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INFORMATION, COMPLEXITY AND EFFICIENCY: THE AUTOMOBILE MODEL*

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ABSTRACT

The new and rapidly evolving field of industrial ecology - the objective, multidisciplinary study of industrial and economic systems and their linkages with fundamental natural systems - provides strong grounds for believing that a more environmentally and economically efficient economy will be more information intensive and complex. Information and intellectual capital will be substituted for the more traditional inputs of materials and energy in producing a desirable, yet sustainable, quality of life. While at this point this remains a strong hypothesis, the evolution of the automobile industry can be used to illustrate how such substitution may, in fact, already be occurring in an environmentally and economically critical sector.

In the United States in the late 1960's, the most desirable automobiles were powered by what affectionados fondly called "Detroit iron": big, 400-plus cubic inch V-8 engines which were relatively crude but effective. These so-called "muscle cars" consumed enormous amounts of gas, frequently getting less than ten miles per gallon, and the untreated exhaust was high in lead, hydrocarbon and NOx concentrations. But gas was cheap, air was free, and environmental concerns were not yet widespread. Then came Earth Day in 1970, and the energy crises of the early 1970's. Pollution control equipment was superimposed on existing engine designs. Demand for improved gas mileage increased, culminating in the passage of the Energy Policy and Conservation Act in 1975 (15 U.S.C. Secs. 2001 et seq.), which established corporate average fuel economy (CAFE) requirements for new automobiles. Accordingly, in the early and mid 1970's, average engine size dropped, engine efficiency dropped, and performance dropped (NRC, 1992; MacKenzie, 1994).

Yet the drop in automotive performance, measured along almost any parameter, was temporary. The average size of the engine in passenger cars did, indeed, drop and

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stay smaller, but the horsepower began to rise as engineering in production engine systems became more sophisticated. More fundamentally, the ratio of average horsepower to engine displacement increased significantly, indicating more efficient operation (Figure 1). Indeed, between 1975 and 1991, the fuel economy of the average new car improved significantly, from 15.8 to 27.8 miles per gallon. At the same time, absolute performance of the product was increasing, as measured by acceleration times (Figure 2). In fact, a 1992 National Research Council report noted that the average passenger car horsepower-to-weight ratio, an important indicator of performance capability, was greater in 1992 than at any time since 1975. The modern automobile unquestionably provides more performance per unit resource (in this case, gasoline). Moreover, the automobile in 1997 is considerably safer, handles better, lasts longer, and offers far more amenities - such as advanced sound systems, on-board diagnostics and climate control systems - than two decades earlier. Impressively, these gains have been matched by similar increases in environmental efficiency: since controls were introduced in 1968, VOC and CO emissions per vehicle have been reduced by some 96 percent, and, since imposition of NOx controls in 1972, emissions of those species have been reduced by over 75 percent (MacKenzie, 1994).

In short, over the last two and a half decades, one of the principal - and defining - artifacts of the modern industrial economy has undergone an almost revolutionary change. It has improved its environmental peformance on a per unit basis substantially; it is a far safer and more desirable product; it has significantly enhanced not only its performance, but the efficiency with which it generates that performance. How? And more to the point, what has that to do with industrial ecology and the information sector?

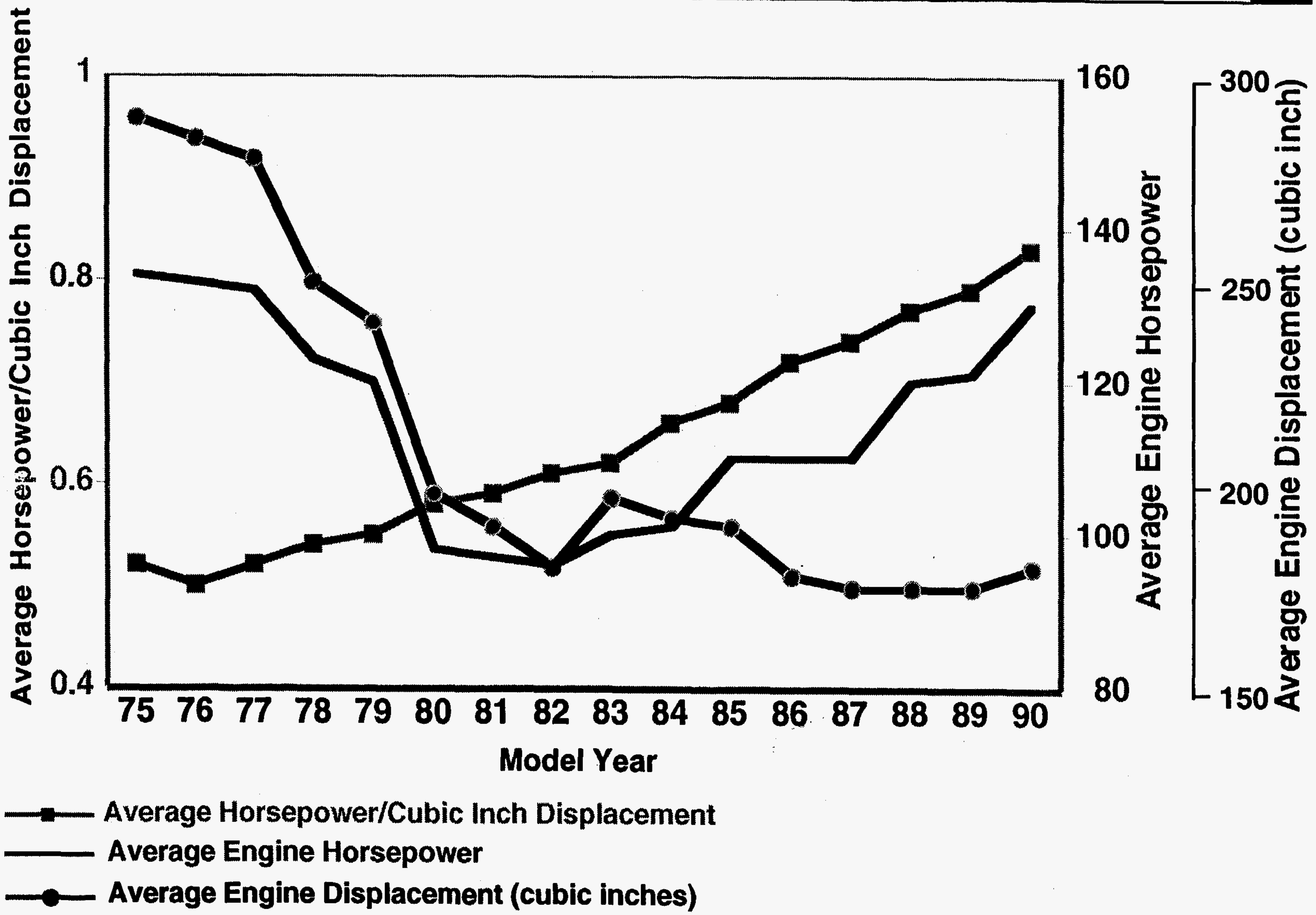
The performance of the modern automobile reflects a number of incremental improvements: reductions in vehicle weight, better aerodynamic design, reductions in tire rolling resistance, reduction in friction losses, new catalytic systems, more efficient engines and drivetrains. But there is one common theme underlying the evolution of the modern automobile: it has become a much more complex system, with a far higher information content than its predecessors (Figure 3). Moreover, increasing intelligence built into the automobile is enabling it to be increasingly linked to its external environment, becoming a subsystem in a yet more complex automotive transportation system.

Internally, older cars were linked mechanically; new cars are linked by systems of sensors feeding into multiple computers. Whereas older cars had minimal electronics, newer ones have substantial systems which need to be integrated both physically and functionally. As Mark Thompson of Motorola notes, the numbers of cables and wiring harnesses required by the modern automobile have increased to such an extent that routing them through the vehicle becomes a design problem in itself: for example, "[d]oors . . . can barely be made to open and close properly, what with wires for window controls, locks, outside mirror controls, and other switches and lights." (Thompson, 1996) Reflecting a greatly more complex engineered system, sophisticated multiplexed microcontrollers thus become a necessary component of the modern automobile.

Producing a more complex system requires, in turn, more sophisticated design tools and manufacturing technologies. For example, "lightweighting" - reducing the weight of vehicles through better design and material substitution - requires precision manufacturing and becomes a far more information intensive activity. Germany's Audi company, for example, believes that only the advent of supercomputing power provided the necessary processing power to design the complicated lighter components that have permitted them to lightweight their product. Difficult design problems are resolved by virtual reality design processes; as **The Economist** (1994) says, "powerful computer-aided design (CAD) systems can replace with a click of a computer-mouse hours of

Figure 1

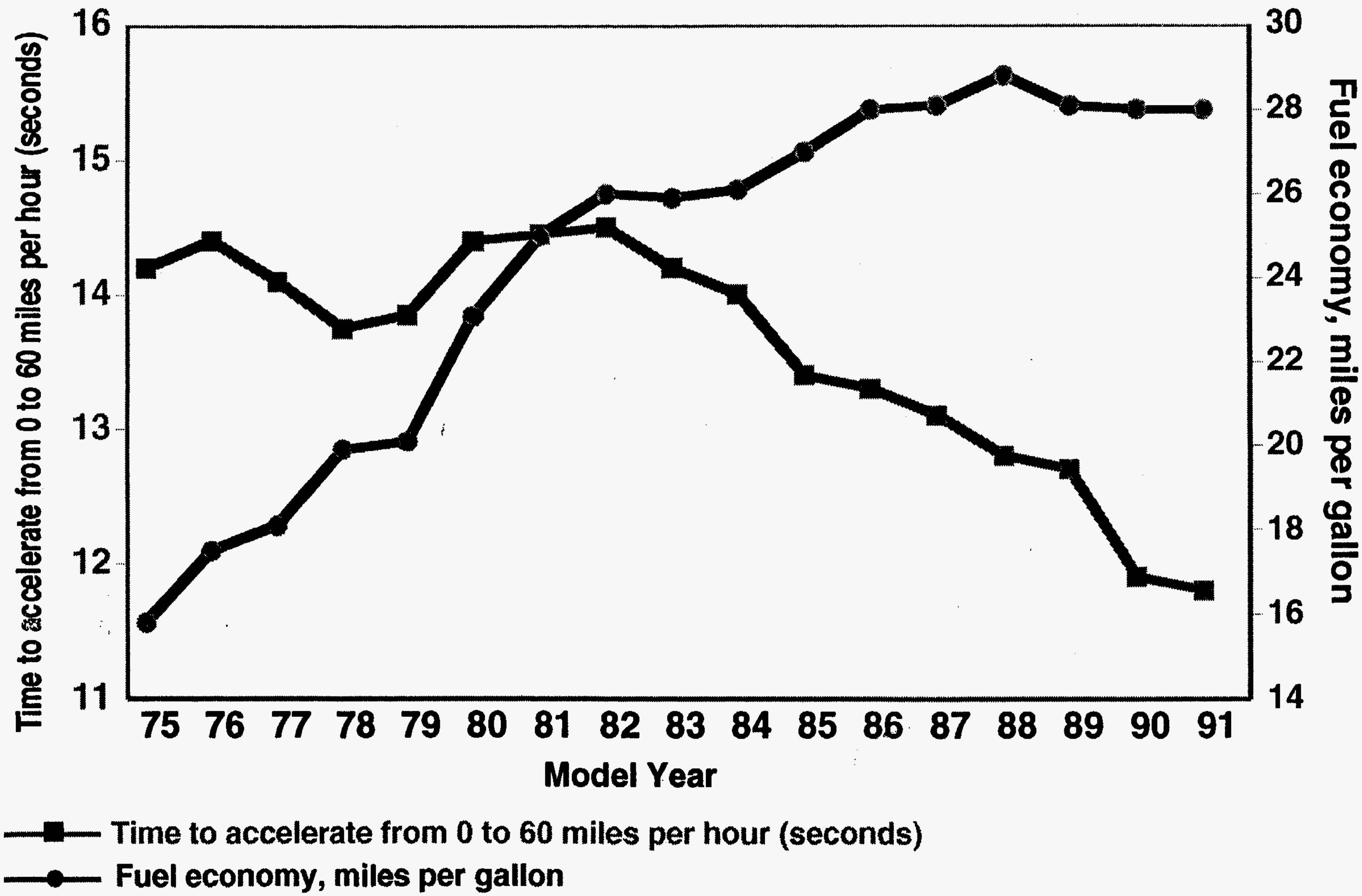
Automobile engine systems, 1975-1990



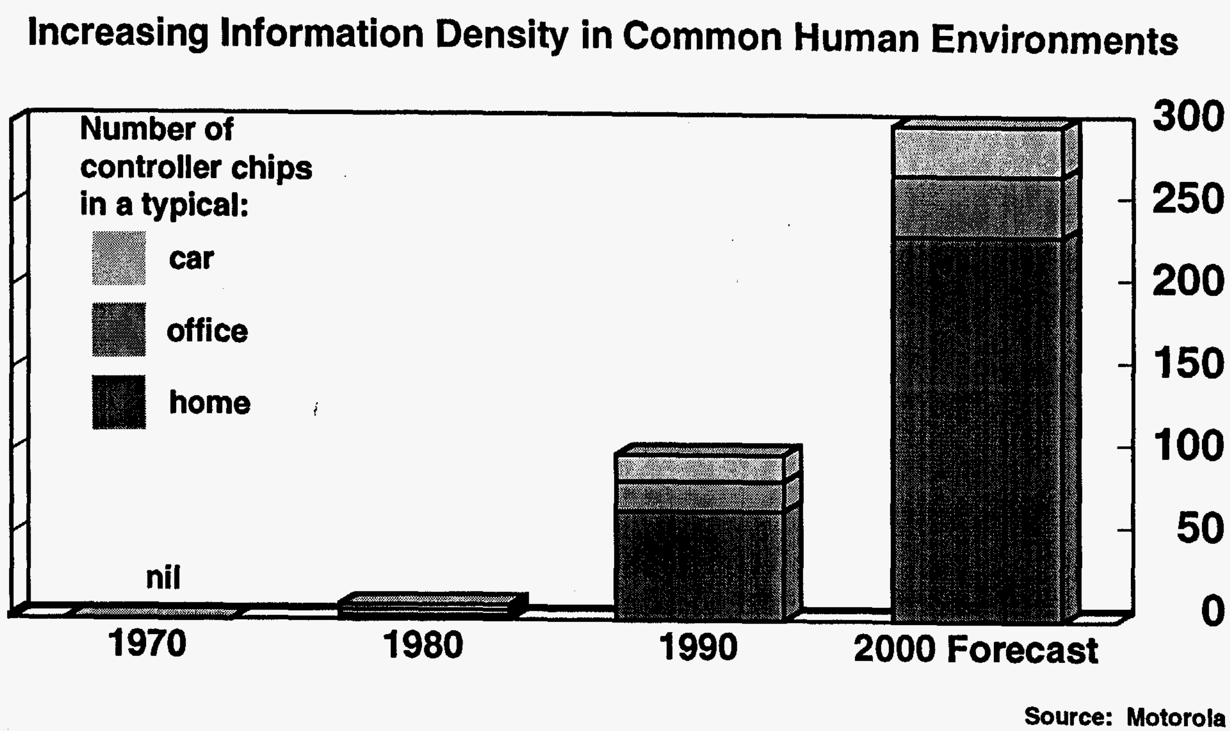
Based on National Resources Council, Automotive Fuel Economy (Washington, D.C., National Academy Press: 1992)

Figure 2

Fuel economy and performance of passenger cars, 1975-1991



Based on National Resources Council, Automotive Fuel Economy (Washington, D.C., National Academy Press: 1992)



Increasing Information Density in Common Human Environments
Number of
controller chips
in a typical:
car
office
home
nil
1970
1980
1990
2000 Forecast
300
250
200
150
100
50
0
Source: Motorola

Figure 3

laborious work done on thousands of drawing boards." In fact, Boeing never built a physical model of its latest aircraft, the 777, which is now flying: it was created entirely within a distributed computational system.

As with the artifact, so with the built infrastructure system within which it functions. In older cars, virtually the only information link between the automobile and the external environment was the driver; today, sensor systems monitor exhaust systems, the oxygen content of air flows, and road conditions, and newer systems already deployed in leading countries such as Japan even map the car's geographical position, provide up-to-date road conditions and optimal real-time routing options, and pay tolls electronically without the need to stop. The technologies that will permit ongoing communication between road networks and automobiles - in essence integrating the automotive built infrastructure, the automobile, and the driver into one automotive transportation system, which can then be optimized for real time efficiency by, for example, use sensitive automatic roadway pricing - already exist (**The Economist**, 1993-1994; Jurgen, 1995).

In sum, the evolution of a more environmentally and economically efficient automobile is an analogy for at least some of the characteristics of a more sustainable economy. To the extent that the analogy is valid, it suggests that such an economy will be more, not less, complex, and, concomitantly, far more information dense. Information generation (through, e.g., appropriate systems of sensors), the evolution of more complex feedback systems, and tighter linking of previously disconnected subsystems (e.g., intelligent cars on intelligent roadway systems), will support a fundamental pattern: the substitution of data and knowledge - information - for other, less environmentally appropriate, inputs into economic activity (Allenby, 1994; Allenby and Richards, 1994; Graedel and Allenby, 1995; IEEE, 1995).

If the information sector taken as a whole is an enabling sector for progress towards sustainability, it is still useful to consider it as several separate components. The first is the services side, which includes such traditional services as telephony, data transmission, as well as the integration of such basic services into more complex offerings such as telecommuting packages. A growing number of less traditional information services such as remote energy meter reading and consumption control systems are also being deployed. The second is the design, manufacture, use and recycling of the end use electronics products which underly the provision and consumption of information services. Electronic communications switches are examples of the former, while televisions, VCRs, and telephones are examples of the latter. The integration of electronics products and services into other products and offerings is intermediate between these two. Although it can be thought of as simply supplying components, such as automotive microprocessors, to other sectors, the functions such components enable, and the degree to which they support the increased complexity of offerings into which they are incorporated, justifies separate treatment.

Although usually viewed as a relatively clean industry, electronics manufacture is energy and water intensive, and uses some highly toxic materials. Moreover, the rapid pace of technological evolution and highly competitive international markets for electronics goods results in rapid product obsolescence, and thus substantial generation of waste materials as old products are discarded. Realization of the full environmental and economic benefits of the substitution of information for other economic inputs requires, therefore, that the environmental impacts of electronics products across their lifecycle be minimized. In the electronics industry, this is accomplished through the implementation of Design for Environment, or DFE, methodologies. These methodologies are discussed in great detail in a number of recent publications (Allenby, 1991; Microelectronics and Computer

Technology Corp., 1993; IEEE **Proceedings**, 1993 - 1995; **AT&T Technical Journal**, 1995).

There are thus a number of different levels in the automotive system at which information is being substituted for material and energy intensity, and where meta-systems are being created by combining systems - such as the automobile itself, and the infrastructure on which it runs - which today are only weakly linked. Among the most important levels are:

1. The design and construction of important sub-systems of the automobile, particularly the engine and drive system;

2. The design and construction of the automobile as a complete artifact; and

3. The increasing linkage of the automobile and its infrastructure in real time, creating the opportunity for much more efficient systems performance.

On the other hand, it is also important to remember that these efficiencies, gained through better use of electronics technology, do not in themselves address important cultural issues. Among the most critical of these are the substitution of much less efficient four wheel drive "sports utility vehicles" for family sedans, and continuing increases in demand, in both developed and developing countries alike, for automobiles and supporting infrastructure. The technologist may focus on specific process or product issues, but achieving continued progress towards a sustainable global economy requires the sophisticated integration of technology, culture and politics, and an appreciation of the complexity of the systems, human and technical, with which we must deal.

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