Commercialization of Major Efficiency-Enhancing Vehicular Engine Innovations: Past, Present, and Future Micro- and Macroeonomic Considerations

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ABSTRACT

Both a general and a particular view of the process and macroeconomic side effects of engine innovation are given. The history of engine innovation in automobiles, railroads, and ships is reviewed and related to the potential path automotive engine innovation may take toward the turn of the century. It is shown that automotive engine innovation in the past has been costly, especially to lower-income consumers, and that potential future adoption of Stirling and Brayton (gas turbine) engines is unlikely to be any different. The danger of negative economic side effects during the innovation process for the automobile industry and nation are noted. Careful corporate and national preparation for automotive innovation is suggested. To that end, advanced (year 2000) engine and vehicle characteristics are used to estimate that the Stirling and Brayton engines are each likely to have specific, different markets. Driving-cycle behavior of the engines in urban and suburban settings is examined to show that the Stirling's most likely market will be as a specialized urban vehicle, whereas the Brayton's best market will be as a specialized suburban and intercity vehicle. It is argued that neither engine has the properties necessary to become a universal replacement for all-purpose vehicles using advanced Otto-cycle and diesel engines, but that proper use of these vehicles could ultimately help to efficiently mitigate national problems of urban air pollution (the Stirling in particular) or excessive fuel consumption or both. Finally, the observation is made that recent methods of the Environmental Protection Agency for evaluating vehicle fuel efficiency could incorrectly lead to a negative economic evaluation of advanced Stirling and Brayton engines, tending to unjustifiably retard their introduction to the market.

Advanced automotive engines were characterized as part of the Argonne National Laboratory's study Technology Assessment of Productive Conservation in Urban Transportation (TAPCUT) (1). In this study, which examined transportation energy use and associated impacts, passenger automobiles powered by Stirling, Brayton, advanced diesel, and improved Otto-cycle engines were characterized in detail for the year 2000. Several of the vehicles characterized in this large study are here examined in further detail to provide an understanding of which elements of each engine would make it the best choice in various vehicle markets in the future.

The engines and vehicles defined for the TAPCUT study were assessed for urban passenger use but were not evaluated for rural and intercity applications. Several different levels of success in technology development were assessed, each achieving different fuel efficiency and performance levels by the year 2000. The purpose of the original TAPCUT study was to define relevant energy conservation strategies in urban transportation, test them, and determine their environmental impacts. The present study focuses not only on urban environmental and energy conservation issues, but also on rural and urban markets for the new technologies. The study concentrates mostly on the costs and benefits of achieving fuel efficiency. Attributes of the engines and vehicles, as well as the fuel consumption estimating techniques, were taken from the TAPCUT reports. To expand that information, further detail was developed on fuel efficiency variation between driving cycles experienced by vehicles using the new engines. With these data, the vehicles were compared in different driving cycles to reveal their strong points in terms of fuel economy realized in specific applications. Applications compared were in-city driving versus suburban driving.

BACKGROUND ON THE ECONOMICS OF ENGINE INNOVATION

History of Automotive Engine Innovation

Recent and ongoing research at Argonne National Laboratory's Center for Transportation Research reveals that the process of introducing new, more efficient automotive engines into the marketplace involves a period of very costly adjustment for consumers, motor vehicle manufacturers, and the national economy (2-5). This research reveals that the inflation-adjusted (real) costs of motor vehicles increase sharply during a period of engine innovation, especially for low-income consumers. As a consequence, motor vehicle sales decline, the income-generating side effects of automobile production decrease, consumers have less money to spend, and real national wealth per capita diminishes or stagnates (see Table 1) (2). Prior research revealed that three distinct periods of automotive engine innovation occurred since World War I (WWI). Within each of these periods (1926-1935; 1952-1959; 1979-1984), there were subperiods of very low automotive sales and weak national economic activity. Automobile sales

TABLE 1 Rates of Change in Real Vehicle Price and Horsepower and Other Economic Indicators, 1921-1983 *(2)*

Measure	Annual Change (%)[a] 1921-1926	Innovation Period I, 1926-1934: 1926-1932	Innovation Period I, 1926-1934: 1932-1934	1934-1952	Innovation Period II, 1952-1960: 1952-1958	Innovation Period II, 1952-1960: 1958-1960	1960-1977	Innovation Period III, 1977-1983[b]
Vehicle price[c] and engine power								
Ford								
Cost (1921 $)	-7.25	17.8	-3.7	1.3	3.8	-13.3	-1.7	4.1
Horsepower	0	16.5	17.7	0.7	5.3	-37.9	-0.1[d]	-8.4[e]
Chevrolet								
Cost (1921 $)	-9.5	10.2	-12.5	2.8	3.9	-3.5	-1.8	2.0
Horsepower	0	15.0	7.2	1.4	7.9	-25.7	-1.3[d]	-3.5[e]
Dodge								
Cost (1921 $)	-9.6	6.7	-7.9	0.9	3.0	-11.3	-0.6	0.8
Horsepower	0	9.4	20.4	0.9	4.6	-13.5	-0.1[d]	-7.2
Buick								
Cost (1921 $)	-9.0	4.9	-9.9	0.9	3.6	-3.8	-1.0	2.7
Horsepower	5.4	3.1	6.0	1.8	18.9	-11.3	-2.3[d]	-3.3
Cadillac								
Cost (1921 $)	-5.8	6.8	-11.1	-3.9	5.0	-1.5	0	-3.7
Horsepower	1.6	5.1	6.3	1.3	9.3	0	-3.7[d]	-10.4
Lincoln								
Cost (1921 $)	-0.5	1.1	3.1	-5.1	5.9	-6.4	-1.3	3.0
Horsepower	-1.1	5.6	9.5	0.4	18.6	-7.2	-4.7[d]	0.9
Other economic indicators								
Index of relative motor vehicle prices[f]	NA	5.0	-6.4	-0.02	1.5	0.2	-1.2	0.1
Passenger car sales per capita	18.4	-19.0	39.1	2.7	-2.0	22.8	0.7	-6.1
Real GNP per capita (1958 $)	6.6	-5.5	2.8	4.1	0.3	2.5	2.8	0.9

[a]See Table 1.1 *(2)*, footnotes a-d; these footnotes identify slight variations in years of data.
[b]The method used tends to understate cost increases here because new, smaller, lower-cost models were added by many makes. When interior volume is held constant, costs go up much faster than shown here. The author's favorite examples are the two American automobiles he bought in 1978 and 1980. From 1980 to 1984, the minimum cost of an equivalent volume (same body style) vehicle of the same make went up in real terms by 11.0 percent per year for the cheaper four-cylinder model, and 5.2 percent per year for the more expensive model in which a V-6 replaced the V-8.
[c]After World War II, model-year introduction prices are used for costs in the calendar year "before" the model year.
[d]Use with caution; the method of computing horsepower changed in the middle of the time interval.
[e]Diesels are used in 1983, although they are not the lowest-cost models.
[f]NA = not available. Relative prices computed from wholesale price indices.

were lower at the beginning than at the end of each of the subperiods 1929 to 1932, 1955 to 1958, and 1979 to 1982, and real gross national product (GNP) per capita had declined (these subperiods are not illustrated in Table 1). Intervening periods, however, were characterized by relatively consistent peacetime economic growth fostered by a general increase in affordability and sales of automobiles. Table 1 illustrates these facts by presenting statistics on real costs (based on deflation with the wholesale price index) for the lowest-cost car available from a range of economy to luxury makes. Rates of change of costs are averaged over critical intervals from 1921 to 1983, enabling comparison between innovative and noninnovative engine development periods.

The annual rate of real cost increases of six representative makes of car is shown for selected time intervals from 1921 to 1983 in Table 1. These makes were selected because they represent the full price range of vehicles available from U.S. producers. They are roughly ranked according to their position in the lowest to highest price range and highest to lowest sales range.

Three graphs (Figures 1 to 3) based on information from Table 1 help to illustrate some key features related to the automobile engine innovation process. First, Table 1 uses horsepower change as an indicator of the rate of introduction of new engines. A high rate of change in horsepower (positive or negative) is used to define an innovative period. The term innovation is used to mean "the introduction of something new" (as defined in Webster's New Collegiate Dictionary), referring to the widespread introduction of new engines by all automobile manufacturers. Table 1 and Figure 1 show that three periods of relatively stable engine horsepower (1921-1926, 1934-1952, and 1960-1977) have been followed in each case by an unusually rapid change of horsepower in nearly all makes. Table 1 shows that during periods of stable engine horsepower, relative motor vehicle prices for all makes mostly tended to decline, while any increases were moderate. In contrast, the initial years of engine innovation (1926-1932, 1952-1958, and 1977-1983) were characterized by real price increases in lower-priced makes that were more rapid than the average for all motor vehicles (see Figure 2) and that also represented a significant increase from the preceding price trend for the make. Figure 1 graphically shows the latter pattern for the two lowest-priced makes, Chevrolet and Ford.

After each of the cost-increasing periods of engine innovation was well under way, sales of automobiles dropped to a depressed level at the same time that economic activity (as measured by real GNP) dropped into what has subsequently been recognized as one of the worst slowdowns of that historical period. The end of the first innovative period, 1932, is now recognized as the lowest point of the Great Depression. The end of the second innovative period (1958) is within a period now labeled the "Eisenhower Stagnation" in economics texts, and the most recent of the three innovative periods has also been described as a time of economic stagnation.

The typical economic interpretation of the link between national economic activity and automobile sales views national economic aggregates (interest rates, national output, and unemployment) as pushing the motor vehicle industry down. Few economists have emphasized the possibility of a systematic reversal of causality in which internally created cost increases pull automobile sales down, with the automobile sector in turn pulling the rest of the economy down. Nevertheless, the evidence presented here is consistent with the latter interpretation. Admittedly, this evidence only addresses three of the worst business downturns since WWI. It does not show a causal link to each U.S. recession. It does show,

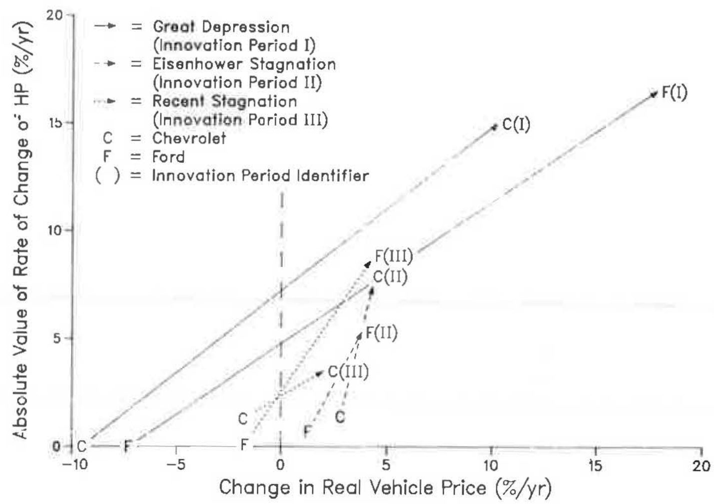

FIGURE 1 Historical relationship between automobile price and engine innovation: Ford and Chevrolet base models, 1921 to 1983 (from Table 1).

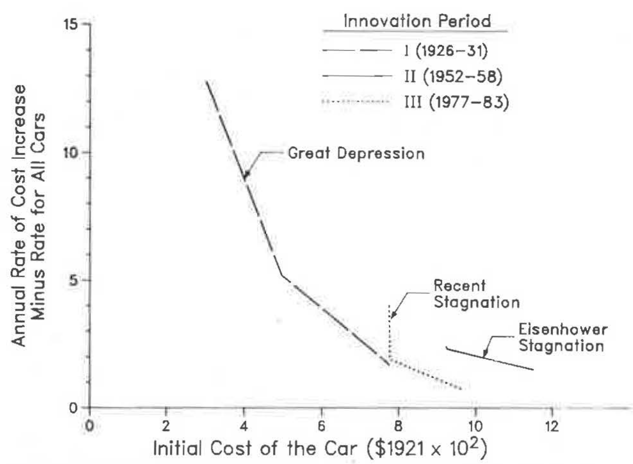

FIGURE 2 Differences between average annual rates of automobile price increase and rates experienced by Ford, Chevrolet, and Dodge during three periods of engine innovation [from Table 1 and Table 1.1 *(2)*].

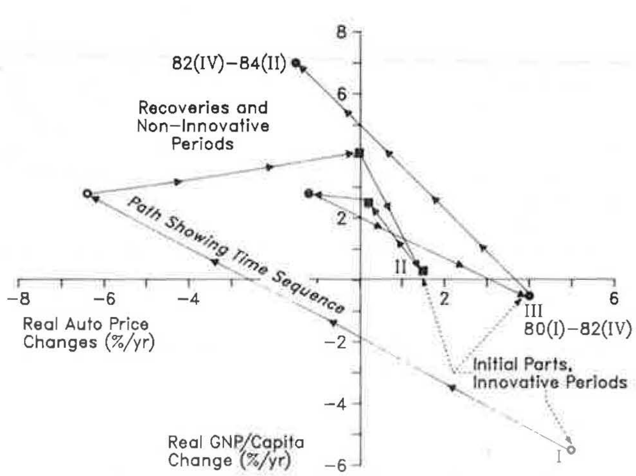

FIGURE 3 Relationship between annual rates of change of aggregate real motor vehicle price and real GNP: selected sequential time intervals, 1926 to 1984 (from Table 1 and text).

however, that costly automotive innovation can logically be argued to be causally linked to many of the periods of low macroeconomic growth occurring since the automobile became the transport vehicle with the largest value of output in the nation.

Figure 3 traces the history of aggregate real automobile price increases and real GNP increases over substantially the same time intervals shown in Table 1. The only change is a shift to carefully selected quarterly data for the 1980 to 1984 time period (2,6). This selection is made desirable by the automobile industry's recently adopted strategy of introducing new makes in the spring, with regular but unscheduled price adjustments. Use of quarterly data also illustrates the fact that the current economic recovery can be argued to have been promoted by real motor vehicle price reductions. Using Figure 3 for the third innovation period and Table 1 for the first two, one can see that each rapid price increase at the start of a period of engine innovation was followed by a period of relatively rapid reduction of prices for many, if not all, makes. This reduction in price occurred in conjunction with a nominal "recovery" that left the economy at a higher but still unsatisfactory (from a political point of view) level of activity in these cases.

The evidence presented here is intended to set the background on the importance of proper preparation to allow engine innovation to take place with minimal cost. A comparison of the three innovative periods discussed most recently implies that the greater the positive shift in trend of cost of low-cost vehicles (and the greater the positive shift in trend of aggregate vehicle costs), the worse the effect on GNP per capita. One interpretation of this pattern is that moderate rates of introductions of innovative engines, accompanied by moderate increases in aggregate vehicle costs, might allow a more successful transition (in the sense of less negative macroeconomic side effects) than would an attempt at an abrupt, industry-wide transition from one set of engine technologies to another.

Arguments Concerning Causes of Engine Innovation and Its Side Effects

Before moving from the discussion of the automobile's past to the automobile's future, one should consider the history of vehicular engine innovation processes in order to develop some judgment about the future. First, the evidence suggests that some triggering mechanism caused all automobile manufacturers to simultaneously change their engine characteristics. One possibility would be competitive pressure as described by the economic model of "perfect competition." However, this is a poor explanation, because competitive pressures are supposed to push price down and sales up. The sensible explanation is that a transition in fuel characteristics (price or quality or both) precedes and triggers an engine innovation period. Another frequently observed factor is the effect of environmental regulation (2-5).

When one introduces fuel price and quality as causal factors in creating incentives for consumers to change and delay engine--and perhaps vehicle--choices, then a theoretical explanation is provided for recently published statistical evidence that crude oil price shocks have been causally linked to nearly every U.S. recession since WWII (7,8). Hamilton's statistical study (7) begins to fill in the gaps in Table 1 with evidence consistent with the hypothesis that changing consumer preferences for automotive engines may be a consistent cause of recessions.

The view that changing consumer purchasing habits are the causes of recessions and depressions is not a new one. Keynes was the most notable proponent of the view that changes in the "propensity to consume" caused business downturns (9). However, although Keynes suggested several reasons for such changes, he performed no empirical evaluation of those reasons. None of Keynes' suggested reasons had anything to do with energy. In the arguments presented here, economic actors rationally change their propensity to buy certain engines based on fuel price and quality shifts. Vehicle and engine manufacturers attempt to meet changed purchaser preferences by investing in the production of new or innovative engines. The limited evidence presented here suggests that this process drives up engine and vehicle costs, thereby depressing vehicle demand. It has been argued elsewhere (3,5) that if this process becomes prolonged because of continuing synergistic interactions between fuel and engine attributes, a depression could result. The more rapidly the process comes to a halt, or the less costly the innovations undertaken, the less severe the business downturn should be.

The downturns examined in Table 1 and Figures 1 to 3 have each been fairly long, and the engine innovations have been costly to the vehicle purchaser. The behavior of the economy during these periods is consistent with the earlier interpretation of events, given that economists have used the words "depression" and "stagnation" to distinguish these periods from other periods of rather steady growth interrupted by occasional recessions. In more lengthy investigations it has been found that the engine innovations attempted during recessions are either immediate and clear successes or immediate and clear failures. Furthermore, they have generally been treated by engineering historians as refinements rather than significant technological innovations (4). The clear absence of significant engine innovations in the noninnovative periods in Table 1 implies that any changes adopted during intervening recessions were relatively minor. However, the author's investigations indicate that minor engine innovations were often characteristic of recessions (4), whereas Hamilton's work suggests that, during the post-WWII period, such changes were induced by positive shifts in crude oil price (7,8).

Since the mention of Keynes' theories concerning the importance of shifts in the propensity to consume, the terminology has been changed from "consumer" to "purchaser" or "economic actor" when changes in the propensity to consume engine and vehicle combinations are discussed. This has been done because, if fuel price and quality shifts occur, there is no reason to believe that only final consumers will readjust their purchase plans. Businesses that use engines should also be expected to alter their choice of engine. In fact, it can be argued that businesses are even more likely than consumers to make economic calculations that might lead them to choose a new engine. Thus, although Keynes emphasizes the importance of the final consumer, this model of engine purchaser behavior recognizes that both purchasers of final goods (consumers) and intermediate goods (businesses) will simultaneously reevaluate their choice of engine after a shift in fuel price and quality.

Pre-1900 Historical Evidence Supporting the Causal Arguments

Research for this paper on the subject of the link between engine innovation and the business cycle has gone as far back as the late 1700s. Although the negative side effects arising from altered engine purchasing patterns can be explained in terms of a consumer response since WWI, one must recognize the similar nature of transport-sector business responses to see that it is essentially the same phenomenon that was consistently repeated in the 1800s and early 1900s. A brief discussion of the 19th-century engine innovation process can help put possible future innovations in perspective.

The steam engine was introduced as a stationary engine in the late 1700s. It was later applied to marine use, railroad use, and finally, by the 1890s, to automotive use. Its introduction to railroads in the United States created competitive pressures on canal builders. In 1836, a form of locomotive was invented that became the mainstay of the U.S. rail transportation system until the 1890s. This was the 4-4-0, or "American" locomotive, a single locomotive type deemed worthy of its own book (10). This locomotive type led to the use of far more expensive locomotives than had been used in the 1830s. Nevertheless, from 1839 to 1842 it almost completely supplanted the outmoded 4-2-0 in production, while the late-1830s boom in canal construction was completely choked off (see Figure 4). Canal spending never revived. The years of 1839 to 1842 were described by

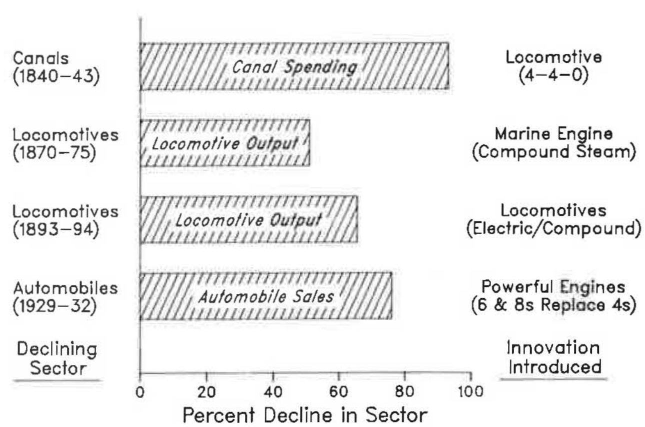

FIGURE 4 Depression-inducing peak-to-trough decline of output of old transport technologies made obsolete by innovative competing technologies [cases given occur at outset of four worst U.S. depressions *(4)*].

Milton Friedman and Anna Schwartz as the "second worst monetary collapse in history" (11). (The period of the worst monetary collapse occurred during the most rapid automotive horsepower change in history, labeled "Innovation Period I" in Table 1).

In the early 1870s, the costly but efficient compound marine steam engine was introduced on the Great Lakes and along the eastern seaboard by integrated transportation companies that owned both railroads and shipping lines. Construction of ships expanded rapidly at the same time that railroad locomotive (see Figure 4), freight car, and track mileage construction dropped sharply. At the time, most railroad mileage was in the Northeast and Midwest regions where competition from Great Lakes to Erie Canal to Long Island Sound shipping routes was prevalent. The drop in rail activity coincided with a decline in business output that followed the Panic of 1873. The low level of business activity lasted for 5 years, a period described by historians as a depression.

Compounding in a reciprocating steam engine adds complexity and increases first cost in order to improve efficiency. Compounding involves stepwise expansion of steam in separate, increasingly large cylinders. As more compounding steps were added, the pressure of the steam in the first cylinder was increased. Similar procedures are now used in electric generating steam turbines (steam is expanded in small, high-pressure turbines first, then in larger low-pressure turbines). In marine reciprocating steam engines, the stages of expansion were increased sequentially over a period of time from two to five. Triple expansion, first widely adopted in the mid-1880s (during a recession) proved to be the most economically successful. Quadruple- and quintuple-expansion ships were few in number, given their lack of economic success. The reciprocating, external combustion marine steam engine was eventually replaced by the external combustion steam turbine and the internal combustion diesel.

The reciprocating internal combustion engine is currently going through a similar sequence. More and more devices are being appended to the engine (turbochargers and intercoolers, for example) in the search for more efficiency (12). In the case of the reciprocating marine steam engine, the process ended when this engine was supplanted by the steam turbine. Today, both the high-pressure steam turbine and the diesel are used in marine applications, with the diesel used in low-speed applications and the turbine in high-speed applications. Later in this paper, the systematic evaluation of the diesel and the internal combustion turbine for automotive applications leads to the conclusion that the greatest advantage of the diesel is in low-speed stop-and-go applications, whereas the turbine is comparatively better when used at higher, steadier speeds. It is also seen that the internal combustion turbine is the next logical step up from the internal combustion reciprocating engine, just as history shows that the same sequence was followed for external combustion (i.e., steam) engines.

Only three stages of steam expansion were tried in locomotives. Severe space and weight limitations prevented further evolution. Two-stage compounding was introduced in U.S. locomotives in 1889, and was widely adopted during the depression of the 1890s, which began in 1892 (see Figure 4). Electric locomotives, which cost two-and-a-half times as much as steam locomotives per unit power, were also adopted for specialized uses where high power, reliable service, dependable cold-weather operation, smokeless operation, or all four were required. A boom in street railway construction occurred during this depression, as urban rail systems almost completely replaced the horse with the electric railcar. Steam locomotive sales dropped precipitously (see Figure 4) and several different models were introduced. The next stage of compounding in locomotives was not tried until the next depression. The only triple-expansion locomotive ever built for a U.S. railroad was the "L.F. Loree," the only locomotive delivered in the Great Depression year of 1933 (13).

The period between the depression of the 1890s and the Great Depression is an informative one because it reminds us that several forms of motive power occasionally coexist in various transportation modes. The gasoline-powered automobile was introduced during the 1890s depression. During the interdepression period, both electric and steam locomotives had significant shares of the market. Early in the period, both electric and gasoline automobiles had significant shares of the market. Electrics were preferred for urban driving by women, because of their quiet, clean operation and the elimination of the manual starting problem of the early gasoline models. The automatic starter was a major cause of the demise of the electric car. Steam-engine cars, which never used the principle of compounding, were successfully introduced before gasoline cars and remained in production until the increase in horsepower of gasoline-powered vehicles during the 1926 to 1932 time period.

The diesel-electric locomotive was introduced in 1924 for railroad yard switching. It also found applications in urban areas where legislation required smokeless running. This was stop-and-go service, for which the diesel is well suited. Although diesel-electrics cost five times as much as steam engines per unit of power (13), they cost only twice as much as electrics, the principal competition in smoke-restricted areas. They carried their own power plant and therefore did not require the costs of rail electrification. Smoke laws and pollution control (the latter related to horses) had played a role in the introduction of the first electric locomotives. Smoke laws also played a role in the introduction of diesel locomotives. Environmental legislation thus forced the initial use of these two innovative locomotive engines (5,13).

Conclusions and Summary of Historical Discussion

Four key points can be derived from this discussion:

1. It is apparent that historically significant engine innovations have consistently begun just before U.S. depressions and have continued during the depressions. However, when one looks at history from the long-term point of view it is doubtful that one would want to prevent engine innovation in order to avoid its negative side effects. The alternative, then, is to recognize that these events must take place but to plan ahead of time so that they cause less damage to the economy.

2. The possibility that the almost universally used internal combustion reciprocating automotive engine may be partially replaced by other engine types is not without historical precedent, given the prior simultaneous existence of steam and electric locomotives and steam, gasoline, and electric automobiles.

3. The eventual economic failure of the reciprocating steam engine was presaged by the increasing complexity of the engine as more and more stages of compounding were attempted. The fact that the internal combustion reciprocating engine is becoming more complex in the quest for efficiency (turbocharging, turbocharging plus intercooling, increasing

the number of valves per cylinder, and possibly turbocompounding) (12) may also presage its slow demise.

4. The role of environmental regulation in forcing the adoption of the first electric locomotive (5) and the first diesel locomotive (13) suggests that the possibility of such effects should not be ruled out when considering costly new engines. It is also true that the regulations that forced the introduction of new locomotive engines also caused the introduction of far more efficient engines that later found use in applications where their environmental virtues were not the critical determinants of their success. This might also happen with the automotive Stirling engine.

In the latter half of the paper the potential introduction of the Brayton internal combustion turbine or the Stirling, an external combustion reciprocating engine that uses a low-molecular-weight gas as a working fluid, is examined. Some of the reasons that diligent advance work should be done on these engines are that such work can allow the engines to be introduced without uncertainty, at a lower initial cost, and perhaps at an earlier time but at a more gradual rate. All of these attributes of engine introduction should reduce the apparent consumer shock effects that caused the kinds of vehicle output declines shown in Figure 4.

There is certainly a possibility that the 1890 to 1930 pattern of multiple-engine locomotive and automobile history might repeat itself in the automotive sector. Ironically, the diesel, previously encouraged by environmental laws and currently one of the engines that enhances fuel efficiency, might in the future be restricted in some urban areas for environmental reasons. The Stirling engine, although costly and economically unproven in any major market, offers the potential for very low emissions, thus making it of interest for potential use in urban applications. The Brayton, already successful in stationary, marine, and aircraft applications, may be able to use cheap (low-octane) fuel efficiently while cruising. However, it might be ruled out for everyday urban use in large metropolitan areas because of smog-promoting nitrogen oxide emissions and poor idle performance. Other attributes of these engines, which are described in this paper, make them potential candidates for specialized future automotive uses, much like the specialized uses of the electric, steam, and gasoline cars in the 1890 to 1926 period.

Future Versus Past Automotive Engine Innovation Costs

Table 1 and Figure 3 show that the real costs of lower-priced makes increase at the greatest rate during a period of engine innovation. This is not a coincidence. In fact, the same behavior observed in the past has now been unintentionally "predicted" by two recent economic studies of future engine innovation. The first, a Los Alamos study (14) estimated such a pattern of 1980 to 1990 cost increases as discussed in the earlier version of this paper (15). The second study, TAPCUT (1), provides the information necessary to calculate the percentage increases in real vehicle cost by vehicle price that would arise if U.S. automobile manufacturers were to shift from Otto-cycle internal combustion engines in 1990 to either diesel, Brayton (gas-turbine), or Stirling engines by the year 2000 (see Table 2) (1). Regardless of the engine type selected, real costs are projected to increase at a higher rate for lower-income buyers. However, as one might expect, a conversion to Brayton or Stirling engines is projected to be far more costly than a conversion to advanced diesel engines.

The TAPCUT-based estimates of the total real-vehicle-cost percentage increases for the introduction of Stirling and Brayton engines (Table 2) are somewhat lower than those of the 1926 to 1932 period that initiated the Great Depression (Table 1) but are greater than the engine and vehicle innovations of the mid-1950s and early 1980s (Table 1). Consequently, given the typical consumer reaction, one might expect a period of general economic difficulty surpassing that of the mid-1950s and early 1980s if future events were to cause a similarly rapid and universal conversion from reciprocating internal combustion automotive engines (diesels and Otto-cycle engines) to Stirling and Brayton automotive engines. However, as this study illustrates, a partial conversion is far more likely and desirable.

Study Purpose

The introductory discussion of the economic impacts of engine innovation suggests that the solution of the technical problems in engine design is only the first step in successful introduction of the engine

TABLE 2 Projected Real Costs of Adopting Innovative Engines in Place of the Otto-Cycle Engine to Improve On-Road Urban Fuel Efficiency, 1990 to 2000 *(1)*

		Advanced Diesel			Stirling			Brayton		
Vehicle Type	1990	2000	Percent Change	Percent per Year	2000	Percent Change	Percent per Year	2000	Percent Change	Percent per Year
Automobile										
Mini										
Cost	5,460	6,550	20.0	1.8	8,160	49.5	4.1	8,460	54.9	4.5
Mpg	36	57	58.3	4.7	57	58.3	4.7	55	52.8	4.3
Small										
Cost	6,144	7,180	16.9	1.6	8,790	43.1	3.6	9,060	47.5	4.0
Mpg	33	51	54.5	4.4	51	54.5	4.4	50	51.5	4.2
Medium-sized										
Cost	7,908	9,010	13.9	1.3	10,600	34.0	3.0	10,790	36.4	3.2
Mpg	23	33	43.5	3.7	36	56.5	4.6	35	52.2	4.3
Large										
Cost	10,200	10,910	7.0	0.7	13,600	33.3	2.9	13,140	28.8	2.6
Mpg	19	29	52.6	4.3	29	52.6	4.3	29	52.6	4.3
Van										
Cost	7,555	8,670	14.8	1.4	10,130	34.1	3.0	10,340	36.9	3.2
Mpg	27	42	55.6	4.5	42	55.6	4.5	41	51.9	4.3

Note: cost is expressed in 1980 dollars.
Fuel economy based on prior TAPCUT work. Methods in this study are related derivatives. Fuel economy estimates are "as driven" estimates and tend to be less than pre-1985 EPA estimates when used for 1980 automobiles.

into the marketplace. The rather negative side effects of the three prior periods of new automotive engine introduction suggest that a careful plan for slow introduction of new engines into the marketplace (with acceptance of slower recovery of engine R&D costs) might help to reduce the negative short-term side effects while allowing the long-term benefits of improved engine designs to be realized.

The purpose of this paper is to take previously developed engineering-based cost and performance information on the expected "post-breakthrough" behavior of Brayton and Stirling engines and systematically evaluate the best potential markets for those engines. It is assumed that if technical breakthroughs occur, they should inevitably lead to the introduction of new engines. However, it is also assumed that early, targeted introduction of new engines, accompanied by a slow expansion of market share, could prevent the problems that previously accompanied the widespread, rapid introduction of new engines. An accurate depiction of the most advantageous uses of new engines will help consumers and producers make better decisions concerning their use, as well as prevent early abandonment of otherwise successful engine technologies. For example, in view of current engine characteristics, it is questionable whether the almost complete abandonment of four-cylinder engines in the early 1930s was economically or technically desirable.

VEHICLE CHARACTERISTICS

The vehicle characteristics used in this study were based on slight modifications of the projected vehicle designs developed for the TAPCUT study (15, 16). Vehicle design variables that were altered over the 1980 to 2000 time interval included (a) materials composition, (b) weight, (c) engine-to-road system or "cruise" efficiency, (d) idle fuel-flow rate, (e) engine location (front-wheel drive), and (f) drag coefficients. Costs of realizing the design characteristics were also estimated. General driving-cycle equations were developed to simulate urban, highway, and combined driving. Characteristics of large and small vehicles that this study projects for the year 2000 are given in Table 3.

In an earlier draft of this paper, further details on materials use, aerodynamics, and the fuel consumption model were given in a discussion that focused more on the Stirling and Brayton evaluation methodology and far less on the historical aspects.

FUEL CONSUMPTION TRADE-OFFS

The properties shown in Table 3, along with engine costs, make the comparison of the Stirling and Brayton to the diesel and Otto-cycle engines a more complex task than the comparison of the diesel to the Otto. The diesel is superior to the Otto both in terms of idle fuel-flow rate and system efficiency. The Stirling is similarly superior to the Otto in both of these categories. However, the Stirling is projected to be superior to the diesel in system efficiency, but inferior in terms of idle fuel-flow rate. Consequently, in terms of vehicle fuel efficiency, the Stirling can do worse or better than the diesel, depending on the percentage of trip time spent in braking and at idle. In contrast, the diesel can never do worse than the Otto, so the recent use of simple point estimates of fuel efficiency was generally acceptable for consumer comparisons of diesel and Otto engines. In the case of the Stirling, however, knowledge of its behavior as a function of its driving cycle would be much more valuable to the consumer.

If this case can be made for the Stirling engine, it can be made with even more vigor for the Brayton. The Brayton has the best cruise and acceleration system efficiency of all of the combustion engines characterized in the TAPCUT study, while also having the worst braking and idle fuel-flow rates. The system efficiencies of both the Brayton and Stirling engines come dear in terms of estimated initial vehicle cost, as Table 2 illustrates. The diesel's 16 percent system efficiency gains with respect to the 1990 Otto engines come at a real cost of about 7 to 20 percent, with the lowest percentage of cost increases occurring in larger six-passenger vehicles. Another 33 percent gain in system efficiency can be obtained in the year 2000 for 20 to 30 percent additional real cost if one purchases a Brayton. The Brayton and Stirling vehicles consistently cost more than the diesel, but shift positions relative to one another as vehicle size increases. In a large vehicle, the Brayton costs less than the Stirling. In all other vehicles, the Stirling costs less. Although these results might appear to be speculative, it should be remembered that extremely small versions of the Stirling engine have been successfully operated, and the Brayton has increased its aviation market by a gradual reduction from larger sizes. The Brayton can thus be expected to enter the automotive engine market from the top end of the horsepower range in larger vehicles. It might have to be successful in heavy-duty vehicles before being introduced into large automobiles.

DRIVING CYCLES

For the purposes of this paper, urban, suburban, and "combined" driving cycles were disaggregated from the TAPCUT SAE J1082 driving cycle, which included urban and suburban segments. For purposes of rough

TABLE 3 TAPCUT Small and Large Vehicle Characteristics for Year 2000

Vehicle and Engine	Laden Weight (lb)	Horsepower	Idle Fuel Flow Rate (gal/min)	System Efficiency (%)	Vehicle Cost (1975 $)	Cost Increment ($) Versus	
						Otto	Diesel
Small							
Otto	1,990	103	0.0094	18	4,005	–	-664
Diesel	1,950	101	0.0027	21	4,669	+664	–
Stirling	2,071	107	0.0059	25	5,720	+1,715	+1,051
Brayton	1,845	97	0.0100	28	5,894	+1,889	+1,225
Large							
Otto	2,940	156	0.0141	18	6,850	–	-593
Diesel	2,887	153	0.0039	21	7,443	+593	–
Stirling	3,015	159	0.0087	25	8,847	+1,997	+1,404
Brayton	2,726	146	0.0142	28	8,553	+1,703	+1,110

comparison, the urban cycle used in this study averages 15.9 mph, whereas the Environmental Protection Agency (EPA) "city" cycle averages 19.6 mph. This study's suburban cycle averages 40.2 mph, whereas EPA's "highway" cycle averages 48.2 mph. The TAPCUT study focused on urban and suburban driving only, but EPA must account for rural and intercity use in the driving cycles that it uses to evaluate vehicle efficiency. Additional details are available from the author.

Large Automobile/Large Engine Driving Patterns

The Brayton's slight cost advantage over the Stirling in large automobiles, which tend to be powered by large engines (see Table 3), suggests that it might have its best market opportunity in large automobiles. A 1975 GM study (see Table 4) (17) shows that large automobiles are driven more miles per day than are medium-sized and small automobiles. It also shows that those with larger engines are driven more miles per day. Geographically, the study shows that residents of low-density zip code regions drive their automobiles the most. These drivers also achieve mileage closer to the EPA ratings than do drivers in more densely populated regions. Because automobiles with low EPA mileage ratings (presumably large vehicles with large engines) were consistently closer to their EPA ratings than other automobiles, it seems reasonable to assume that these vehicles were driven less in heavy traffic and in stop-and-go driving. The low-residential-density region appears to be a good potential market for the fuel-efficient Brayton engine, because the figures in Table 4 imply that automobiles are driven intensively in that region and they are driven relatively less frequently in a stop-and-go fashion. Consequently, the Brayton's superior cruise efficiency could be used to its advantage, allowing the vehicle to realize better on-road mileage than its competition. Given the intensive use of the vehicle, its lower fuel expenses could more rapidly repay its high initial cost. The national benefits of a more fuel-efficient engine technology for rural and suburban use could be very substantial, given the fact that about two-thirds of the mileage driven is in such regions (see Table 4).

This study and other studies cited in the earlier paper (15) have found that the diesel's relative fuel-efficiency advantage in small automobiles increases when it is driven fewer miles per day (a surrogate for urban driving) and at lower speeds. This behavior is due to both the relatively flat torque and power curves of the diesel engine and its low rate of fuel consumption at idle. It is worth noting that General Motors now plans to abandon diesel engines in its large- and medium-sized automobiles, but will retain the diesel option in the small Chevette (15). Good low-speed torque and low idle fuel-flow rates are also characteristics of the Stirling engine, making it a logical urban competitor to the diesel. Furthermore, the front-end aerodynamic penalties arising from the bulk of the Stirling engine are unimportant in urban driving-cycle applications.

In this paper discussion will be limited to automotive applications. A discussion of other possible vehicle applications of Stirling and Brayton engines can be found in the earlier version of this paper (15).

Year-2000 Economic Payoff Estimates Comparing Engines in Selected Markets

Table 3 shows the weight, horsepower, idle fuel-flow rate, system efficiency, and year-2000 vehicle costs for large and small vehicles with Otto-cycle, diesel, Stirling, and Brayton engines. Differential 1975 dollar costs for the Stirling and Brayton engines in comparison to Otto and diesel engines are also presented.

Table 5 shows the incremental benefit-cost ratio obtained by comparing a Stirling or Brayton engine with an Otto or diesel engine. It is assumed that the vehicle is driven in a suburban cycle in a relatively lightly populated area, where average miles per day (AMPD) values are high (17,776 mi/year or

TABLE 4 Dependence of AMPD on Population Density and Other Factors, Model-Year 1975 GM Automobiles *(17)*

Selected Characteristics of Various Size Regions	Population (Owner Zip Code)[a] 25,000	25,000-999,999	≥1 million	U.S. Avg Sample-Weighted	VMT-Weighted
Percentage of cars in sample	48.0	47.6	4.4	NA	NA
Percentage of vehicle miles of travel[b]	66.3	27.3	6.4	NA	NA
AMPD	46.6	39.1	29.6	42.3	43.5
Standard deviation of AMPD	61.3	41.2	18.0	NA	NA
Average slip, road/EPA	0.90	0.86	0.80	0.87	0.88
AMPD versus vehicle weight (lb)					
3,000	40.9	31.3	28.1	35.9	37.5
4,000	44.8	36.6	29.1	40.2	41.6
5,000	48.7	41.9	30.0	44.5	45.6
AMPD versus engine displacement (in.^{3})					
150	42.3	34.3	23.1	37.9	38.9
250	44.5	36.8	26.2	40.2	41.2
350	46.8	39.3	29.4	42.4	43.6
Road mpg/EPA mpg					
10 (EPA)	0.92	0.86	0.80	0.89	0.90
15 (EPA)	0.89	0.83	0.78	0.85	0.87
20 (EPA)	0.86	0.81	0.76	0.83	0.84
27.5 (EPA)	0.82	0.77	0.74	0.79	0.80

Note: NA = not applicable; AMPD = average miles per day.
[a]As a rule, zip code regions with fewer residents are actually larger in area than those with many residents. Thus, the assumption that the low population of a zip code region means low population density is justified.
[b]Nationwide Personal Transportation Study, Report 7 *(17)*.

TABLE 5 Incremental Year-2000 Benefit/Cost Ratios for Innovative Engines in Large Automobiles Driven in a Suburban Cycle in Low-Density Areas

		Actual Fuel-Saving Benefit Versus Incremental Engine Cost for Correctly Projected Suburban-Cycle Use					Misestimated Fuel-Saving Benefit Versus Incremental Engine Cost for Incorrectly Assumed Combined-Cycle[a] Use				
			Very High Fuel Cost Versus		High Fuel Cost Versus			Very High Fuel Cost Versus		High Fuel Cost Versus	
Engine	Vehicle Cost (1975 $)	Mpg with Cold Start	Otto	Diesel	Otto	Diesel	Mpg with Cold Start	Otto	Diesel	Otto	Diesel
Otto	6,850	30.1	–	0.21[b]	–	0.59[b]	24.2	–	0.13[b]	–	0.36[b]
Diesel	7,443	42.6	4.72	–	1.69	–	39.6	7.53	–	2.79	–
Stirling	8,847	46.2	1.56	0.22	0.57	0.09	37.5	2.06	No benefits	1.07	No benefits
Brayton	8,553	49.9	2.14	0.73	0.80	0.32	35.5	2.20	No benefits	1.22	No benefits
Brayton (revised)[c]	8,164	49.9	2.78	1.12	1.03	0.49	35.5	2.85	No benefits	1.58	No benefits

Note: It is assumed that vehicle is driven 17,776 mi/yr or 48.7 AMPD (see Table 4).
[a]Combined-cycle mileage developed with a 7.5-mi urban trip, 10.2-mi suburban trip, 55 percent urban driving, and 45 percent suburban driving.
[b]Engine cost reduction benefits versus fuel cost increases.
[c]The Brayton engine is estimated to cost 2.5 times the Otto engine in the same car (*15*).

48.7 mi/day; see Table 4). Estimates in Tables 5 and 6 are based on the assumption that the vehicle is driven for 7 years and then scrapped (regardless of total mileage) and that future real dollars are discounted at a rate of 5 percent. The unrealistic but usefully illustrative assumption that the vehicle is driven the same number of miles in each year of its life is used. (This was judged to be a useful way to simplify approximation of estimates of present values of fuel savings. In reality, vehicles are driven longer but annual mileage declines.) Cold-start calculations are based on an assumption of four equal-length trips per day for suburban and city driving cycles, while EPA city and highway driving-cycle distances are used for combined-cycle estimates. The estimator of the value of innovative new, rather than advanced existing, engines is based on a ratio of the present value of the expected fuel savings to the additional cost that must be paid for the innovative new engines. The ratio should be greater than 1.00 if consumers are to buy the alternative engine. The high year-2000 fuel costs from the TAPCUT study are used ($2.53/gal for gasoline and $2.42/gal for diesel fuel in 1975 dollars), along with "low"--but still higher than current--gasoline and diesel fuel costs equal to $1.00/gal in 1975 dollars. In this study, these two price levels are referred to as "very high" and "high" fuel costs. Gasoline is used in the Otto cycle engine (at 115,400 Btu/gal), while diesel fuel is used in all other engines (at 127,200 Btu/gal). The frontal area of all large automobiles is 26 ft^2; for small automobiles it is 20 ft^2.

The first set of estimates in Table 5 is based on the assumption that a large vehicle is driven in a suburban cycle and its fuel economy is evaluated on the basis of suburban-cycle performance. Under this assumption, the advanced diesel has the highest benefit/cost ratio compared to the Otto engine; the ratio is greater than 1.0 regardless of whether high or low fuel cost is used. The question then is whether the Stirling or Brayton offers any other advantage over the diesel. The Brayton has the best suburban-cycle mileage of any of the engines, but its high cost reduces its benefit/cost ratio below 1.0 compared to the diesel. However, when fuel costs are very high, the ratio is close to 1.0. If the annual mileage of the large vehicle was 24,200, then the Brayton vehicle would be just as good an investment as the diesel. A market for a dependable, high-mileage Brayton vehicle could therefore develop in suburban and rural areas if fuel prices rise enough.

The TAPCUT engine cost equations may overestimate the cost of a Brayton engine. Volkswagen expected to be able to build a smaller Brayton than that in these large cars for 2.5 times the cost of an Otto-cycle engine (15). The TAPCUT estimates cause the Braytons of Table 5 to cost 3.6 times more than the Otto engine. If this ratio is reduced to 2.5, a Brayton vehicle becomes economically attractive with very high fuel costs if driven in an average low-density suburban pattern (17,776 mi/year).

The latter set of estimates in Table 5 shows how critical the consumer's estimating information can be. Since the Brayton has very poor urban-cycle mileage, a combined-cycle mileage figure lowers its "estimated mpg" by EPA-type methods (55 percent urban, 45 percent highway) so much that the suburban-driven large Brayton would be judged an unqualified loser compared to the advanced diesel. Yet these estimates would unfairly penalize an engine that, when used appropriately, could save fuel for consumers and the nation. Furthermore, such an estimating technique would retard efficiency-enhancing engine innovation when it was most needed (i.e., if fuel

TABLE 6 Incremental Year-2000 Benefit/Cost Ratios for Innovative Engines in Small Automobiles Driven in an Urban Cycle in High-Density Areas

		Actual Fuel-Saving Benefit Versus Incremental Engine Cost for Correctly Projected Urban-Cycle Use					Misestimated Fuel Saving Benefit Versus Incremental Engine Cost for Incorrectly Assumed Combined-Cycle[a] Use		
			Very High Fuel Cost Versus		High Fuel Cost Versus				
Engine	Vehicle Cost (1975 $)	Mpg with Cold Start	Otto	Diesel	Otto	Diesel	Mpg with Cold Start	Very High Fuel Cost Versus Otto	High Fuel Cost Versus Otto
Otto	4,005	31.1	–	0.30[b]	–	0.79[b]	35.4	–	–
Diesel	4,669	55.5	3.36	–	1.26	–	57.4	2.62	0.97
Stirling	5,720	47.8	1.06	No benefits	0.39	No benefits	NE[c]	NE	NE
Brayton	5,894	41.4	0.71	No benefits	0.25	No benefits	NE	NE	NE

Note: It is assumed that vehicle is driven 10,256 mi/yr or 28.1 AMPD (see Table 4).
[a]Combined-cycle mileage developed with a 7.5-mi urban trip, 10.2-mi suburban trip, 55 percent urban driving, and 45 percent suburban driving.
[b]Engine cost reduction benefits versus fuel cost increases.
[c]NE = not estimated.

prices reached very high levels). The suburban-driven large Stirling is economically squeezed between the diesel and the Brayton. If fuel prices are high enough to make a Stirling economically desirable compared to the advanced diesel, the Brayton will be even more attractive.

Table 6 compares year-2000 engines in small automobiles driven and evaluated on urban cycles in high-density regions where the automobile is driven only 28.1 mi/day, or 10,260 mi/year (see Table 4). In this situation, the Stirling and Brayton engines are simply not desirable when compared with the diesel. They cost more and get worse mileage than the diesel, making them unqualified losers by these criteria. With the TAPCUT characteristics, neither of these engines is destined to take over the urban automotive market on the basis of fuel consumption economics alone. The diesel looks good even when fuel costs in the year 2000 are $1.00/gal in 1975 dollars ($1.73 in 1983 dollars). Its benefit/cost ratio exceeds 1.0 in both cases, but it is close to 1.0 in the high-fuel-cost case. Interestingly, the diesel would not be attractive at 1985 fuel prices, which is consistent with the weak 1985 market for diesels. If the diesel is ruled out on environmental grounds, the Stirling would be a better urban alternative than the Brayton, but it would only be a desirable innovation relative to the Otto engine if fuel costs rose to a very high level.

The last two columns of Table 6 illustrate that the averaging problem inherent in the "combined" EPA fuel economy and corporate average fuel economy (CAFE) ratings could retard the urban adoption of diesel engines. If engines are driven in an urban pattern but are evaluated using a combined rating, the incremental benefit/cost ratio of the diesel drops. In the high-fuel-cost case, the ratio drops 23 percent, enough to bring the ratio below 1.0. This would make consumers evaluate the diesel as a loser even though they could save fuel and money by using this engine in an urban setting.

Taken together, the results of the calculations presented in these tables suggest that the efforts by EPA to present separate, realistic estimates of expected city and highway mpg are of great value in helping consumers to make an economically efficient engine choice for their vehicle. However, reliance on the current CAFE estimating method, with its statistical fiction that vehicles are driven 55 percent in city use and 45 percent in highway use regardless of vehicle type or ownership location, might someday lead to disincentives toward engine innovation on the part of producers. If a producer knows that a Brayton-powered vehicle can get high enough mileage in suburban and rural use to make the added engine expenditure worthwhile to those consumers, but at the same time expects to be penalized on his CAFE ratings because EPA assumes that the vehicles will be used differently, what will the producer do? Given the likely long period before fuel prices rise enough to make this question important, there is probably enough time for policymakers to consider it carefully.

CONCLUSION

It has been shown that the Brayton and Stirling engines are likely to have very well defined, limited, but nevertheless significant, markets. It is important to verify this analysis so that it may be used as a framework to define research and policy changes that can lead to successful and timely introduction of the Brayton and/or Stirling engines when and if fuel and environmental market conditions make them desirable.

This research tends to support established directions in Stirling and Brayton engine research. Because these engines are long-term technological options and are suitable for a limited market, they are not likely to get adequate R&D support from the private sector alone. From the national point of view, these are technologies that, it is hoped, will never be needed, but if conditions arise that make them desirable (i.e., a return of high fuel prices or unacceptable urban pollution, or both), it would be good to have them "on the shelf." These are technologies that could offer a high payoff to the nation in very high national risk situations that have a low probability of occurring in any one year in the near- or medium-term future. However, it can be argued that these events have a high probability of occurring in some future year. It is generally recognized that this defines an area in which basic government R&D is appropriate and necessary. If that is not enough, the macroeconomic penalities implied to exist for a nation that fails to plan ahead for its engine technology transitions should encourage advanced government preparation for the inevitable next transition.

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A Quick Assessment of Local Area Impacts Resulting from National Energy Shortages

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ABSTRACT

A method to aid in estimating the local area impacts of national energy shortages is presented. Using data from the 1977 Nationwide Personal Transportation Study and forecasting models developed in NCHRP Report 229, the study examines the potential travel impacts of fuel shortages in six different-sized urban areas under seven different energy future scenarios. These scenarios are defined by fuel supply shortfall, by government actions taken to offset this shortfall, and by whether long-range conservation actions are taken by the public. The study found that the most effective actions for reducing fuel use were long-range conservation actions such as moving closer to work or buying a more fuel-efficient automobile. In the absence of a fuel shortage, the 1990 scenario with long-range actions showed a decline in fuel use from 1980 of 13 to 15 percent, while the 1990 scenario without these actions showed a decline in fuel use of only 2 to 4 percent. The most effective type of transportation system management (TSM) actions for reducing fuel use are those that discourage solo driving. In addition, there is a significant difference in the amount of fuel saved by work versus nonwork TSM actions in future scenarios that do not contain long-range adjustments. However, in future scenarios with long-range adjustments, the amount of fuel saved by work versus nonwork travel becomes more of an even split. Smaller-sized urban areas will be affected the most by future energy shortages because of lack of available transit and fewer opportunities for carpooling. The impact of long-range actions on fuel use is greater in these areas because of a greater proportion of automobile travel. However, this does not fully compensate for the reduced availability of alternatives to automobile use in these areas.