Minimizing Vehicle Environmental and Economic Cost Via Thermodynamic Work Potential

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Abstract

The objective of this paper is to highlight several research opportunities currently being pursued at Georgia Tech to advance the state-of-the-art in vehicle design methods by applying the concept of *thermodynamic work potential*. The paper begins with a broad definition of thermodynamic work potential and describes several attributes that make it useful for vehicle design. Among these attributes are the ability to link aerothermodynamic performance and vehicle mass together in a "unified theory of vehicle design," as well as the ability to provide a means for explicitly calculating vehicle operating cost accountability. In addition, work potential methods are suggested as an excellent framework from which to conduct technology risk and benefit studies.

Introduction

The advances in transportation technology over the past century have revolutionized the world around us, impacting commerce, warfare, exploration, productivity, social affluence, etc. Vehicles of every form and mode of locomotion are becoming increasingly important to sustaining our way of life. Consequently, there is a strong demand for newer, more efficient, more capable vehicles. In addition, there is mounting concern in society regarding the dwindling energy resources available and the environmental impact of these vehicles.

However, the realization of this demand is no trivial task. The art and science of vehicle design is one of the most challenging engineering endeavors undertaken by mankind. All truly good vehicle designs are always a compromise between all competing aspects of design merit including thermodynamic performance, weight, cost, maintainability, etc. It is precisely this need to balance the many facets of design performance that makes vehicle design challenging. A necessary prerequisite to achieving this balance is an understanding of the *fundamental nature* of the trades involved and knowledge of the exact cost (in terms of performance, weight, and dollars) of every decision made during the design process. It is this type of information that ultimately will lead to more energy-efficient, environmentally acceptable vehicles.

This may at first seem an untenable need. However, all vehicles must obey the same laws of physics and are subject to the same fundamental limitations. Given this situation, there *must* be a common thread of analysis applicable to all classes of vehicle. Specifically, if all vehicles must obey the same laws of physics, then *there must be a common figure of merit* applicable to any vehicle, and it should be possible to formulate a *generalized theory of vehicle design* based on these fundamental principles.

The fundamental principles most applicable to vehicle deign are Newton's Laws of motion and the Laws of Thermodynamics. Newton's Second Law and the First Law of Thermodynamics are the cornerstones upon which virtually all vehicle analysis methods are built today. The other laws play a supporting role, but have not generally been applied to their full extent. In particular, the second law of thermodynamics has never been central to the vehicle design process, but holds considerable promise as a fundamental principle to guide vehicle designers to better designs in the future.

The reason that the second law is a promising tool for vehicle designers is that it enables the concept of *thermodynamic work potential*. To understand this, consider that all vehicles must consume work potential of some form in order to move. At the most fundamental level, *it is the usage and loss of thermodynamic work potential that drives virtually every aspect of a vehicle's environmental and economic performance*. Yet, modern vehicle design methods make little or no use of the second law of thermodynamics or the concept of work potential. *There simply is no rational and organized method in place today to enable the estimation and tracking of work potential usage in vehicle design*, even though work potential is the lifeblood of vehicular motion! Application of work potential concepts to vehicle design is the key to enabling calculation of the magnitude of the work loss incurred in each thermodynamic process relevant to a vehicle's operation such that the most significant sources of loss can be identified and targeted for improvement.

The need to accurately calculate loss of work potential relative to a thermodynamic ideal has led to interest in methods employing the second law of thermodynamics as a basis for loss estimation. This approach is appealing because it provides an unambiguous definition of an ideal against which the actual process can be compared. Thus, whereas conventional analysis methods give information as to the flow of *energy*, a second law-based method enables calculation of *work potential*. This capability will facilitate the creation of analytical models to identify and track all sources of thermodynamic loss in an entire vehicle or subsystem. Such an approach would make it possible to estimate the *absolute* loss associated with each loss mechanism in terms of a *single figure of merit* applicable to *all* vehicle components and processes.

A General Definition of Work Potential

The idea of work potential is a concept that all people naturally intuit. It has been understood for centuries that a rock at the top of a hill has more work potential inherently stored in it than does one at the bottom. Over the centuries, mankind has learned to utilize the work potential stored in his environment to power sailing ships, drive windmills, transport goods, conduct business, etc. Yet although it is an easily intuited concept, a formal definition of work potential eluded scientific inquiry for centuries. It is only recently that the general concept of thermodynamic work potential has become a precisely (scientifically) defined quantity.

In the broadest sense, that which we think of as work potential is thermodynamically related to equilibrium (in a physical, chemical, thermal, or any other sense). Specifically, the *farther a given substance is out of equilibrium with its environment, the greater its potential to do useful work*. The higher a rock is on the hill, the more work can be extracted in taking it to the bottom of the hill. The stronger the wind blows, the more energy can be extracted in decelerating it relative to the ground. It is the constant state of non-equilibrium that drives the world around us. Today, we know this concept as the second law of thermodynamics, and the analytical techniques developed to quantify work potential are referred to as second-law methods.

A substantial body of work has appeared in the past several decades dealing with second-law approaches to measuring work potential and loss thereof. One such approach is the exergy concept, which has been applied to the gas turbine cycle by several authors, notably Clarke and Horlock,[1] who applied it to a simple turbojet example and showed where the most significant exergy losses were occurring. It is the best-known and most formalized method to estimate the magnitude of losses relative to a thermodynamically ideal process,[2,3] and first appeared in the United States due largely to the work of Keenan in the 1940s.[4] Put simply, *exergy is a thermodynamic state describing the maximum theoretical (Carnot) work that can be obtained from a substance in taking it from a given chemical composition, temperature, and pressure to a state of chemical, thermal, and mechanical equilibrium with the environment.* Note that while energy is a conserved quantity, exergy is *not*, and is always destroyed when entropy is produced. Note also that the definition of exergy depends on the ambient environment. A considerable body of literature exists describing the theory and application of exergy analysis, such as references 5, 6, 7, and 8.

Usefulness of Work Potential for Vehicle Design

The concept of work potential is naturally suited to aerospace vehicle design. The potential applications for these techniques towards simplifying and improving the aerospace vehicle design process are only now beginning to be explored. This section will point out features that make work potential methods useful in vehicle design.

The Limits of Design Perfection: One of the most basic advantages of viewing vehicle aerothermodynamic performance in terms of work potential is that it inherently focuses all attention on what the *absolute magnitude* of loss is in the vehicle's systems and unambiguously identifies the source of each loss. It becomes immediately obvious using the work potential method how much improvement is possible and how close the actual system is to ideal. Moreover, it is immediately evident which components of the system are causing the most loss, thereby attracting attention to those areas where the most improvement is possible. In short, *the concept of work potential is as fundamental to defining the limits of vehicle design as Carnot cycle is to defining the limits of thermodynamic performance*.

A "Universal Currency" for Vehicle Design: One advantage that thermodynamic work potential has over efficiency as a measure of performance is that work potential is a more fundamental quantity directly related to the physics of the problem. In fact, work potential is an extensive *thermodynamic property* of a substance, in the same sense that enthalpy, entropy, etc. are thermodynamic properties. Consequently, work potential has the same definition for all thermodynamic processes, regardless of the physical component. It therefore seems logical to presume that the concept of work potential can be used as a common figure of merit (FoM) for judging the absolute value of losses compared amongst disparate components and thermodynamic processes. In short, *just as a viable country must have a common currency to facilitate commerce and trade, so must vehicle design have a common currency to facilitate design trades*. Thermodynamic work potential is the "universal currency" of aerothermodynamic performance that is needed for vehicle design.

The bridge between Aero-thermo Performance and Vehicle Weight (Mass): It is intuitively obvious that one can think of mission fuel as being a form of stored work potential, which implies that there must be a relationship between weight of fuel required to complete a mission and usage of thermodynamic work potential. In other words, there must be a relationship between *aerothermodynamic performance* and *weight*. This naturally leads to the idea that both thermodynamic performance and weight aspects of design can be quantified in terms of gross weight.

To understand this, consider performance from a thermodynamic point of view. The work used for vehicle motion must come from the work potential stored in the fuel. Furthermore, there must be a one-to-one correspondence between fuel weight and total usage of work potential (loss incurred) during the mission. Therefore, *it should be possible to quantify losses incurred during the mission (such as drag work, engine inefficiencies, etc.) in terms of the fuel weight required to offset those losses*. This is the crux of the loss management methods under development at Georgia

Tech: *to quantify aerothermodynamic aspects of design performance in terms of fuel weight chargeable to each individual source of loss*. The result is effectively a unified weight/performance theory of modern design.

Loss Accounting as a Means for Cost Accounting: It is becoming increasingly evident that cost is the primary driver influencing the design, manufacture, and operation of future aerospace vehicles. This trend cuts across all traditional boundaries: it is applicable to civil as military vehicles, be they helicopters, aircraft, missiles, space launch systems, or spacecraft. For this reason, cost control will become an increasingly important part of future aerospace vehicle design.

It is intuitively obvious that the first step in controlling cost is understanding and accounting for its underlying sources. Therefore, accurate and comprehensive cost accounting is an important element needed for future aerospace vehicle design. In fact, cost accounting is an integral part of modern business practice, and it would be inconceivable to contemplate running a sizeable business without it. Yet *this is precisely what is practiced in the aerospace industry*.

To understand this, consider the earlier statement that all the work potential initially stored in the fuel of an aircraft eventually appears as a loss. Therefore, the partitioning of work potential loss throughout the vehicle mission is what determines the partitioning of fuel cost. Fuel cost is one of the largest components of vehicle LCC, yet *the aircraft industry has no practical means of accounting for fuel cost chargeability*. Loss management methods based on the concept of thermodynamic work potential offer a comprehensive, consistent, physics-based means of allocating fuel cost chargeability to the underlying aerothermodynamic loss mechanisms.

A Framework for Understanding Technology Impact: Based on the development presented to this point, it should be clear that work potential methods have considerable potential to facilitate evaluation and selection of those technologies that impact vehicle aero-thermodynamic performance and/or weight. Specifically, the concept of gross weight chargeability can provide an integrated framework for multidisciplinary design wherein the aerothermodynamic cost and benefit of technology concepts can be explicitly evaluated. In effect, chargeable gross weight is a means of comparing disparate performance metrics and technologies.

Technology Uncertainty and Risk: Uncertainty is an inherent feature of new technologies, and it is seldom possible to incorporate a new technology without incurring some degree of risk attendant to that technology. Therefore, if loss management methods are to be useful for evaluation of technology impact, they must admit some means of treating uncertainty in terms of chargeable gross weight.

The technique described in the previous section allows the quantification of thermodynamic and mass impacts of new technologies in terms of chargeable gross weight. In fact, *technology uncertainty can be modeled by using chargeable gross weight as a metric not only of design merit, but also of design risk*. This is accomplished by allowing chargeable gross weight groups to be represented not only in terms of a deterministic quantity, but also in terms of a *probability distribution*. This implies that uncertainty in technology performance will translate into distributions on those chargeable weight groups impacted by that technology.

Conclusions

Work potential methods have the ability to revolutionize the way vehicles are designed in the future. Comprehensive application of these ideas makes the concept of "efficiency" superfluous, and provides a common framework for comparison of performance. These techniques provide the designer *for the first time* with a means to equate aerothermodynamic performance to vehicle fuel weight, resulting in an unprecedented level of visibility as to the impact that design decisions have on vehicle environmental and economic performance. In addition, work potential allows the assignment of cost accountability, *a result that cannot be obtained using today's analysis methods.* Finally, these methods provide an ideal framework for technology risk and benefit studies, thereby facilitating design improvement by targeting those technologies that have the greatest potential to minimize overall environmental and economic cost.

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References

[1] Clarke, J.M., Horlock, J.H., "Availability and Propulsion," *J. Mech. Eng. Sci*., V17, No4, 1975.

[2] Haywood, R.W., "A Critical Review of the Theorems of Thermodynamic Availability, with Concise Formulations, Part 1: Availability," *J. Mech. Eng. Sci*., Vol 16, No 4, 1974.

[3] Haywood, R.W., "A Critical Review of the Theorems of Thermodynamic Availability, with Concise Formulations, Part 2: Irreversibility" *J. Mech. Eng. Sci*., Vol 16, No 4, 1974.

[4] Keenan, J., "Availability and Irreversibility in Thermodynamics," *Br. J. Appl. Phys*., vol 2, July 1951.

[5] Szargut, J., Morris, D., Steward, F., *Exergy Analysis of Thermal, Chemical, & Metallurgical Processes*, Hemisphere, New York, 1988.

[6] Ahern, J.E., *The Exergy Method of Energy Systems Analysis*, Wiley, New York, 1980.

[7] Li, K.W., *Applied Thermodynamics, Availability Method and Energy Conversion*, Taylor & Francis, D.C., 1996.

[8] Moran, M.J., *Availability Analysis, A Guide to Efficient Energy Use*, ASME Press, New York, 1989.