. An excellent example of an application that stands to benefit from the ideas developed in this work is discussed by Claeys et al.[10] In this paper, the authors investigate the benefits possible by integrating aircraft thermal management and auxiliary power generation systems. They identify sources of needless loss, and show that significant energy savings are possible through innovative design.

GENERALIZED VEHICLE LOSS MANAGEMENT MODEL

Since the objective of this paper is to define general loss accounting models that are applicable to any vehicle, it is intuitively obvious that one must start by contemplating those elements that all vehicles have in common. Every vehicle must have some provision for production of useful work to propel it through its environment, regardless of its means of locomotion or the medium through which it passes. Therefore, the logical point of departure in this discussion is the propulsion system. All propulsion systems function by transforming work potential of some form into useful physical work, usually through action on a fuel of some type. For any given engine and thermodynamic cycle of interest, it is intuitively obvious (and has been thermodynamically proven)[11,12] that the second law of thermodynamics places an upper bound on the maximum work that can be extracted from a fuel. Any deviation between the ideal engine power output and the actual engine power output constitutes a loss chargeable to the propulsion system. For most vehicles, the useful work produced by the engine is used to overcome various dissipative mechanisms specific to the vehicle itself. The work output that is not dissipated is stored in some form (kinetic energy of the vehicle, for example).

This idea is illustrated in Figure 1, which shows a diagrammatic representation of a very simple and general model for vehicle loss accounting. The origin of this figure corresponds to the ground state (or dead state) in which there is no potential to do work. The fuel work potential is shown at far left and initially has some finite potential to do work. It is then processed in the engine, at which point some of the work potential is dissipated while the remainder appears as useful work. A portion of this work output is in turn lost to dissipative mechanisms inherent to the vehicle itself, while the remainder is stored as some form of useful energy.

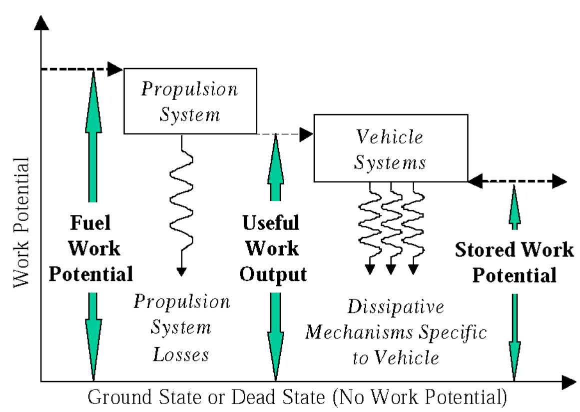

Figure 1. A Generalized Model of Work Potential Consumption for Vehicular Applications.

1. The term "duty cycle" is here implied to mean any period of vehicle operation that is of interest as being representative of the vehicle's function. For example, the duty cycle of an aircraft may be the design mission, that of an automobile may be some nominal mix of city/highway driving using a single tank of gas, etc.
2. For most applications, it is satisfactory to assume that the dead state is simply equal to local ambient static pressure and temperature. For high-speed applications such as hypersonic flight, the validity of this assumption may break down because even though the ambient static temperature may be quite low, the wetted surfaces of the vehicle do not experience this temperature due to frictional heating. Consequently, it is not possible for a heat engine to transfer heat into the environment at the local static temperature, because the minimum temperature in the "low temperature reservoir" can be no lower than some nominal surface recovery temperature. In this scenario, it may be more accurate to take the recovery temperature experienced at the surface to be the reference temperature. However, if the vehicle fuel served as the heat sink, it may be appropriate to take the instantaneous bulk fuel temperature as the dead state temperature. The correct approach is far from clear, and is a topic of current research.

Thus, this simple model postulates three basic “sinks” of work potential available to a typical vehicle: losses due to the propulsion system, losses specific to the vehicle and its systems, and work storage mechanisms. The relative importance of these three sinks will vary according to the vehicle’s function. For instance, vehicles designed for long range cruise (such as aircraft or ships) ultimately dissipate all of the fuel work potential into the atmosphere as heat, with little or none being stored as work potential of another form. Launch vehicles, on the other hand, store a great deal of the fuel work potential in the form of vehicle kinetic and potential energy at burnout. In an abstract sense, one can think of the propulsion system and entire vehicle as being nothing more than a transfer function that takes the work potential of the fuel into: 1) losses and 2) useful energy stored in other forms.

It is self-evident that the sum of propulsion system losses, vehicle-specific dissipative mechanisms, and work potential storage in the vehicle and its systems must be equal to the total work potential initially present in the storage reservoir (fuel tanks). Expressed Mathematically:

$$\begin{aligned}&(\text{Initial Work Potential}) = (\text{Propulsion System Losses}) + \\ &+ (\text{Vehicle Losses}) + (\text{Final Work Potential})\end{aligned} \quad (2)$$

Moreover, this rule must also hold for all times in between the start of the mission and any arbitrary intermediate time, t:

$$\begin{aligned}&(\text{Work Potential Consumed})\Big|_0^t = \int_0^t \sum_i \frac{(\text{Propulsive Loss})_i}{dt} dt + \\ &+ \int_0^t \sum_j \frac{(\text{Vehicle Losses})_j}{dt} dt + \int_0^t \sum_k \frac{(\text{Stored Potential})_k}{dt} dt\end{aligned} \quad (3)$$

where: t= Mission Time
i = Counting Index on the No. of Propulsive Losses
j = Index on the No. of Vehicle-Specific Losses
k = Index on the No. of Work Storage Mechanisms

This simple model is the basis for development of a generalized vehicle loss management model and analysis methodology presented in the next section. It should be pointed out that the division of losses into propulsive and vehicle-specific components is somewhat arbitrary in that there is no thermodynamic difference between the losses. In reality, there are many equally valid ways to partition losses, but the model presented in Figure 1 is the most convenient for practical vehicle analysis problems.

METHOD

The general methodology for construction of detailed loss management models is divided into four basic steps, as shown in the flowchart of Figure 2. In brief, step “0” in the construction of a loss management model is to explicitly define loss in a way most suited to the needs of the current analysis. It was previously mentioned that are a variety of ways to measure thermodynamic loss, and the choice of which to use depends on the situation at hand. When this is known and clearly understood, the first step is to explicitly identify all loss mechanisms that are significant to the operation of the vehicle. This is done with the assistance of a functional decomposition tool known as a relevance tree, and the ultimate outcome is a detailed listing of all sources of loss.

Next, a mathematical representation of each loss source is created in step two, which necessarily requires extensive information on propulsion system and vehicle systems performance. The result of steps 0-2 is a differential loss model that describes the instantaneous loss breakdown of the vehicle as a function of operating condition. The construction of an accurate and complete differential representation of loss is an essential feature that enables the creation of vehicle loss management models.

Step three is to integrate this differential loss model through time over a single vehicle mission or duty cycle to obtain total loss chargeable to each loss mechanism. Obviously, it is imperative to use a vehicle mission which is representative of the operation that the vehicle will actually experience in service. Finally, one must assign chargeability for each loss to its underlying source. The objective of step four is to allocate each loss to the factor(s) that drive it such that the true thermodynamic cost of each design decision can be understood.

STEP 0: DEFINE LOSS – This step may at first seem unnecessary and perhaps even trivial, but it is included here because it is important to have a clear understanding of what the “true meaning” of loss really is in any particular situation. In many instances, the definition of loss is not always what it appears to be. For instance, it is intuitively appealing to use loss in work potential as a metric of loss for vehicle analysis applications. However, as shown in references 4, 5, and 6, this is not as simple as it appears because there is more than one metric of work potential available, and the choice of which metric to use depends on the circumstances. This is because the definition of loss depends to some extent on the system under consideration as well as the objectives of the analyst. Consequently, what may constitute a chargeable loss in one book-keeping scheme is not necessarily so in another.

Loss can also be defined in ways other than reduction in ability to do work. For example, aircraft designers typically use vehicle mass as a de-facto loss figure of merit due to its strong influence on loss. Therefore, it may be useful in some situations to book-keep loss in terms of vehicle weight groups instead of partitioning loss in work potential. This has the additional advantage that mass is an intuitive and readily measurable quantity. Likewise, losses in high performance rockets such as space launch vehicles are strongly driven by mass, though the relative importance of work potential loss and storage mechanisms are fundamentally different than those encountered in aircraft.

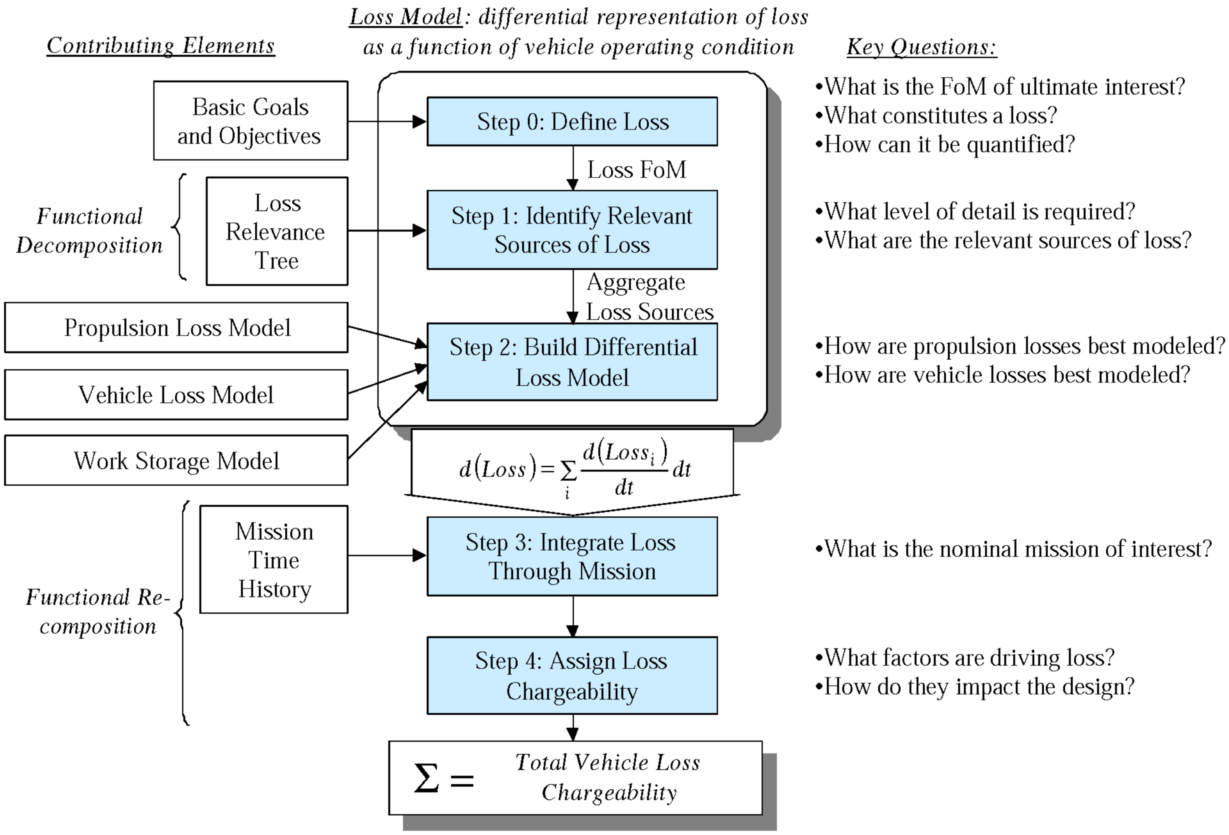

Figure 2. General Methodology for Construction of Loss Management Models.

On the other hand, the design of a seagoing vessel such as a ship or submarine is not as strongly driven by vehicle mass. This is because the drag due to lift for an aircraft changes as the square of the vehicle mass (induced drag), while fluid dynamic drag for a ship or submarine scales with wetted area and volume, which is roughly proportional to the cube root of vehicle mass. Mass is therefore a much less appealing figure of merit for naval systems. Instead, a work potential figure of merit such as exergy may be a more appropriate metric of loss for this class of vehicle.

Finally, one should always be aware that *the ultimate figure of merit for loss in any vehicle regardless of type or construction is cost*. Cost is a universal figure of merit in which virtually every aspect of a vehicle's design and operation can be quantified. It has the additional merit that it is an intuitive quantity with which everyone is familiar. Indeed, the development of the methods presented in this discussion will ultimately lead towards a means of converting the *chargeable losses* calculated using the advanced loss management methods developed herein into *chargeable cost*. This is truly the ultimate unification of vehicle design disciplines: a unified weight/performance/cost theory of modern design.

The thermodynamic loss figure of merit finally selected for a particular application is immaterial as far as the methods presented here are concerned. There are many loss figures of merit which are suitable for use with the loss management model developed herein. The only requirements are that the loss figure of merit be *comprehensive* and *consistent*. This first requirement implies that every loss relevant to the operation of the vehicle under consideration must be quantifiable in terms of that loss figure of merit, otherwise it will not be possible to construct a complete loss management model. The second requirement simply implies that the loss figure of merit must obey equations (2) and (3).

STEP 1: IDENTIFY ALL SOURCES OF LOSS – The first step in the construction of a loss management model is identification of all loss sources relevant to the problem at hand. The starting point for the identification process is the generalized loss model given in Figure 1, which partitions losses into three general "work sinks:" propulsion-chargeable loss, vehicle-chargeable loss, and alternate work storage mechanisms. Vehicle-chargeable loss can in turn be broken down into more specific classes of loss mechanism according to current analysis requirements.

A useful tool for assisting in the loss identification process is the loss relevance tree. This is nothing more than a formalized method to assist in decomposition of an item into its constituent parts. It is a brainstorming tool that uses a top-down decomposition approach, and in this case, the object of decomposition is total vehicle loss. The exact accounting scheme used is immaterial, as long as it is comprehensive and consistent. Once completed, the loss relevance tree makes an excellent starting point for construction of an analytical loss management model.

It must be understood from the outset what level of analytical detail is desired when executing this step in order to ensure that the loss management model is suitable to its intended purpose. For instance, it may be desirable to have only a gross notion of vehicle loss breakdown for preliminary design purposes, but the vehicle operator may want to understand the loss breakdown in very fine detail. These two models would necessarily be constructed from loss relevance trees having different levels of fidelity.

A general example of a loss relevance tree is shown in the bottom half of Figure 3, along with a listing of the most common loss mechanisms found in most vehicles. The top of this figure is a diagram depicting all sources of work potential that feed into the total vehicle work potential available for use. Note that this figure is intended to be a general guide rather than an exhaustive listing of items for consideration.

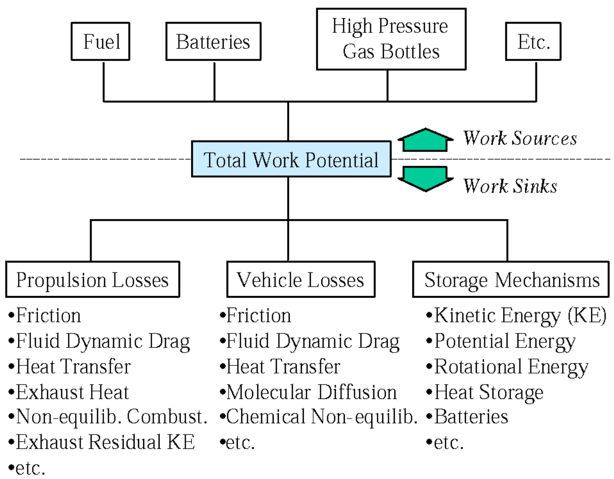

Figure 3. Typical Contributors Used in Loss Management Model Construction.

STEP 2: DEVELOP DIFFERENTIAL LOSS MANAGEMENT MODEL – The objective of this step is to develop a differential representation of total vehicle loss that can be integrated through time to yield the total loss due to each contributing mechanism. The differential loss model is necessarily a function of operating condition, which is usually described in terms of ambient temperature, pressure, velocity, and throttle setting. As mentioned previously, there are two broad sources of loss in a typical vehicle, the propulsion system and the other vehicle systems and subsystems. This section will discuss each of these separately.

For a typical heat engine, the first step in the analysis process is to apply the first law of thermodynamics to estimate overall performance of the propulsion system. This process is usually referred to as cycle analysis, and is today considered to be a well-developed field. In addition, cycle analysis yields detailed knowledge of the thermodynamic state at every station and operating condition. This knowledge can then be used to perform a second law analysis to determine thermodynamic work potential at every station in the engine and for every operating condition. Based on knowledge of work potential at every station, the loss due to the various components connecting the stations can be deduced, as demonstrated by Roth and Mavris for a High Speed Civil Transport Application.[13] The result of this analysis is a "loss deck," as shown in Figure 4. The loss deck is a component-wise breakdown of every propulsion system loss as a function of operating condition, and is somewhat analogous to the tabular "engine decks" commonly used to represent propulsion system performance in vehicle analysis today.

The analysis of vehicle-specific losses does not lend itself to generalizations and rigidly-defined methodologies as easily as the propulsion system due to the various and sundry nature of the loss mechanisms that can impact vehicle performance. The most common losses in most vehicles are dissipative losses such as mechanical friction and flow resistance. It is relatively easy to calculate losses due to mechanical friction effects, as the loss is simply given by the friction force multiplied by the distance through which it acts. Losses due to flow resistance, such as aerodynamic drag work, can be somewhat more complicated to estimate, but the fundamental principle is the same. Calculation of these losses merely requires the estimation of aerodynamic drag through conventional aerodynamic analysis methods, and then multiplication of the drag force by the distance through which it occurs.

Another significant source of loss in many vehicles is heat transfer through a finite temperature difference, as occurs in all practical heat transfer equipment. Typical examples include dissipation of waste heat due to vehicle systems, and heat exchangers used in various system processes. Calculation of loss due to heat transfer is also a well-developed topic, and is discussed in detail in references 1, and 14.

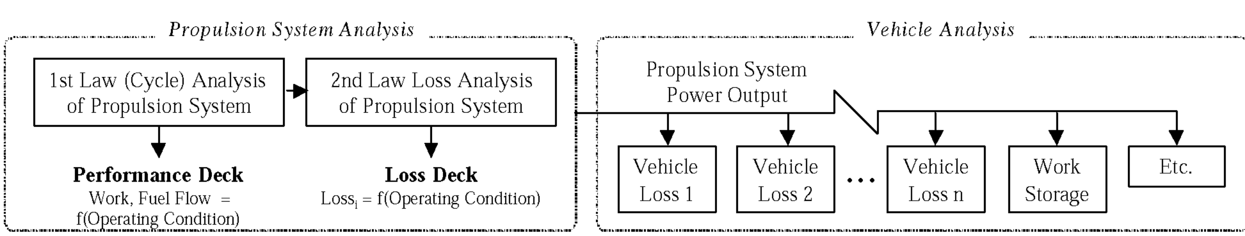

Figure 4. General Thermodynamic Loss Model for Vehicles Powered via Heat Engine.

This step, when used in conjunction with standard analysis models for engine and vehicle performance, yields a differential loss model which describes total vehicle loss in terms of vehicle operating condition. The differential loss model has the general form:

$$d(\text{Total Loss}) = \sum_i \frac{d(\text{Loss}_i)}{\text{dt}} dt \tag{4}$$

where Loss_i is the loss due to dissipative mechanism 'i' and is a function of vehicle operating condition.

STEP 3: INTEGRATE CHARGEABLE LOSS THROUGH MISSION – The differential loss model constructed in the previous steps can now be integrated through time using a prescribed mission time history to produce total loss chargeabilities for each contributor to vehicle loss. In effect, the results of this step describe the partitioning of work potential usage through the mission. The result of this process is an analytical description of the losses and useful work transfer occurring in each component of every vehicle system through the vehicle duty cycle.

It is typically necessary to numerically integrate the differential loss model through the mission, because the losses are usually highly nonlinear with respect to vehicle operating condition (particularly for the propulsion system). In addition, most vehicle missions are defined only in a piecewise continuous basis, with each mission leg representing a considerably different operating condition than the last. Consequently, the most convenient means of evaluating total loss is to generate a tabular listing of propulsion system losses as a function of operating condition (earlier referred to as a "loss deck") and a tabular listing of all vehicle loss and storage mechanisms as a function of operating condition. One can then use a table lookup routine to find the instantaneous loss due to each mechanism as a function of operating condition. If a discrete time history for the vehicle mission is known (as from vehicle mission analysis), then integration of total losses becomes nothing more than a matter of accumulating totals from a series of repeated table look-ups, one for each time step.

STEP 4: ASSIGN CHARGEABILITY – The notion of chargeable losses is a concept that is quite useful in defining a scheme for loss management models. The basic objective of chargeability is to allocate responsibility for losses to their underlying source. A loss is termed "chargeable" to a component or functional group if that component or group is the primary source driving the loss. In general, loss is most easily allocated by functional group because functional components are natural boundaries that are readily identifiable and intuitive. This greatly simplifies the job of tracking components of chargeable loss during later stages of the accounting process. In addition, many of the cost accounting schemes used today use a similar breakdown of cost chargeability and would thus be more amenable to incorporation of loss management models of similar design.

Definition of loss chargeability is an important step and one that can be very ambiguous from an engineering point of view. This is because loss chargeability depends on the circumstances, the breakdown used in the loss relevance tree, and the intent of the analyst. The most convenient starting point for definition of loss chargeability is usually the loss relevance tree created in step one. However, it may be necessary to further assign loss chargeability based on the needs of the problem, and the best guide in this process is typically the experience of the designer. As a rule, the focus should be on accounting for first-order effects, at least in the initial stages of model development. Second order effects can always be accounted for later if necessary. In addition, one must implicitly decide what level of detail is necessary in the assignment of loss chargeability.

For instance, in the design of supersonic aircraft, wave drag is chargeable to the volume of the vehicle, to a first order (assuming that good design practice is used in optimizing the volume distribution of the vehicle). In the case of the propulsion system, losses due to imperfect transformation of work potential into useful work constitute losses chargeable to the propulsion system. These, in turn, can be decomposed into their constituent parts at the component, and even part level, depending on how much fidelity is desired.

One aspect of chargeability deserving special note is the influence of vehicle mass and its chargeability in terms of loss. For vehicular applications, vehicle mass carries with it an implied loss of some kind for virtually every application. The strength of this impact varies depending on the mode of transport, with the general progression from highest sensitivity to lowest being launch vehicles, aircraft, automobiles, and seagoing vessels. There are no absolute rules for assigning loss chargeability to vehicle weight, but it is possible to make several generalizations that hold for most cases. Hydrodynamic drag on a ship or submarine's hull is driven primarily by wetted area, which is in turn roughly proportional to the cube root of displacement. Thus hydrodynamic drag is at least partially chargeable to displacement (mass). Rolling friction in an automobile is usually proportional the mass of the vehicle, and so is partially chargeable to vehicle mass. Drag due to lift for an aircraft in cruising flight is directly chargeable to the mass of the vehicle. Most or all of the thrust work generated by the propulsion system of a launch vehicle is used to directly lift the weight of the vehicle, and is thus chargeable to vehicle mass in some sense.

APPLICATION

The application selected to illustrate the basic loss management methods described in this paper is the analysis of losses for a lightweight fighter aircraft. Since aircraft consume a great deal of work potential (fuel) and are subject to numerous sources of loss, they lend themselves well to implementation of loss management models. As the focus of this paper is on methods rather than applications, it is desirable to analyze an aircraft that is a known quantity with well-defined characteristics. The aircraft selected for this purpose is the Northrop F-5E "Tiger II" lightweight fighter, powered by two J85-GE-21 engines. Demonstration of loss management methods on this airplane required the development of a cycle and installation model for the J85-GE-21 engine in addition to a mission analysis model. These were developed based on the best available manufacturer's published data[15,16] and modeled using NEPP[17] for engine cycle analysis, INSTAL[18] for propulsion installation analysis, and FLOPS19 for mission analysis.

The mission considered here is a simple subsonic area intercept of 500 nmi range. This mission consists of a maximum power takeoff and climb, subsonic cruise to a combat zone, 5 minutes allowance at M1.3 50,000 ft maximum power for combat (no range credit), followed by a subsonic return cruise and 20 minute reserve loiter plus 5% fuel reserve. Basic airframe, engine, and mission parameters for the F-5E are summarized in Table I.

Table I. Vehicle + Mission Characteristics and Assumptions.

Basic Load:	***(2) AIM-9J, Wing Tip Stn 394 lb Ammunition 4,501 lb Internal Fuel***
Aircraft:	***Takeoff Gross Weight = 15,734 lb Fixed Empty Weight Wing Area = 186.2 ft2***
Engine:	***(2) J85-GE-21, 5,000 lbf Thrust ea.***
Assumptions:	***All Cruse @ Best Alt/Mach 5% Fuel Flow Conservancy 5% Reserve Fuel All Climbs @ Max Rt. of Climb 500 nmi Range***

STEP 0: DEFINE LOSS – The figure of merit selected to measure loss of thermodynamic work potential for the present application is "gas horsepower", described in references 5 and 13. *Gas horsepower is defined as the maximum work that can be obtained via isentropic expansion of a high enthalpy gas to ambient pressure through an imaginary turbine*. It is therefore a meaningful measure of work potential obtainable in gas turbine engines, as the ideal engine for all machines operating on the Brayton cycle is isentropic expansion. In addition, gas horsepower is a physically intuitive quantity and yields results which can be readily assimilated and used.

Selection of gas horsepower as a thermodynamic loss figure of merit will have significant repercussions on the analysis results, as will be shown forthwith. One of these repercussions is that exhaust kinetic energy (relative to the stationary observer's reference frame) will be the dominant source of loss. If exergy had been selected as a loss FoM, exhaust heat and irreversible combustion losses would also appear as a significant contributors to loss, and these three would completely dominate all other individual sources of loss. If thrust work potential were used, neither exhaust kinetic energy nor exhaust heat would be bookkept as a loss, a result that is explained in reference 5.

STEP 1: IDENTIFY ALL SOURCES OF LOSS – The loss relevance tree that will serve as the starting point for the development of an F-5E loss management model is shown in Figure 5. This relevance tree consists of four layers and is consistent with a level of detail typically required for preliminary design analyses. It is entirely possible to add additional levels of detail, as may be desirable during the detailed design phase. Although the particular loss relevance tree shown here is specific to the Northrop F-5E aircraft, the basic structure is applicable to any vehicle in general. Also, note that this relevance tree categorizes losses first according to functional group and second according to loss mechanism, but this categorization is not the only valid scheme. One could just as well break losses down by loss mechanism then functional component, or any other logical method. The end result is a comprehensive breakdown of all loss mechanisms throughout the mission.

STEP 2: DEVELOP DIFFERENTIAL LOSS MANAGEMENT MODEL – The next step in the analysis process is to develop a mathematical model for each of the specific loss mechanisms shown in level 2 of Figure 5. This is done by first calculating instantaneous propulsion system and aerodynamic performance at every flight condition and then calculating power required to overcome each loss mechanism. The result is a set of data tables for propulsion and aerodynamic losses, as shown in Figure 6 and Figure 7. Figure 6 is a graphical presentation of the propulsion system loss deck referred to previously and shows a series of panels, one panel per loss mechanism. These are presented in a "flight envelope" style contour plot showing horsepower required to overcome a particular loss mechanism as a function of altitude and Mach number. Engine power setting is set at maximum afterburner, and a similar set of plots would be required for each power setting in order to obtain a complete representation of propulsion system power consumption. These plots give a very clear and comprehensive view of the relative importance of each loss mechanism. Note that inlet losses are only significant at high Mach numbers, whilst turbomachinery losses are highest at high dynamic pressure (and high physical flow) conditions. Likewise, nozzle thrust coefficient (C_{fg}) and boattail drag losses are worst at high dynamic pressure, while exhaust residual kinetic energy is highest at low altitude. In fact, the only loss mechanism that is not strongly correlated with dynamic pressure is bearing windage/accessories power required, (lower right corner). Also note that Mach number has a surprisingly mild impact on exhaust residual KE losses.

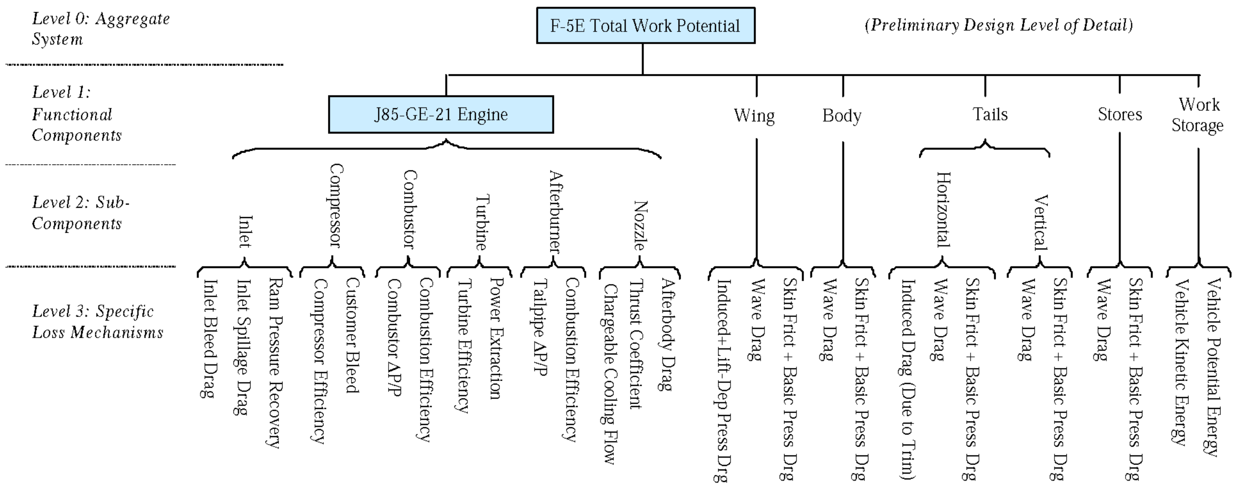

Figure 5. Loss Relevance Tree for the Northrop F-5E Loss Management Model Construction.

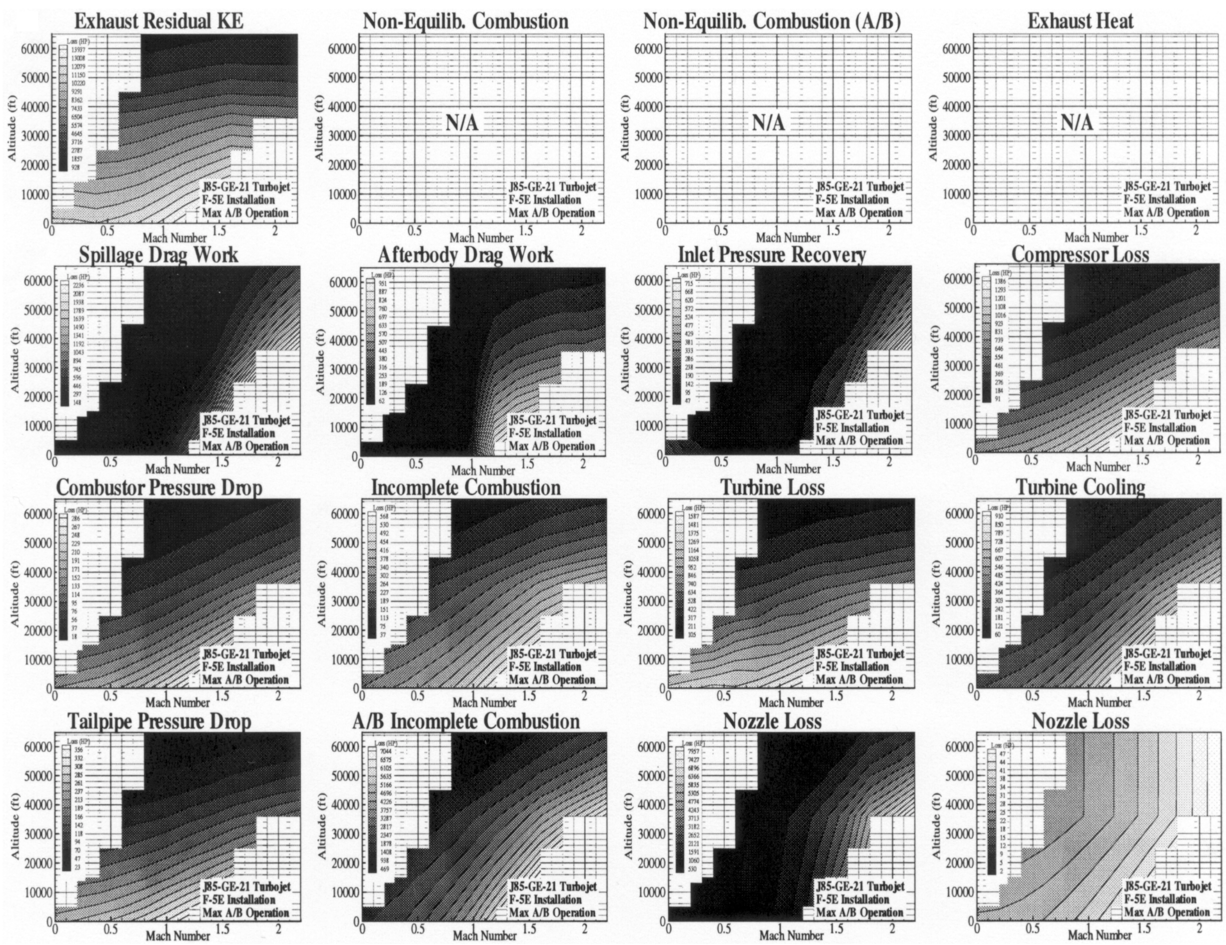

Figure 6. Propulsion System Differential Loss Model (Installed, Maximum Afterburner).

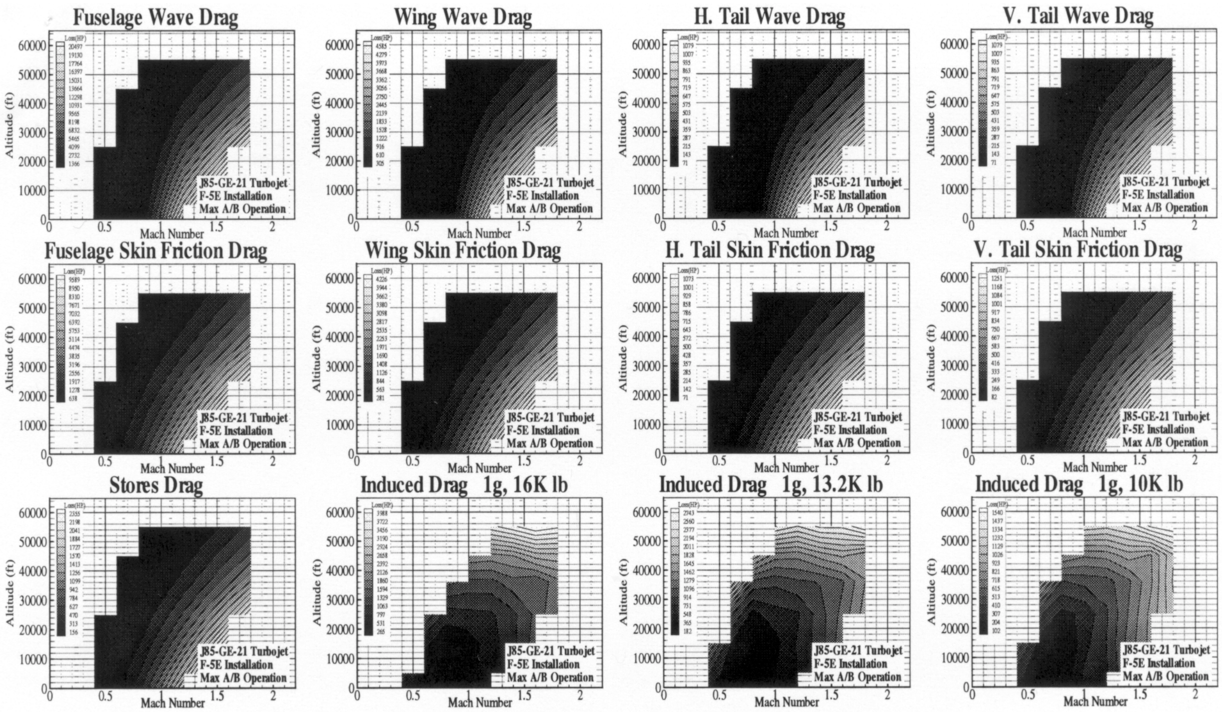

Figure 7. Aerodynamic Drag Loss (Power Required) Model.

Figure 7 shows power required as a function of flight condition for each of six major sources of aerodynamic loss. Note that the top 8 panels show contours of power required having a marked dependence on dynamic pressure and are qualitatively similar to one another. Three of the bottom panels show induced drag power for 1g level flight at various gross weights. Note that induced drag loss for 1g level flight increases with altitude, as would be expected. Since induced drag loss is a function of flight condition and vehicle weight, a series of induced drag loss plots spanning a range of vehicle weights would be required to obtain a complete representation of aerodynamic loss.

STEP 3: INTEGRATE CHARGEABLE LOSS THROUGH MISSION – The next step in the analysis process is to integrate the instantaneous losses shown in Figure 6 and Figure 7 through the mission using a time history obtained from mission analysis. This is a straightforward process of piecewise integration through mission time from takeoff to landing. The instantaneous power consumption for propulsion system losses is shown in Figure 8. This figure shows a plot of power loss chargeable to each engine component as a function of mission time, with major mission legs annotated at the top (several of the detailed loss mechanisms shown in the bottom of the relevance tree have been consolidated in the interest of brevity). Note that the various loss mechanisms are “layered” one atop another such that the total power consumption used by all engine loss mechanisms is the sum of each layer (given by the heavy line forming the top of the uppermost layer). Note that the total power loss during climb and combat are far higher than during cruise, averaging roughly 8,000 HP lost per engine versus ~3,800 HP loss per engine in cruise. The total work potential used by a particular loss mechanism over the mission is given by the area of its respective layer. Note that the dominant gas horsepower loss in the F-5E propulsion system is residual kinetic energy left in the wake of the vehicle by the propulsion system.

A similar plot for instantaneous loss due to aerodynamic drag is shown in Figure 9. This plot shows drag power required for each vehicle functional component at each instant in the area intercept mission time history. Once again, drag power required is highest during combat and climb. It is evident from this figure that fuselage drag and induced drag are the dominant aerodynamic loss mechanisms throughout the mission. Note that the average power required to move the F-5E through the atmosphere at subsonic cruise conditions is ~2,000 HP.

The final results from the piecewise integration of power loss over time is given in Figure 10. It is clear from this figure that residual kinetic energy left in the exhaust stream is the dominant gas horsepower loss in the F-5E propulsion system for the subsonic area intercept mission. This loss is a natural consequence of the thermodynamic cycle on which the J85 engine operates. It is important to note that the magnitude of the residual KE loss is a function of the mission. Clearly, an all-supersonic mission would show greatly reduced KE losses relative to the subsonic area intercept mission. Also note that the engine component losses decrease in magnitude from back to front of the engine, with the nozzle contributing roughly 8% of total loss while the inlet contributes relatively little to total loss. Finally, note that if the kinetic energy losses are excluded, total propulsive loses and aerodynamic losses are roughly equal. Since the best vehicle design is always a compromise between all competing sources of loss, it is not surprising that they tend towards an equilibrium of similar proportions.

STEP 4: ASSIGN CHARGEABILITY – The last step in the construction of a loss management model is to assign chargeability for each loss to its underlying source. In many cases, this step is trivial, such as is the case engine component losses, etc. However, other losses are not fundamental in and of themselves but are driven by other mechanisms, as shown in Table II. For instance, drag due to lift of the F-5E wing is incurred because the aircraft weight must be supported in the atmosphere. Therefore, induced drag (and perhaps wing zero-lift drag as well) is directly chargeable to vehicle weight. Skin friction drag is roughly attributable to wetted area of each airframe component. Wave drag at supersonic speeds is roughly proportional to the volume of each component, etc.

Table II. General Definition of Thermodynamic Loss Chargeability for F-5E.

Loss Mechanism	***Underlying Source***	***Comment***
Induced Drag	*Vehicle Weight*	*Drag due to lift is partitionable by vehicle weight fractions.*
Wave Drag	*Vehicle Volume*	*Wave drag is partitionable by volume of each component.*
Skin Friction	*Wetted Area*	*Skin friction is roughly partitionable by wetted area of each component.*
Customer Bleed	*Vehicle Systems*	*Work potential used to drive vehicle systems → heat load.*
Power Extraction	*Engine Acc. + Systems*	*Work potential used to drive systems + accessories → heat load.*

Furthermore, it should be obvious from the work presented here that fuel potential work is proportional to the rate of fuel consumption and therefore, *fuel weight consumed can be directly linked to loss*. This is in turn a function of the effectiveness, performance, and operating cost of the vehicle and its subsystems. For example, Figure 10 suggests that *47% of total mission fuel weight and cost is due to residual KE*, a result that *cannot* be obtained through conventional analysis techniques. If the vehicle propulsion system does work through action on a fuel of some type, then the *total loss chargeabilities are also equivalent to total fuel mass chargeabilities in that the fuel used to offset each source of loss must be proportional to the loss in work potential itself*. Likewise, 8% of the fuel weight used for the subsonic area intercept mission in the F-5E is chargeable to nozzle losses, and so on. These chargeable fuel weights are readily quantified in terms of fuel cost, which can in turn be integrated over the life of the vehicle to obtain the *total cost* associated with the losses in any given component.

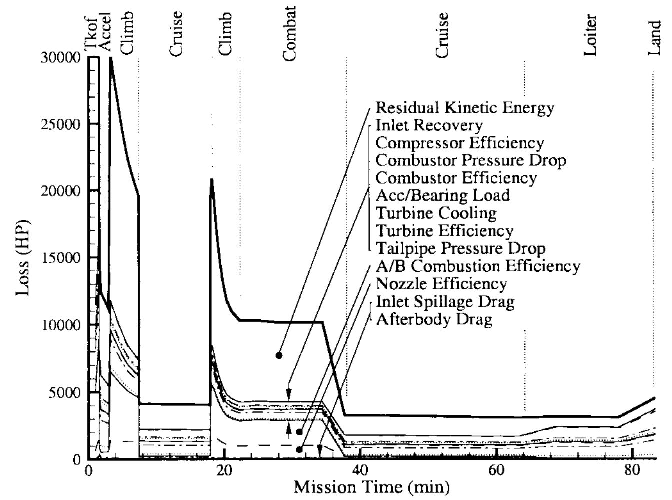

Figure 8. Loss of Available Gas Horsepower During F-5E Area Intercept Mission.

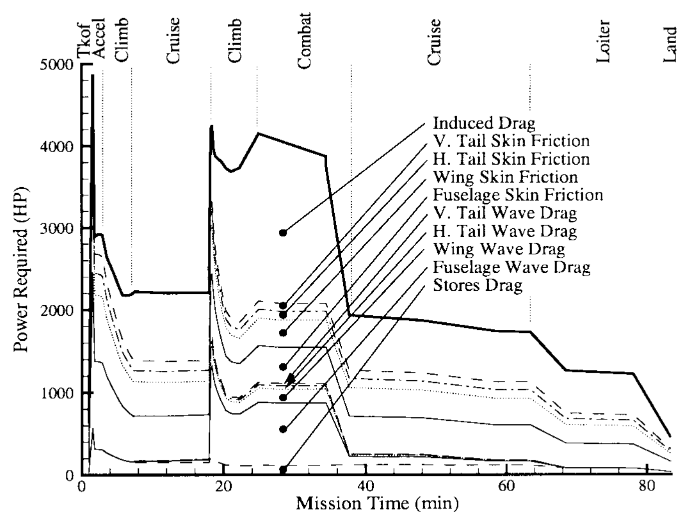

Figure 9. Aerodynamic Drag Work During F-5E Area Intercept Mission.

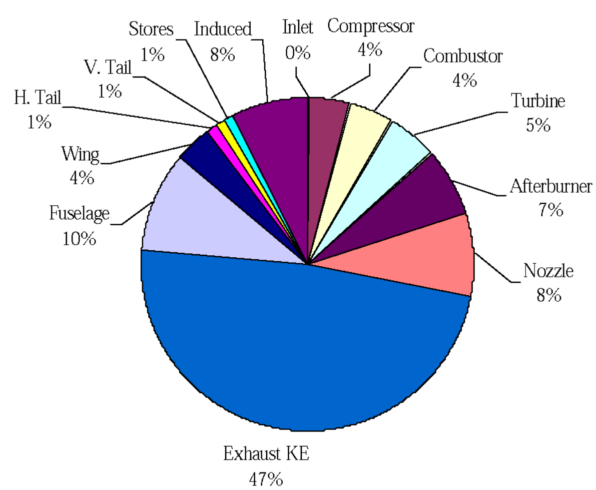

Figure 10. Total Loss in Gas Horsepower Work Potential Integrated Over F-5E Area Intercept Mission.

CONCLUSIONS

An implicit objective of vehicle design optimization is minimization of total loss. The ability to discern the individual components contributing to loss is certainly a step towards their conquest. This is a powerful addition to today's best practices, which offer only the ability to estimate total loss and not the *individual contributions* that go into it. This capability becomes increasingly important for vehicles in which thermodynamic loss is a major driver in determining the form and function of the vehicle, particularly for high-speed aircraft and high delta-v space vehicles. Moreover, for vehicles whose design is driven heavily by fuel mass, the total loss chargeability can be converted into chargeable fuel mass and compared to empty weight groups on an "apples-to-apples" basis.

Although it was not demonstrated in this paper, it should be evident that the method developed herein can be applied to evaluate the impact of advanced technologies in greater detail than is possible using conventional techniques. For instance, the typical approach to technology evaluation would be to define and evaluate a baseline design, then infuse new technology into the baseline and re-evaluate the design. The difference between the baseline and advanced technology results is then taken to be the net technology impact. Application of loss management techniques to the technology evaluation process allows one to clearly discern the *underlying mechanisms* that give rise to that net effect.

Finally, it should be noted that the ideas presented here for techniques to manage loss, cost, and evaluate technology opportunities are not new, and indeed, have always been used by designers. The difference is that the material presented herein is a formalized accounting system whereas the designer usually relies on an intuitive accounting system that is developed over time as design experience accrues. However, as tomorrow's designs become more complex and increasingly integrated, the depth and breadth of knowledge required for a designer to develop a well-honed understanding of the impact due to every design aspect becomes increasingly difficult. Thus the need for some degree of formalization of what was once a purely intuitive process.

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