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Generalized Model for Vehicle Thermodynamic Loss Management

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A general-purpose loss management model to account for the usage of thermodynamic work potential in vehicles of any type is developed. The key to accomplishing this is the creation of a differential representation for vehicle loss as a function of operating condition. This differential model is then integrated through mission time to obtain an analytical estimate for total usage of work potential consumed by each loss mechanism present during vehicle operation. This leads to a better understanding of how the work potential initially present in the mission fuel is partitioned amongst all loss mechanisms present during the vehicle's operation. This result can also be used in conjunction with cost accounting to gain a better understanding of underlying drivers on vehicle manufacturing and operating costs. The method is demonstrated for the analysis of a lightweight fighter aircraft.

Introduction

FROM a strictly thermodynamic point of view, the job of the designer is to find the best possible trades between the various competing sources of loss to arrive at a vehicle design that performs a given mission with the least possible cost. It follows that designers have a need for loss accounting methods that enable systematic analysis of loss such that the systemwide consequences of design trades can be evaluated with the greatest possible efficacy.

Unfortunately, no truly comprehensive means for vehicle loss accounting currently exists. Modern mission analysis models can estimate total loss (usually in the form of mission fuel consumption) with a relatively high degree of accuracy, but it is seldom possible to discern directly individual contributions to loss using these models. This is because standard vehicle analysis methods make extensive use of the first law of thermodynamics, but very little use of the second. The objective of this work is to show how the second law of thermodynamics can be used in the vehicle design and analysis process. Not only does its application facilitate the development of comprehensive loss accounting systems, it also provides a basis for relating losses directly to vehicle weight and cost.

This discussion begins by introducing the concept of thermodynamic work potential for vehicle design. This concept is then used as a basis for developing an analysis model to enable detailed accounting of all sources of loss in work potential. This is known as a vehicle loss management model, defined here as a comprehensive, systemwide vehicle thermodynamic model that accounts for usage of work potential amongst all vehicle systems and processes. The theoretical basis for development of vehicle loss management models is explained, with emphasis on development of a very general model for vehicle loss accounting. This general model is applicable to any form of automotive motion and is the centerpiece for a step-by-step development of a general loss management methodology. Each step is explained in detail and is then demonstrated on the analysis of a lightweight fighter aircraft.

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Thermodynamic Work Potential

The foundation on which the idea of vehicle loss management models is principally derived comes from the concept of thermodynamic work potential. The primary body of work in this area 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. Exergy is a thermodynamic quantity defined as

$$Ex \equiv H - H_{\mathrm{amb}} - T_{\mathrm{amb}}(S - S_{\mathrm{amb}}) + (\text{additional terms}) \qquad (1)$$

where Ex is total exergy (work potential), H denotes total enthalpy, S is total entropy, T is temperature, and the subscript amb denotes ambient conditions. The "additional terms" are used to denote exergy due to kinetic energy (KE), potential energy, chemical potential, radiation, heat transfer, etc.[1,2] Also note that calculation of exergy requires one to define a reference state (usually taken to be ambient conditions), as does the datum against which work potential is measured.

Although exergy is the best-known measure of work potential, there are other loss figures of merit (FOM) that are useful for vehicle analysis. One of the most useful is gas-specific power (or "gas horsepower"), which is defined as the ideal work that would be obtained by isentropic expansion of a high-enthalpy gas to atmospheric pressure through an imaginary turbine.[3] A third useful work potential FOM is that based on the stream thrust concepts pioneered by Curran and Craig.[4] This is known as thrust work potential, defined by Riggins as the ideal thrust work that would be obtained by isentropic expansion of a high-enthalpy gas in a thrust nozzle.[5]

Each of these is a valid work potential FOM.[6] The primary differences between each FOM are in their definition of useful work potential; what may constitute a loss when measured from an exergy point of view is not necessarily a loss in gas-specific power or thrust work potential. An extensive discussion on this topic is given in Ref. 7.

The application of work potential as a tool for vehicle analysis requires two significant changes from the typical analyses found in current literature: 1) The analysis must be able to accommodate the wide variety of operating points typically encountered in vehicle operation. 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: Most literature on work potential analysis focuses on process machinery or stationary power generation equipment that is typically operated at a single condition for long periods of time. The thermodynamic performance of these machines can be characterized by loss analysis of a single, steady-state operating condition. However, most vehicles are required to operate over a wide variety of conditions and throttle settings when performing their function. One must, therefore, have knowledge of the instantaneous machine loss at every operating condition experienced during a nominal duty cycle (mission) of the vehicle, and this instantaneous loss must be integrated over the entire duty cycle to obtain cumulative loss induced by each loss mechanism.

The second point relates to most vehicles experiencing a wide variation in ambient operating conditions as compared to those 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 vehicle mission may not be the same at a later time, due to changes in the ambient or reference conditions. Consequently, the definition reference conditions must change to match the instantaneous conditions surrounding the vehicle.

Generalized Vehicle Loss Management Model

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 for development of a general loss management model 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 apparent (and has been thermodynamically proven)[8,9] 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 (KE of the vehicle, for example).

This idea is illustrated in Fig. 1, which shows a diagrammatic representation of a very simple and general model for vehicle loss accounting. The origin of Fig. 1 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, whereas the remainder appears as useful work. A portion of this work output is in turn lost to dissipative mechanisms inherent to the vehicle itself, whereas the remainder is stored as some form of useful energy.

This simple model, therefore, 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 KE 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.

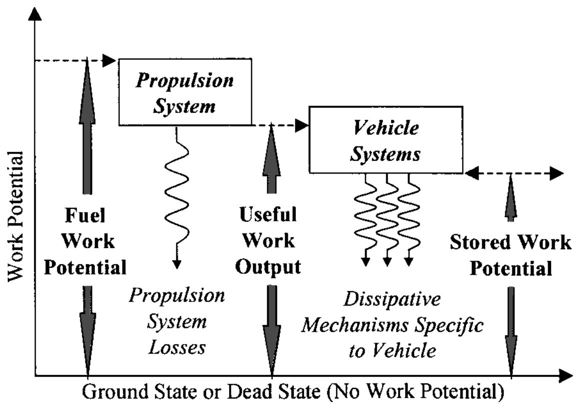

Fig. 1 Generalized model of work potential consumption for vehicular applications.

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,

$$\text{(initial work potential)} = \text{(propulsion system losses)} + \text{(vehicle losses)} + \text{(final work potential)} \tag{2}$$

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

$$\text{(work potential consumed)}\big|_0^t = \int_0^t \sum_i \frac{\text{(propulsive loss)}_i}{\mathrm{d}t}\,\mathrm{d}t + \int_0^t \sum_j \frac{\text{(vehicle losses)}_j}{\mathrm{d}t}\,\mathrm{d}t + \int_0^t \sum_k \frac{\text{(stored potential)}_k}{\mathrm{d}t}\,\mathrm{d}t \tag{3}$$

where:

t = mission time
i = counting index on the number of propulsive losses
j = index on the number of vehicle-specific losses
k = index on the number 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. 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 Fig. 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, Fig. 2. In brief, step "0" in the construction of a loss management model is to define loss explicitly in a way most suited to the needs of the current analysis. It was mentioned earlier that are several FOM suitable for measuring thermodynamic loss and that the choice of which to use depends on the situation at hand. When this is known and clearly understood, the first step is to identify explicitly 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 2, 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 3 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 that 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 4 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.

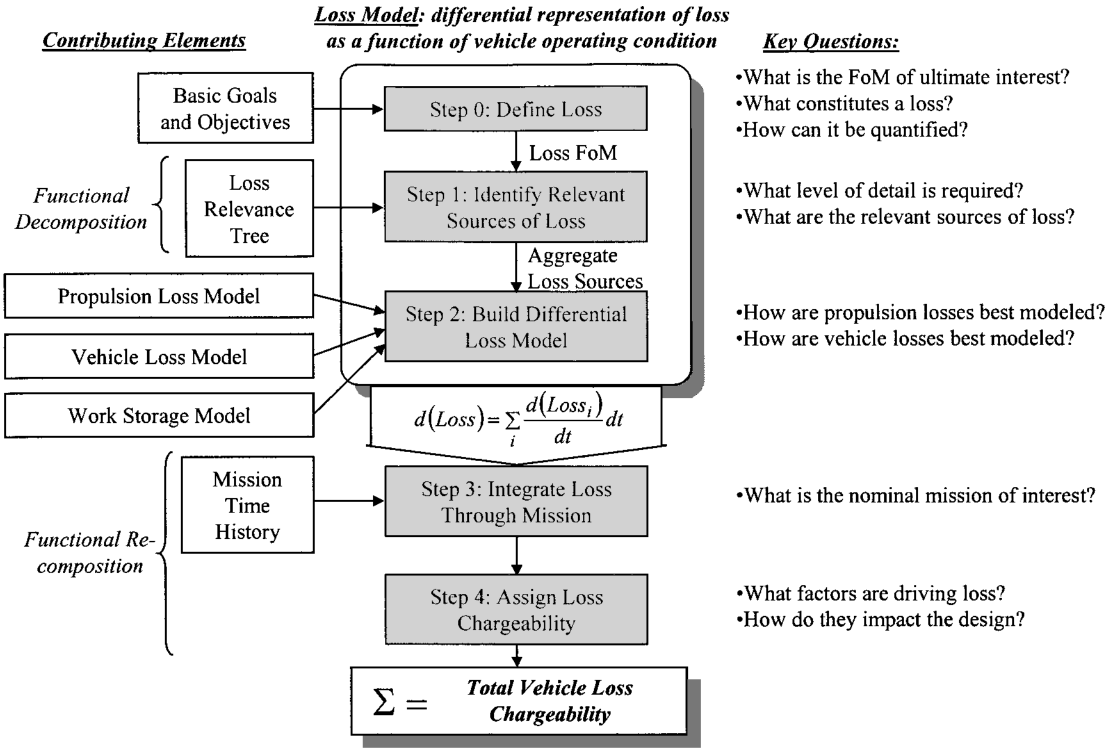

Fig. 2 General methodology for construction of loss management models.

Step 0: Define Loss

Step 0 may at first seem trivial, but accurate loss management analysis is not possible without a precise definition of loss. Exergy, gas-specific power (GSP), and thrust work potential were mentioned earlier as suitable measures of loss, but each bookkeeps loss in subtly different ways from the others. Exergy measures loss relative to the absolute limits of thermodynamics. GSP measures losses relative to an ideal Brayton cycle and is a special case of exergy. Thrust work potential measures loss relative to the ideal thrust work available and is a special case of GSP. The loss FOM most suitable for a given study application is largely dependent on study objectives and assumptions.

Loss can also be defined in other ways. Aircraft designers typically use vehicle mass as a defacto loss FOM due to the strong correlation between loss and mass. Mission fuel is nothing more than a form of stored work potential, and so it is possible to quantify thermodynamic losses in terms of "chargeable fuel weight" (described in Ref. 10). This has the additional advantage that mass is an intuitive and readily measurable quantity. Chargeable gross weight groups, therefore, make a good loss FOM for aircraft.

Also note that the ultimate FOM for loss in any vehicle is cost. Virtually every aspect of a vehicle's design and operation can be quantified in terms of cost. It is also an intuitive quantity with which everyone is familiar. Indeed, loss management methods ultimately lead toward a means of converting the chargeable losses 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 FOM selected for a particular application is immaterial as far as loss management methods are concerned. The only requirements are that a loss FOM must be comprehensive and consistent. The former implies that every loss relevant to the operation of the vehicle under consideration must be quantifiable in terms of that loss FOM, otherwise it will not be possible to construct a complete loss management model. The latter requirement simply states that the loss FOM must obey Eqs. (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 vehicle's operation. The starting point for the identification process is the generalized loss model given in Fig. 1, which partitions losses into three general "work sinks" propulsion-chargeable loss, vehicle-chargeable loss, and work storage mechanisms. Vehicle-chargeable and propulsion-chargeable losses can, in turn, be broken down into more specific classes of loss mechanism according to the desired level of analysis fidelity.

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 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 Fig. 3. This gives a listing of the most common loss mechanisms found in most vehicles. The top half of Fig. 3 depicts typical sources that feed into total work potential available.

Step 2: Develop Differential Loss Management Model

The objective of this step is to develop a differential representation of (instantaneous) total vehicle loss. To develop a differential loss model for the propulsion system, one must apply the first law of thermodynamics in the form of a thermodynamic cycle analysis. This yields detailed information on the thermodynamic state at every engine station and operating condition. This information can then be used in conjunction with a second law analysis to determine thermodynamic work potential at every engine station and operating condition. Once this is known, the losses inside the various components connecting the stations can be deduced.[11] The result of this analysis is a "loss deck," as shown in Fig. 4. The loss deck is a componentwise 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 for mission analysis.

The analysis of vehicle-specific losses does not lend itself to generalizations 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 mechanical friction, flow resistance, and heat transfer. It is relatively easy to calculate losses due to mechanical friction effects because 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 by vehicle velocity to obtain power required. Heat transfer through a finite temperature difference is another significant source of loss in many vehicles. Calculation of loss due to heat transfer is discussed in detail in Refs. 1 and 12.

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

$$\mathrm{d(total\ loss)} = \sum_i \frac{\mathrm{d(loss}_i)}{\mathrm{d}t} \tag{4}$$

where loss_i is the loss due to dissipative mechanism i and is a function of vehicle operating condition. The differential loss model is necessarily a function of operating condition, which is usually described in terms of ambient temperature/pressure/velocity (or altitude/Mach number) and throttle setting.

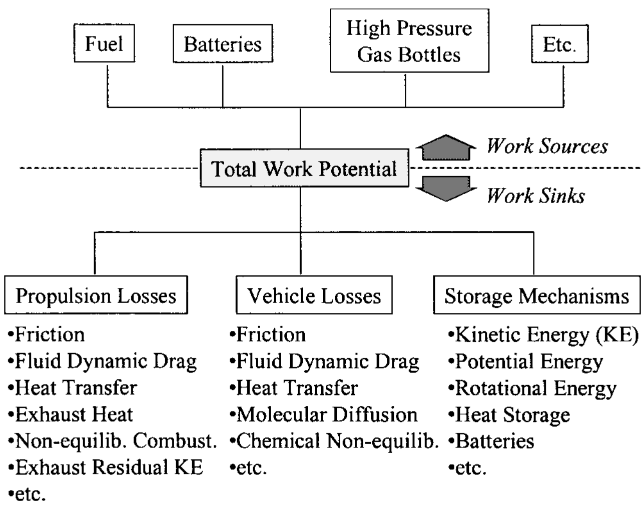

Fig. 3 Typical contributors used in loss management model construction.

Step 3: Integrate Chargeable Loss Through Mission

The differential loss model constructed in the preceding step can now be integrated through a prescribed mission time history to produce total loss chargeable to each component of 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 mission.

It is typically necessary to integrate numerically 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 lookups, 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.

The definition of loss chargeability is an important step, and it is one that can be very ambiguous from an engineering point of view. The most convenient starting point for definition of loss chargeability is usually the loss relevance tree created in step 1. 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.

The concept of chargeability is perhaps best illustrated through example. For instance, in the design of supersonic aircraft, wave drag is chargeable to the volume of the vehicle (assuming that good design practice was 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

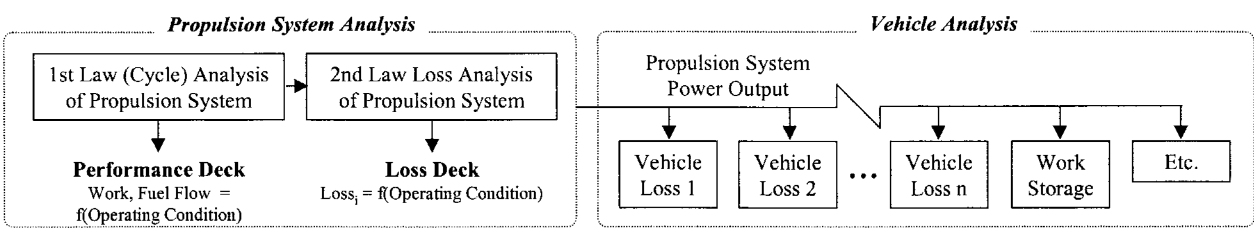

Fig. 4 General thermodynamic loss model for vehicles powered via heat engine.

decomposed into their constituent parts at the component, and even part level, depending on what level of analysis 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, thus, is partially chargeable to vehicle mass. Induced drag for an aircraft in cruising flight is directly chargeable to the mass of the vehicle. Much 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

Perhaps the most effective way to convey the usefulness of the loss management methods proposed herein is simply to illustrate their application. Because 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. 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[13,14] and modeled using well-known cycle,[15] propulsion installation,[16] and mission analysis tools.[17]

The mission considered here is a simple subsonic area intercept of 500-n mile range. This mission consists of a maximum power takeoff and climb, subsonic cruise to a combat zone, 5-min allowance at M1.3 50,000-ft maximum power for combat (no range credit), followed by a subsonic return cruise and 20-min reserve loiter plus 5% fuel reserve. Basic airframe, engine, and mission parameters for the F-5E are summarized in Table 1.

Step 0: Define Loss

The FOM selected to measure loss of thermodynamic work potential for the present application is GSP. Recall that GSP 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. Use of GSP as a thermodynamic loss FOM has significant repercussions on the results. One of these repercussions is that exhaust KE (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 (though not chargeable as losses when viewed from a GSP perspective), and these three would completely dominate all other individual sources of loss. If thrust work potential were used, neither exhaust KE nor exhaust heat would be bookkept as a loss, as explained in Ref. 6.

Table 1 Vehicle and mission characteristics and assumptions

Parameter	Value
Basic load	(2) AIM-9J, wing tip station
	394 lb ammunition
	4501 lb internal fuel
Aircraft	Takeoff gross weight = 15,734 lb
	Fixed empty weight
	Wing area = 186.2 ft^2
Engine	(2) J85-GE-21, 5000 lbf thrust each
Assumptions	All cruise at best altitude/Mach
	5% reserve fuel
	All climbs at maximum rate of climb
	500 n mile range

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 Fig. 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, which 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 and then functional component, or any other logical method. The final product 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 Fig. 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 Figs. 6 and 7.

Figure 6 is a graphical presentation of the propulsion system loss deck referred to earlier 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 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, whereas turbomachinery losses are highest at high dynamic pressure (and high physical flow) conditions. Likewise, nozzle and afterbody drag losses are worst at high dynamic pressure, whereas exhaust residual KE 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, Fig. 6m. Also note that Mach number has a surprisingly mild impact on exhaust residual KE losses.

Figure 7 shows power required as a function of flight condition for each major source of aerodynamic loss. Note that Figs. 7a–7h show contours of power required having a marked dependence on dynamic pressure and that they are qualitatively similar to one another. Figures 7j–7l show induced drag power for 1-g level flight at various gross weights. Note that induced drag loss for 1-g level flight increases with altitude, as would be expected. Because 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. Note that the loss data contained in these loss decks are estimated based on manufacturer's data and are, therefore, of comparable accuracy to the original test reports. However, the induced drag power plots tend to be less accurate due to interpolation errors at very low angles of attack, as is evidenced by the numerical error evident in the induced drag plots.

These loss decks provide useful information in and of themselves because they quantify all losses and clearly show the absolute magnitudes of each. This is in contrast to standard presentations wherein propulsion system losses are presented as component efficiencies that are neither comparable to one another, nor comparable to aerodynamic losses.

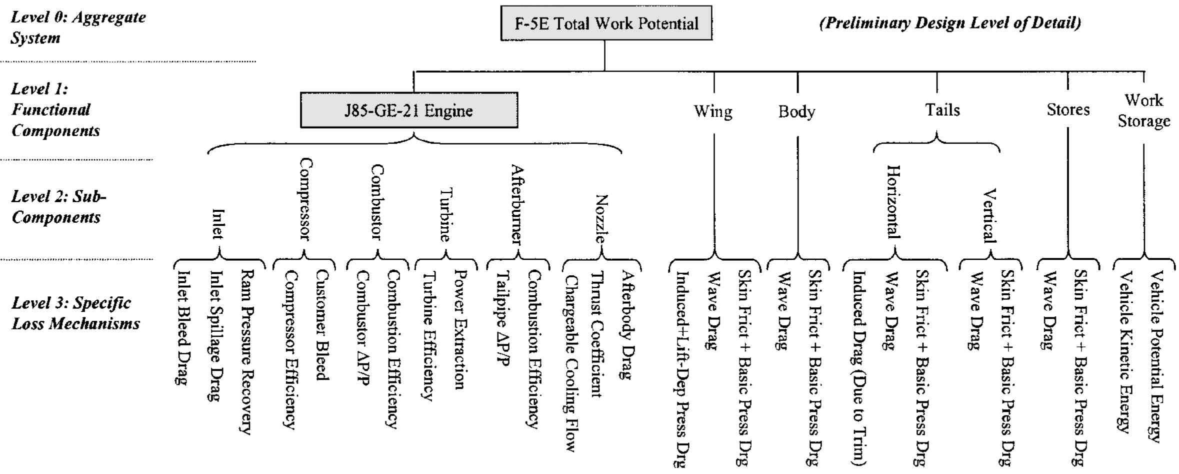

Fig. 5 Loss relevance tree for the Northrop F-5E loss management model construction.

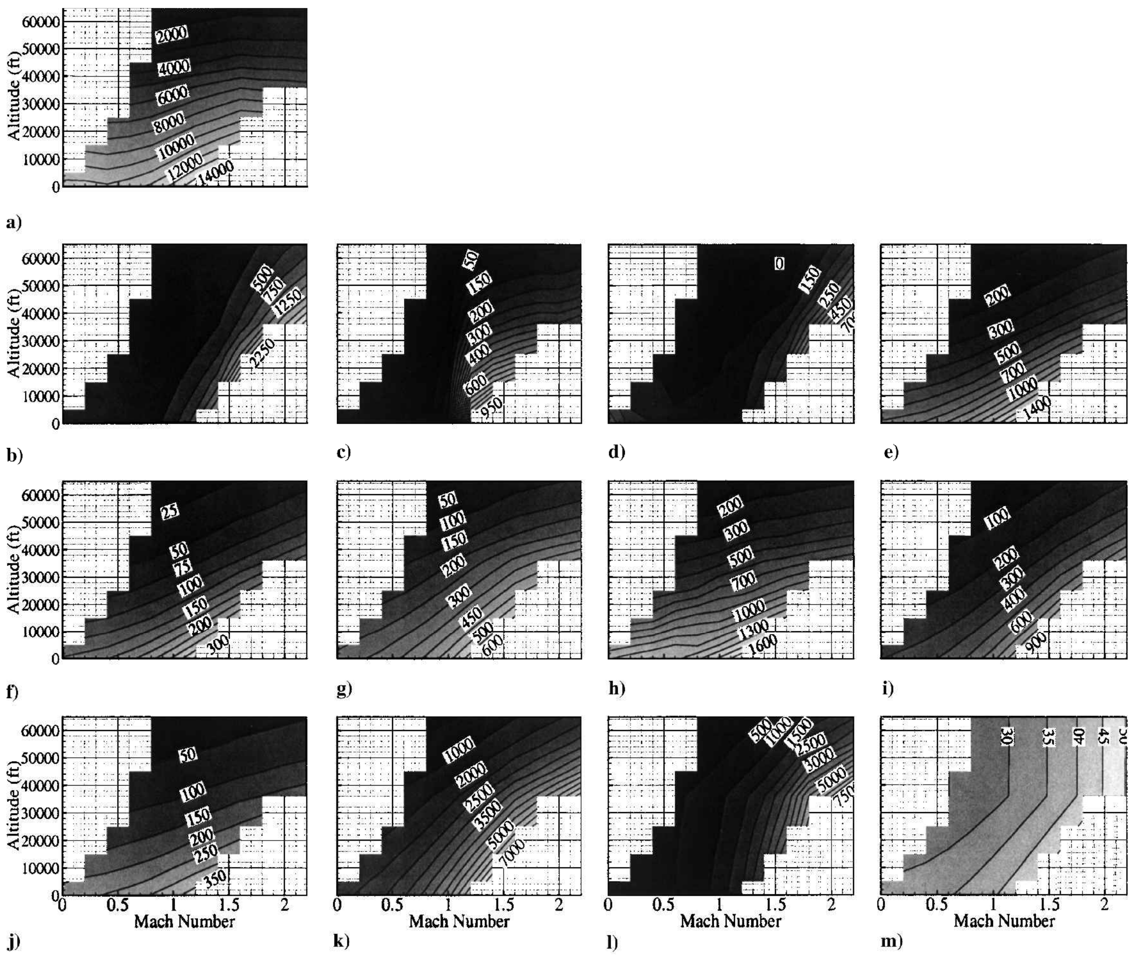

Fig. 6 Propulsion system differential loss model (J85-GE-21 turbojet engine, F-5E propulsion system installation maximum afterburning operation losses expressed in horsepower): a) exhaust residual kinetic energy; b) spillage drag; c) afterbody drag; d) inlet pressure recovery; e) compressor losses; f) combustor pressure drop; g) incomplete combustion; h) turbine losses; i) turbine cooling losses; j) tailpipe pressure drop; k) afterburner incomplete combustion; l) nozzle loss; and m) accessories, bearing, and windage losses.

Step 3: Integrate Chargeable Loss Through Mission

The next step in the analysis process is to integrate the instantaneous losses shown in Figs. 6 and 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 Fig. 8. Figure 8 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 on top of 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 8000 hp lost per engine vs ~3800 hp loss per engine in cruise. The total work potential used by a particular loss mechanism over the mission is

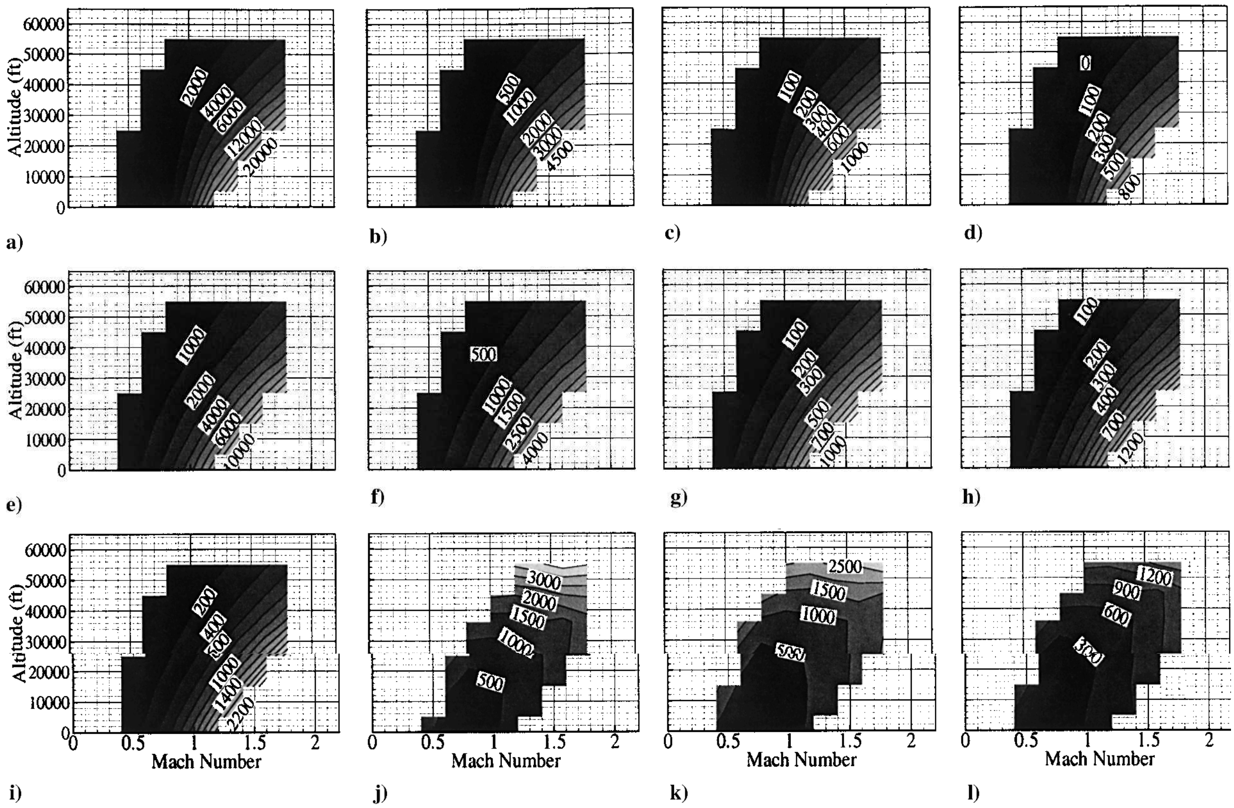

Fig. 7 Aerodynamic drag loss (horsepower required) model: a) fuselage wave drag; b) wing wave drag; c) horizontal tail wave drag; d) vertical tail wave drag; e) fuselage skin friction; f) wing skin friction; g) horizontal tail skin friction; h) vertical tail skin friction; i) stores drag; j) induced drag, 1*g*, 16,000-lb gross weight; k) induced drag, 1*g*, combat weight; and l) induced drag, 1*g*, 10,000-lb gross weight.

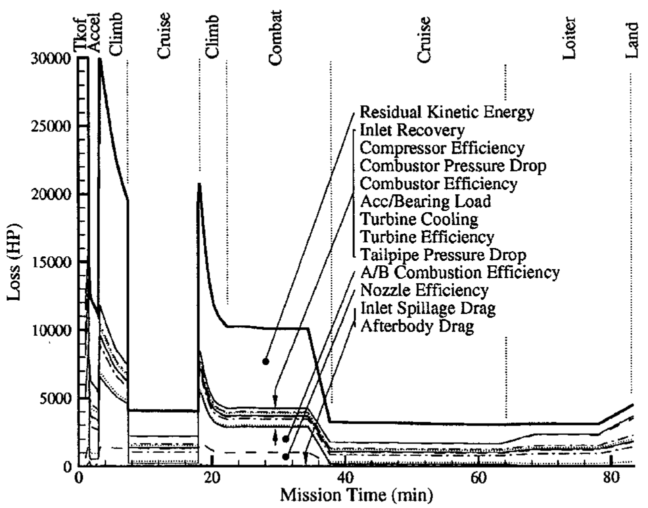

Fig. 8 Loss of available gas specific power during F-5E area intercept mission.

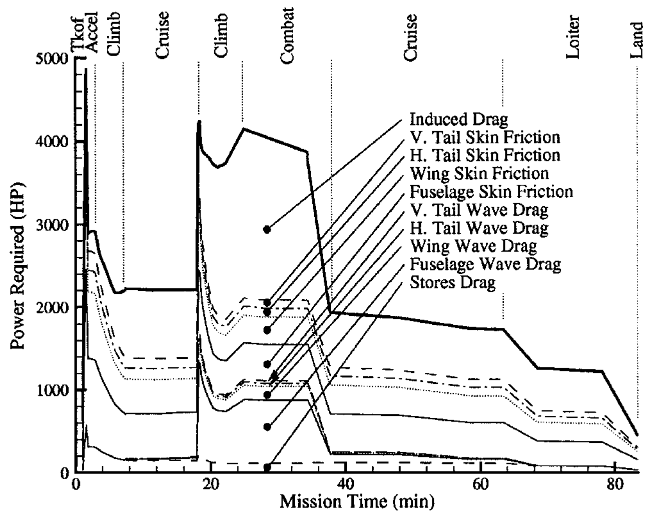

Fig. 9 Aerodynamic drag work during F-5E area intercept mission.

given by the area of its respective layer. Note that the dominant GSP loss in the F-5E propulsion system is residual KE left in the wake of the vehicle by the propulsion system.

A similar plot for instantaneous loss due to aerodynamic drag is shown in Fig. 9. Figure 9 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 Fig. 9 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 ~2000 hp.

The final results from the piecewise integration of power loss over time are given in Fig. 10. Figure 10 shows that residual KE left in the exhaust stream is the dominant GSP 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. 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 the back to the front of the engine, with the nozzle contributing roughly 8% of total loss, whereas the inlet contributes relatively little to total loss. Finally, note that if the KE losses are excluded, total propulsive loses and aerodynamic

Table 2 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 accessories and systems	Work potential used to drive systems and accessories → heat load.

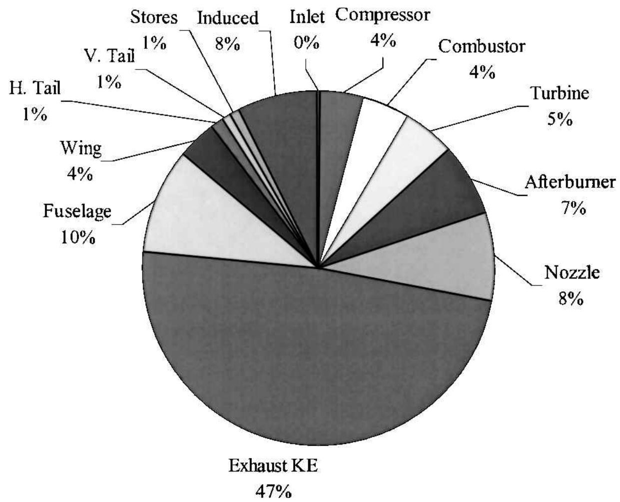

Fig. 10 Total loss in gas specific power integrated over F-5E area intercept mission.

losses are roughly equal. Because the best vehicle design is always a compromise between all competing sources of loss, it is not surprising that they are 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 in the case of engine component losses, etc. However, other losses are not fundamental in and of themselves, but are driven by underlying mechanisms, as shown in Table 2. 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 the wetted area of each airframe component. Wave drag at supersonic speeds is roughly proportional to the volume of each component, etc.

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, Fig. 10 suggests that 47% of total mission fuel weight and cost is converted to residual KE, an analysis result that can not be obtained through conventional 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.

Conclusions

The concept of thermodynamic work potential, and the loss management models they imply, can be used as a universal currency to facilitate design trades in vehicles of any type. Loss management methods enable thermodynamic losses to be quantified in terms of chargeable gross weight, as well as monetary cost. These ideas are key to creating what is essentially a "unified performance/weight/cost" theory of modern design wherein the performance, weight, and cost aspects of design are viewed not as separate FOM, but as interchangeable manifestations of the same thing.

Loss management methods have the additional advantage that they can be used to discern individual components contributing to loss. This is a powerful addition to today's best practices, which offer the ability to estimate total loss, but offer little insight into the individual contributions that go into it. This capability is especially useful 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.

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References

[1]Bejan, A., *Advanced Engineering Thermodynamics*, 2nd ed., Wiley, New York, 1997, Chaps. 3–5.

[2]Bejan, A., and Seims, D. L., "The Need for Exergy Analysis and Thermodynamic Optimization in Aircraft Development," *Exergy International Journal*, Vol. 1, No. 1, 2001, pp. 14–24.

[3]Nichols, J. B., "An Energy Basis for Comparison of Performance of Combustion Chambers," *Transactions of the ASME*, Vol. 75, No. 1, 1953, pp. 29–33.

[4]Curran, E. T., and Craig, R. R., "The Use of Stream Thrust Concepts for the Approximate Evaluation of Hypersonic Ramjet Engine Performance," U.S. Air Force Aeropropulsion Lab., Rept. AD-769 481, Dayton, OH, July 1973.

[5]Riggins, D. W., "Evaluation of Performance Loss Methods for High-Speed Engines and Engine Components," *Journal of Propulsion and Power*, Vol. 13, No. 2, 1997, pp. 296–304.

[6]Roth, B. A., and Mavris, D. N., "Comparison of Thermodynamic Loss Models Suitable for Gas-Turbine Propulsion," *Journal of Propulsion and Power*, Vol. 17, No. 2, 2001, pp. 324–332.

[7]Roth, B. A., "A Theoretical Treatment of Technology Risk in Modern Propulsion System Design," Ph.D. Dissertation, School of Aerospace Engineering, Georgia Inst. of Technology, Atlanta, GA, May 2000.

[8]Moran, M. J., *Availability Analysis: A Guide to Efficient Energy Use*, Prentice–Hall, Englewood Cliffs, NJ, 1982, p. 146.

[9]Li, K. W., *Applied Thermodynamics: Availability Method and Energy Conversion*, Taylor and Francis, New York, 1996, p. 133.

[10]Roth, B. A., and Mavris, D. N., "Whither a Scheme for Vehicle Fuel Weight Accountability?" *Weight Engineering*, Vol. 60, No. 1, 2000, pp. 53–77; also Society of Allied Weight Engineers, Paper 3001, June 2000.

[11]Roth, B., and Mavris, D., "Analysis of Advanced Technology Impact on HSCT Engine Cycle Performance," AIAA Paper 99-2379, June 1999.

[12]Bejan, A., *Entropy Generation Through Heat and Fluid Flow*, Wiley, New York, 1982, Chaps. 1–3.

[13]Vance, C. H., "Standard Aircraft Characteristics Performance of the Northrop F-5E Air Superiority Fighter with Two J85-GE-21 Engines," Northrop Corp., Rept. NOR 76-158, Hawthorne, CA, Dec. 1976.

[14]"Anon Model Specification: E1164-A Engine, Aircraft, Turbojet, J85-GE-21," General Electric Company, Lynn, MA, Feb. 1971.

[15]Klann, J. L., and Snyder, C. A., "NEPP User's Manual," NASA Lewis Research Center, Cleveland, OH, NASA TM 106575, 1994.

[16]Kowalski, E. J., and Atkins, R. A., "Computer Code for Estimating Installed Performance of Aircraft Gas Turbine Engines, Vol. II: User's Manual," NASA CR159692, 1979.

[17]McCullers, L. A., "FLOPS Release 5.94 User's Guide," NASA Langley Research Center, Hampton, VA, 1998.