Linking Truck Design to Public and Private Life-Cycle Costs

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Heavy-duty vehicles are purchased according to the buyer's specifications and are subjected to a very long and intense service life. Correspondingly, the truck buyer and subsequent owners, as well as the motoring public, must find the as-built vehicle acceptable for a long time and over many miles of operation. In the course of its extended use, the design and configuration of each heavy vehicle will objectively affect its acceptability in terms of the life-cycle costs incurred by both the truck operator and the public. This paper will address the issue of private and public life-cycle costs as they are linked to the design specifications on which the vehicle, itself, was purchased. It is recognized that trucks, tractors, and trailers are purchased individually and that each vehicle will pose costs that trace ultimately to designs that have been specified extensively by the buyer.

Private costs, of course, will be borne by those who own or operate the truck. To understand why trucks are configured and equipped as they are, one must first recognize the natural economic mechanism that promotes truck design features that help the truck owner manage costs. Since the owner is making a business decision when buying the vehicle, the truck specification obviously tilts toward design features and configuration variables that will maximize the return on investment. Accordingly, components and features that do not square with financial payback to this business generally are not ordered, unless they are mandated by law.

Because trucking services do not add value to the shipped product, as far as the end consumer is concerned, pressures to cut trucking costs are continual. Although new service innovations are beginning to differentiate markedly one trucking operation from the next, for-hire trucking has traditionally been a commodity service, with fierce competition pitting large fleets against very small operators or even owners of single trucks. Ultimately the competitive pressures ensure that the design and configuration of the vehicle reflect the economic demands of shippers—the customers of truck operators—to receive reliable cartage services at minimum freight rates. Even in the private trucking sector, where a company operates trucks to meet its own hauling needs, competitive markets for the end product serve to put the squeeze on trucking-related costs.

When the truck purchase is rationalized against these pressures, it is obvious that the truck will become specified in a way that places the premium on productivity and efficiency. Additional components or design features that are not needed for satisfying the premium goals appear on the truck only if required by regulation, union contract, or a specific policy of the purchaser based on, say, company image or some higher operating ideology. Thus the private costs, especially those that will be incurred early in the truck's life cycle, will be reflected directly in the specifications on vehicle design due to the simple economics of trucking businesses.

On the other hand, only limited mechanisms are in place to ensure that the vehicle is designed and configured in such a way as to contain public costs. Such costs are incurred only indirectly by the public, by means of negative outcomes that include the following:

- The pollution of air with less-than-pure exhaust emissions,
- Deterioration of the public roadway due to truck loading,
- Energy consumption by trucks, with its corresponding impact on our national energy security and the production of carbon dioxide and other "greenhouse gases," and
- Truck-involved crash damage and injury to other road users.

Of course, various regulations and taxing mechanisms have been set up for containing differing aspects of public cost arising from trucking. Nevertheless, certain truck-induced costs continue to be borne by the citizenry without corresponding compensation or mitigation, although these costs may be addressed practicably through vehicle design and configuration. No private incentive exists for covering these costs, so there is little reason to expect that the uncompensated public costs will be considered without a public intervention of some kind.

Furthermore, looking forward from 1993, the political climate is one with a strong national concern to minimize governmental burden on industry, so additional federal standards on truck design and configuration may be few in number and relatively timid in their content. If this is true, an approach that is more subtle than the blunt instrument of federal standards is needed. This paper intends to rationalize the need for innovative methods that can ensure adoption of truck designs and configurations that suitably manage both public and private life-cycle costs within a politically realizable framework.

Before these public cost issues are considered directly, a brief discussion of the truck-user industry will be presented. This section of the paper will establish the scope of the industry and introduce the process by which new trucks are specified and purchased. These considerations show that because the industry as a whole is highly diverse, the designs of heavy trucks are prescribed to a remarkable degree of detail by each individual purchaser, reflecting only the purchaser's economics unless some other constraint holds sway. Once specified and built, the typical heavy truck lasts such a long time and accrues so many miles that the accumulated public cost attributable to each individual vehicle can be great.

The four categories of public cost indicated earlier will be addressed in the light of the public's exposure to each truck, however designed, over its service life. Differing levels of discussion will be devoted in each category, with lesser emphasis on the emissions and highway damage costs than on energy consumption and truck crashes.

The issues of exhaust emissions and highway damage are seen as genuine public concerns that are already receiving a high, and perhaps adequate, level of attention. Because the public concerns are well aligned with the trucker's desire to cut fuel expenses, further intervention by the public sector may not be warranted. Indeed, historical data on the specification and purchase of energy-saving options on new trucks will show that truck design is unquestionably being driven to account for the private-side expenses on fuel. Whether this compensatory action is in adequate proportion to the public burden is less clear.

With truck-involved crashes, however, it appears that costs borne by the public are large and more or less uncoupled from the economic mechanisms that bear on the truck operator. Furthermore, certain innovations in truck safety design may be achievable at an incremental private cost that is low relative to the public benefit. This observation is pursued in the final section of the paper by means of a proposed process for allowing new truck configurations that satisfy more productive size and weight limits only as a "package deal," with new safety and, say, highway-loading requirements attached. It is thus suggested that there may be a politically practicable approach to implementing truck designs that better manage public as well as private costs.

INDUSTRY SKETCH

More than 100,000 fleets operate combination unit trucks in the United States, of which more than 80 percent own five or fewer trucks (*1*). Thus, a huge number of individual companies are involved, each having its own operating practices and perspectives on the vehicle equipment that it requires. The vehicles are used over a wide range of hauling services: nearly a third operate on a for-hire basis and the rest are more or less dedicated to supporting a private vocational business such as manufacturing, agriculture, and construction (*2*). The diversity of hauling missions results in the distribution of heavy vehicles over the road system with highly differing loading conditions, mileage accumulations, road type selection, day versus night operations, and so forth.

The largest segment of heavy hauling is accomplished in five-axle tractor semitrailers, a vehicle group whose total tractor population in 1987 has been estimated at 706,000 vehicles (*3*). These power units were manufactured generally in the Class 8 weight range under essentially seven brand names, whose respective 1991 market shares are given here (*4*):

Manufacturer	*Market Share (%)*
Ford	9
Freightliner	23
Kenworth	12
Mack	11
Navistar	23
Peterbilt	10
Volvo GM	12

The total number of sales in this heaviest class in 1991 was 99,000 units (a volume depressed by 20 percent or so below average by the recession in the early 1990s). In almost all such sales, the product will have been marketed according to the process outlined in the following.

Heavy Truck Marketing

The heavy-duty truck is purchased by means of a buyer's order that includes a great specificity regarding the desired equipment. The order sheet will typically include selections from hundreds of optional specifications for, say, a road tractor. In each specification, the buyer may choose from a variety of alternatives in selecting individual components—frames, axles, springs, brakes, engines, transmissions, instruments, seating, fuel tanks, batteries, and on and on. The price list from one large manufacturer, Navistar (*5*), shows that a certain conventional-cab model is ordered by means of a "line setting ticket" that specifies 88 items, with options selected from among 21 seat options, 11 mirror selections, 13 fuel tanks, 18 rear axles, 11 rear suspension assemblies, and 51 diesel engine selections, each matched for compatibility against a matrix of 55 optional transmissions.

For the power train, the choices that have traditionally been available in terms of hardware are now vastly expanded through the tailored setting of programmable engine control software. And the trend is toward more and more specificity and selectability on the part of purchaser.

In short, when it comes to truck buying, the customer has a high degree of authority and latitude in selecting the equipment. Correspondingly, the truck manufacturer exercises much less assertiveness in pushing certain equipment packages on the buyer than is seen in the marketing of passenger cars. In the vast majority of medium and heavy truck sales, there is simply a "pull-marketing" relationship between the buyer and maker of the truck: very little is bundled into inseparable groups of optional components. This way, what the truck buyer doesn't want, the truck buyer doesn't get. This principle was confirmed in recent years by certain European manufacturers that attempted to introduce highly integrated vehicle packages into the medium and heavy truck market in North America and met with very little success.

The traditional assumption that underlies the remarkable level of specificity in the United States is that the differences that distinguish one trucking operation from the next must be reflected in detailed truck specifications if the operation is to be both productive and efficient. The tradition of detailed specification yields a system that is maximally responsive to the truck buyers' desires while slowing truck innovation to the buyers' pace of technical awareness and confidence. And the buyer is typically tilted toward conservatism, as well, in selecting unproven features since the vehicle will be used intensively over a very long service life: the buyer knows that specification mistakes can be costly.

If innovative features are to be sold on original equipment manufacturer (OEM) trucks, the crucial interactions will occur between potential truck buyers and (a) component salespersons who visit in advance of vehicle ordering to prompt the selection of proprietary items when the truck order is placed, and (b) the OEM salesperson who facilitates the ordering itself. If the vehicle is to incorporate an innovative item, the truck buyer must have been persuaded to take it through one of these two exchanges or through some other input. But if the functionality of the item is unrecognized, unfamiliar, or of marginal cost-justification in the buyer's mind, the chances of its inclusion on the order list will be low.

Truck Service Life

Perhaps the single most valued quality in any piece of truck equipment is durability, that is, the uninterrupted delivery of the needed functions over a long service life, given the specific hauling mission. As an indicator of the intensity of usage that is expected, Figure 1 shows the average annual mileage to which Class 8 tractors are subjected over a typical 17-year service life. [The values were obtained by computing average miles traveled during 1987 by vehicles whose age was also reported in the 1987 *Truck Inventory and Use Survey* by the Census Bureau (*3*). The data have been truncated to an effective limit lifetime of 17 years, estimating the diminished use

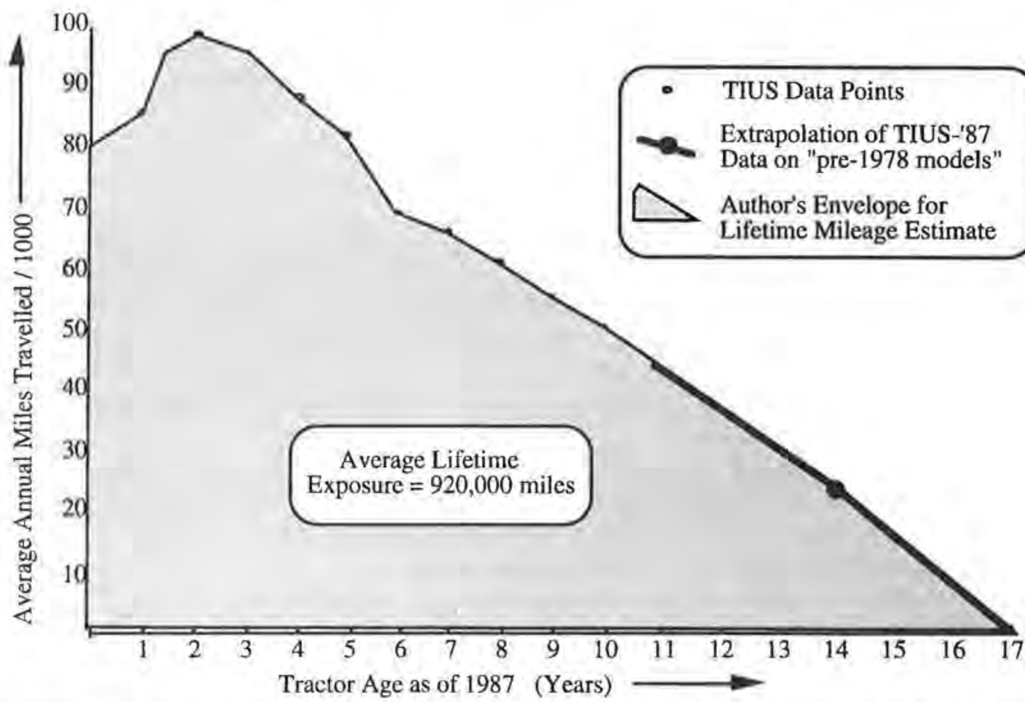

FIGURE 1 Average annual miles traveled by three-axle tractors in combination with two-axle semitrailers, as function of tractor age.

that continues with vehicles even older than 17.] The integral under this curve reveals a typical lifetime exposure of 920,000 mi.

Casual information from the industry suggests that the original purchaser is seldom the same party operating the vehicle at the end of a 17-year service life. Thus, the purchase specifications are obviously tilted to ensure highly efficient and reliable performance during the early years of service, when typical annual mileages are 80,000 to 90,000 mi/year. Clearly, the vehicle is specified to ensure high satisfaction for the original buyer as well as reasonable resale value when it is transferred to other users.

The service-life data show that the modern vehicle is so durable that it can sustain high-mileage use over a long string of years. This observation, suggesting that the American road system will be exposed to the as-specified vehicle for nearly 1 million mi of operation, is clearly central to the issue of public cost due to trucks and to the significance of an OEM design. Indeed, only after about 15 years does the annual mileage of an average heavy tractor drop into the range of 10,000 to 15,000 mi/yr to which the typical new automobile is exposed. Accordingly, the public costs that are attributable to each individual truck are scaled according to the lifetime exposure of the vehicle and are thus magnified in the case of the heaviest trucks and tractors.

Primary Sources of Public Cost Due to Trucking

The four previously identified sources of public cost due to trucking will be discussed in turn. Each presents a different context by which public costs can be managed if some means is found to control truck design, as follows:

- For exhaust emissions, the locus of design for controlling public costs is in the combustion and gas-handling technology of clean burning;
- For highway damage, it is through axle spacing, axle and tire loading, and perhaps suspension dynamics;
- For energy consumption, it is in combustion efficiency and parasitic loss mechanisms;
- For traffic crashes, it is broadly distributed among dynamic control qualities, conspicuity of the vehicle at night, splash and spray generation, load securement mechanisms, ride qualities affecting driver fatigue propensity, structures that determine aggressivity of the truck during impact, and other items.

Exhaust Emissions

The Environmental Protection Agency (EPA) has established a schedule of increasingly demanding requirements for the emission containment of heavy-duty diesel engines. In fact, U.S. standards on diesel emissions are the most stringent in the world. Clearly, a governmental regulation was necessary in this case since truck buyers have no natural economic incentive to specify a low-emission engine, per se. Thus, some public-sector role is required if the environmental agenda is to advance.

The EPA requirements cover a broad spectrum of pollutants. Table 1 indicates that a continued tightening of regulations on heavy diesel truck engines has been under way since 1974, with the most recent round of improvements dwelling on oxides of nitrogen and the particulates that are peculiar to diesel combustion (6).

Given that diesel emissions have been the subject of a vigorous process of federal regulation, it is apparent that the public costs of environmental damage have been recognized in this case and that countermeasures have been adopted. The needed corrections have been effected almost entirely by the manufacturers of heavy diesels, some of which are also OEM truck makers. To the degree that a modern, electronically controlled diesel retains a low-emission performance throughout the lifetime of the chassis, with overhauls, the EPA standard has

TABLE 1 New-Vehicle Emission Standards, Heavy-Duty Diesels (*6*)

Year	Hydrocarbons (g/bhp-hr)	Carbon Monoxide (g/bhp-hr)	Oxides of Nitrogen (g/bhp-hr)	Hydrocarbons and NOs (g/bhp-hr)	Particulates (g/bhp-hr)	Smoke (% opacity)
1970–1973	—	—	—	—	—	Accel = 40 Lug = 20
1974–1978	—	40	—	16	—	Accel = 20 Lug = 15 Peak = 50
1979–1983	1.5	25	—	10	—	Accel = 20 Lug = 15 Peak = 50
1984	1.5 (A test) 1.3 (B test)	25 (A test) 15.5 (B test)	— 10.7 (B test)	10 (A test)	—	Accel = 20 Lug = 15 Peak = 50
1985–1987	1.3	15.5	10.7	—	—	Accel = 20 Lug = 15 Peak = 50
1988–1990	1.3	15.5	6	—	0.60	Accel = 20 Lug = 15 Peak = 50
1991–1993	1.3	15.5	5	—	0.25	Accel = 20 Lug = 15 Peak = 50
1994–1997	1.3	15.5	5	—	0.10	Accel = 20 Lug = 15 Peak = 50
1998	1.3	15	4	—	0.10	Accel = 20 Lug = 15 Peak = 50

constituted a highly effective means of controlling the associated public cost, despite the long mileage exposure of the vehicles involved. The extent to which the typical modern engine will, in fact, deliver low-emission performance over its service life, however, is unknown. Furthermore, the author has not sought to establish how the cost of regulatory compliance compares with the public benefit of reduced rates of pollution.

Highway Damage

It is well recognized that the deterioration of highway pavement and bridge structures is strongly dependent on truck use of the roadway. In particular, there is a profound, approximately fourth-power relationship between truck axle load and the rate of pavement break-up (*7–9*). This aspect of truck-induced public cost has figured prominently in the taxation of trucks and appears implicitly in cost allocation approaches to highway financing. Namely, states have, with federal guidance (*10*), established graduated scales of road use and licensing taxes that differentiate among vehicle types on the basis of the perceived highway damage and ancillary highway costs that each vehicle imposes. Although a continuing debate ebbs and flows on the extent to which truck-induced highway costs are recovered by road agencies, one can assert that costs are being recovered to the degree supported by the overall political context (noting that the trucking community normally represents its interests vigorously in each state's legislative debate.)

To give a first-order estimate of the magnitude of tax revenue generated by heavy trucks to support highways, nationwide, a simple computation can be made on the basis of average tax rates and average vehicle cost and use. Diesel fuel is taxed at a federal rate of $0.201/gal and an average state rate of $0.18/gal (*11*). Assuming that the 1 million Class 7 and 8 trucks (*1*) each travel an average of 50,000 mi/year (*3*) at an estimated average fuel consumption rate of 6 mi/gal, the total annual revenue from fuel tax on heavy-duty vehicles is on the order of $3.2 billion. Annual federal tax on the vehicle itself is about $400/unit, depending on gross vehicle weight. A 12 percent excise tax is applied to the retail price of newly manufactured trucks and trailers, and an excise tax of about $15 is imposed on each new truck tire. It is estimated that these vehicle-based federal taxes total approximately $2.5 billion/year. In addition, states impose individual registration fees, surcharges on fines for violations, and weight-distance taxes in a few cases. Altogether, the collections from the heavy end of the truck population amount to approximately $6 billion, or 11 percent of the $55 billion in state and federal revenue collected from highway users. Out of the total revenue, some $46 billion in state and federal funds is spent on capital outlay, maintenance, administration, and law enforcement on the nation's highways (*11*). Another 25 percent or so is spent from receipts collected by county and municipal governments.

The cost allocation issue addresses the question of whether the amount that heavy vehicle owners pay compensates the public for the net costs associated explicitly with heavy truck use of the road infrastructure. Although this question is exceedingly difficult to answer in a comprehensive manner, it is apparent that the total highway program in the United States is substantially underfunded, overall, and that greater tax revenues must be generated in the future to suitably maintain its sprawling network of bridges and highways. Being sobered by the many vagaries of the cost allocation question, this author chooses to address only the mechanistic link between road wear and tear and the design of the truck itself.

It is generally believed that the first-order road damage factors derive only from axle load and the spacing between loaded axles as addressed in bridge formula calculations. Neither of these poses a very clear "design issue" relative to trucks since the only design characteristic in question involves the geometric layout of the vehicle configuration—in particular, the axle placement. Research also suggests that truck suspension is instrumental in determining transient load peaks that locally aggravate pavement deterioration, especially downstream of bumps and other surface faults (*9,12*). These results tend to argue for well-damped suspensions having relatively low vertical stiffness levels. Air suspensions and some of the more carefully designed spring suspensions are favored in this regard, but no requirements regarding suspension type have been imposed in the United States.

One innovative approach to minimizing truck-induced road damage was proposed by former FHWA Administrator Frank Turner (*13*). The Turner Proposal was to allow bigger, more productive truck configurations outfitted with additional axles that carry loads below current levels, thus accruing a large reduction in pavement cost that exceeds the value of an accompanying hike in bridge-related costs. The inherent attractiveness of the Turner Proposal is that a net public savings of approximately $326 million/year in highway costs is obtained through a policy that also offers a savings of approximately $2 billion/year in truck operating costs. TRB analysis clearly shows a "win-win" situation, where the savings to truck operators derive from the higher payloads that could be carried on an individual vehicle.

It appears that the for-hire trucking industry does not generally favor the Turner Proposal, however, since the transition to new vehicles requires a surge in capital investment while competitive pressures on freight rates will, in the long run, eliminate the cost advantages accruing to any individual trucking company. The macroeconomics look great, but the micro view taken by a for-hire trucking operation is not favorable. (An exception to the "micro" stalemate has been seen, however, when the for-hire operators have acted very quickly during a transition in truck size and weight allowance, buying new equipment immediately and striving to grab market share through the new productivity advantage before their competitors could catch up.)

Any shipper of freight, and thus all companies in the private trucking sector, should favor a proposal such as Turner's if it truly offers a net reduction in shipping costs. The apparent failure of the entire manufacturing community, and the private trucking segment in particular, to rally behind the Turner Proposal is, then, something of a puzzle. A suggested explanation is that the people who run the trucking divisions of large private product and service corporations are not, themselves, engaged in the strategic direction of these companies and thus are not well tuned to the company's long-term concern with global competition. Thus, when representing their corporate interest through, say, the National Private Truck Council, they may not readily concern themselves with the more esoteric long-term issues that stand to affect shipping costs across the board but instead are focused on the myriad tactical issues that face fleet operations. Nevertheless, the concept of a quid pro quo approach toward balancing public and private costs via truck design, as in the Turner Proposal, should be of interest to all private parties concerned with reducing the cost of freight movement; at the same time the concept offers a means to recover publicly borne trucking costs. This concept will be revisited on behalf of generic improvements later in this paper.

Energy Consumption

Considerable improvements in the fuel economy of heavy-duty vehicles have been obtained since the mid-1970s, beginning with buyer-specified components that helped to reduce parasitic losses and the selection of diesel engines offering more fuel-efficient operation. In this case, the perceived public cost associated with fuel use is expressed in terms of the level of national dependency on foreign oil importation (the so-called energy security issue), the release of greenhouse gases, and the sheer volume of toxic pollutants as it results from total gallons consumed.

But the public concern for these outcomes happens to line up with the obvious private concern of truck operators to limit what they pay for the fuel itself. When fuel prices more than doubled in 1974 and 1975, truck owners felt the stimulus right away. Thus, a truck owner's enhanced desire for a high level of fuel economy, measured in miles per gallon consumed by the truck, was squarely in line with the public desire as well. Whether today's fuel prices reflect the extent of public costs by attaining the needed level of private incentive is another question. Clearly, the public costs are not driven to zero through this mechanism, but they should certainly drop as the extant price of (diesel) fuel rises—albeit with some delay while economy-enhancing products are prepared for market. The progress toward improved energy efficiency in trucking will be reviewed both in terms of the state of achievement and as an example of the natural economic mechanism at work, by which the private costs of trucking tend to cause truck design and configuration to respond to the commercial pressures of the business.

All motor vehicles have seen a dramatic improvement in their fuel economy performance since the oil embargo of 1973. Passenger cars in the United States made improvements under the strong prod of the Corporate Average Fuel Economy (CAFE) rules, but the heavy truck sector did so largely on its own, with manufacturers collaborating through the Voluntary Truck and Bus Fuel Economy Program (*14*). Industry experts have told the author that the fuel economy performance of a typically loaded tractor semitrailer rose from about 3.5 mi/gal in 1973 to nearly 7 mi/gal in 1990. Evidence of the natural economics of fuel conservation is given in Figure 2, showing that heavy-duty trucks began to be specified with a strong concern for fuel economy soon after the oil embargo.

The data show that the specification of variable fan drives, for example, as a component installed on Class 8 trucks and tractors went from 4 to 96 percent of sales in 8 years (admittedly with a boost in 1978 from an EPA regulation that helped to cost justify the thermatic fan.) Radial tires, already popular in Europe in the early 1970s, gained rapidly in popularity because of both the remarkably lower rolling resistance (and thus improved fuel economy) and the better treadwear performance and recap ability. Aero cab shields showed a more modest rate of adoption, presumably because of some early structural problems and the somewhat reduced overall market, since they are not helpful when hauling flatbeds and most tank-style semitrailers.

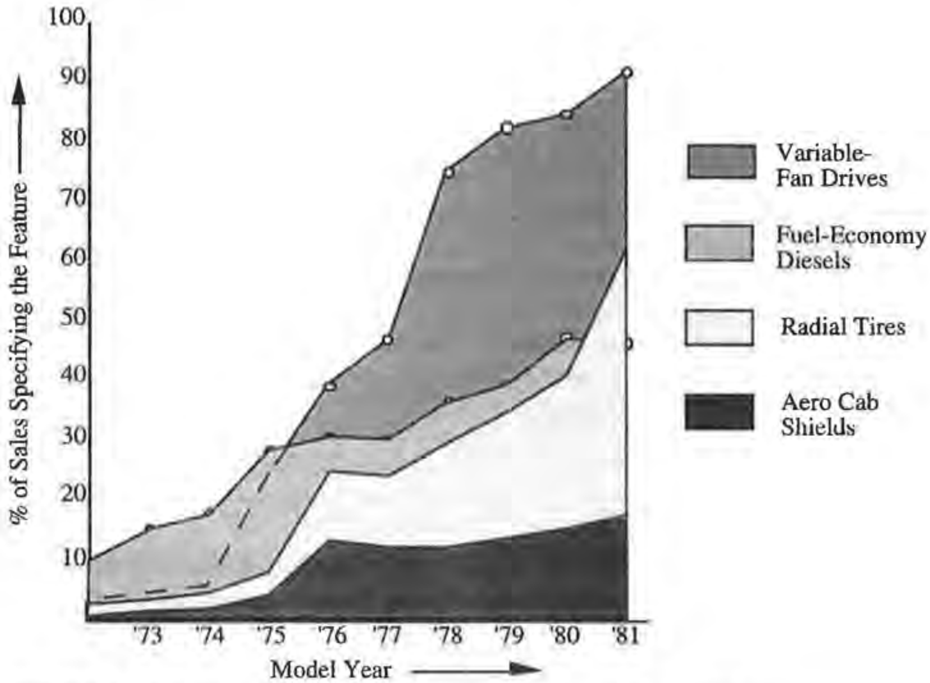

FIGURE 2 Adoption of design improvements versus model year (*14*).

The rapid rise in adoption of energy-enhancing features reflects the combined influence of the natural predisposition of truck buyers to contain rising fuel costs, as discussed, and the accelerated action by truck makers who were concerned about both meeting customer needs and avoiding a CAFE-equivalent regulation of their industry. The data make the obvious case that the truck buyer will respond to economic pressures, adopting new truck design elements as required to manage the private costs of trucking. It is clear that truck owners did not specify energy-saving features simply because of some newfound concern about geopolitical risk to the nation. Instead, it made good business sense—and truck owners are in the trucking business. It is elementary economics that wherever private costs arise, private response mechanisms will appear.

An interesting twist on the matter of energy economy is the growing obstacle to trucking posed by urban traffic congestion. To the extent that trucks encounter delay on congested highways, fuel is wasted because of the inefficiencies of shifting up and down the gear range in dense traffic, with the engine operating far from its peak economy regime. Accompanying this form of inefficiency is the much higher private cost of time—that is, the time-cost of the driver, the capital equipment, and the delayed-delivery payload that pose an economic burden calling for a solution, wherever it may be found.

It would appear that the congestion-driven issue plus other time inefficiencies can be addressed by electronics systems yielding automatic vehicle location, mobile communications, and computer-aided dispatch, especially if vehicles can be routed individually in response to real-time traffic information. These functions, enabled by surging advancements in computing, mobile data networks, new satellite facilities, and associated information technology, fall under the rubric of intelligent vehicle-highway systems (IVHS) (*15*). Large truckload fleets and parcel services are beginning to adopt such technology, by way of aftermarket channels rather than the OEM truck maker, at a significant rate (*16*). The intriguing aspect of these innovations is that although they have been first rationalized on the basis of the time-efficiency argument, operators are discovering that wholly new forms of customer service can be offered, thereby differentiating the "intelligent-technology" fleets from their conventional competitors and perhaps re-sorting market shares in the not-too-distant future.

A compelling example of the new services was cited recently by a large truckload operator (*17*). The availability of automatic vehicle location and mobile communications has enabled a central dispatcher to continuously control the routing, and even the destination assignment, for a large group of individual trucks that have been loaded with mixed freight headed for any of a group of warehouses operated by a large national retailer. As inventories develop dynamically across many of the company's facilities, a corresponding dynamic reassignment of each truck has led to a wholesale reduction in the incidence of intermediate stops for partial unloading and reloading. The increasingly common experience of this operator is that of near-optimum, single-stop routing aided by a corresponding loading of trucks at the outset to match the dynamically reroutable logistics of the operation.

The lesson of fleet adoption of IVHS technology, again, will be that the economics of the trucking business will readily attend to minimizing private costs (perhaps with the fortuitous by-product of more competitive services). The public aspect of these developments is that IVHS solutions may reduce the trucking contribution to traffic jams and may support a means of enforcing on-road trucking regulations at reduced public expense. Again, it can be generalized that when truck efficiency is at risk, whether measured in units of time, energy, or any other currency, a natural mechanism will exist that tends to resolve the inefficiency, perhaps helping to contain the associated public cost in the process. To the degree that truck design or equipment helps achieve efficient operations, the industry will tend to press for the cost-beneficial improvements.

Traffic Crashes

Truck crashes impose both private and public costs. Clearly, the truck owner incurs private costs from truck damage repair, liability insurance, workmen's compensation, freight damage, and the alienation of a shipping customer whose payload is wrecked. Public costs deriving from truck crashes are thought to vastly outweigh the private costs to the truck owner, though, and appear to represent a large uncompensated burden over the life of the typical heavy-duty truck.

The entire safety picture, in terms of accident loss per mile of exposure, has steadily improved in the United States, with the total national fatality rate now below 2.0 fatal accidents per 100 million vehicle-mi of travel (100M vmt) (*18*). Taking the latest authoritative figures for truck travel—those collected in 1987 by the Census Bureau (*3*)—a corresponding rate of 6.17 fatal involvements per 100M vmt was seen with 3S2 tractor semitrailer combinations (where this vehicle configuration is chosen simply as a convenient, large-population surrogate for all heavy vehicles) (*19*). It is also recognized that, because of the aggressivity of such vehicles in collisions with passenger vehicles, an average of 1.15 fatal injuries are produced per fatal involvement with tractor semitrailers. [As an aside, it should be acknowledged that a remarkable improvement in the protection of truck occupants has occurred from 1979 through 1991, with the truck occupant fatality rate dropping approximately in half over that period (*20*). Apparently the lion's share of this improvement has derived from a wholesale increase in seat-belt use by truck drivers, although significant upgrades in the crash integrity of cabs and truck fuel systems were made toward the end of the period as well.]

Without going further into the issue of statistical trends—a controversy that becomes readily enmeshed in debate over the applicable exposure figures—it is useful to consider the public cost implications of the national truck accident experience, taking the gross numbers from 1987 as representative. The author suggests that a likely change of, say, 10 or 15 percent in truck accident rates since 1987, up or down, would be immaterial to the point of the following observations and thus a further exploration of the statistical base of information is not merited here.

Focusing on the public cost of truck crashes, it is helpful first to simplify the problem by integrating the accident rate across the lifetime mileage traveled by the typical three-axle tractor; doing so obtains a life-cycle accident count attributable to one individual vehicle in this class. Then, using federal rates for computing the economic cost of accidents, this figure can be converted into a life-cycle public cost due to traffic crashes involving this vehicle. This public-side cost may be compared with an estimate of the private costs that are incurred over the same life cycle by the private operator of such a truck combination. Recognizing the private costs as business expenses, the question of covering the public loss is an issue in cost-recovery policy.

If 6.17 fatal involvements are incurred in each 100M vmt units of exposure, then (6.17/100M) multiplied by the lifetime exposure of the typical three-axle tractor—920,000 mi—gives the lifetime fatal-involvement risk for one vehicle of this type. The result is 0.057 fatal involvements per tractor lifetime, or 1 for every 18 vehicles manufactured. The significance of this astonishing result can be portrayed in a mental picture: Imagine standing at the end of a heavy vehicle assembly line and watching newly manufactured vehicles exiting the plant. Consider the question, "If this is our last chance to alter the equipment, is there anything reasonable that can be done to each batch of 18 vehicles to minimize the risk of an otherwise inevitable fatal crash that will involve one of them?" On a per-vehicle basis, the lifetime concentration of risk is startling.

The dollar magnitude of public crash costs has been studied by a number of investigators (*21–23*). Although compelling arguments are made for both economic and so-called comprehensive forms of costing, only the smaller-cost federal economic approach will be employed for illustrations presented here. The most recent evaluations conducted by NHTSA show an annual national cost of $137.5 billion accruing from the 1990 total of 44,531 fatalities, 5.4 million reported injuries, and 28 million vehicles damaged (*23*). Assuming that heavy truck crashes produce approximately the same proportions of injury and property damage losses per fatality as all accidents, one can simply lump the injury and property costs in with each fatality as a convenient means of computing the cost of operations per fatal accident. This figure comes to a total annual cost of $3.08 million/fatality that is counted (including the pro rata cost of injuries and property damage). If this total is spread across the 18 tractors that will accrue such costs per vehicle lifetime, multiplying also by the 1.15 persons that are actually killed per fatal tractor involvement, the lifetime crash-related cost per three-axle tractor is $197,000.

Clearly, the lion's share of this life-cycle crash cost is borne by the non-trucking public. In crashes involving cars striking combination-unit trucks, for example, the fatality ratio—deaths to car occupants versus deaths to truck occupants—is about 37 to 1 (*2*). It is reasonable to assume that the distribution of injuries and property damage losses is overwhelmingly tilted toward the passenger vehicle, as well. For purposes of discussion, it is assumed that the public bears $180,000, or approximately 90 percent of the cost per crash.

On the private side, the corresponding life-cycle costs associated with purchase and use of a three-axle tractor over 920,000 mi of operation are estimated as follows:

	Cost ($ thousands)
Capital outlay	100
Cost of capital (10 percent for 5 years)	38
Accident costs ($197,000–$180,000)	17
Maintenance costs (8¢/mi)	74
Fuels and lubricants (20¢/mi)	184
Total	413

Accordingly, note that for every three-axle tractor that is built (again, with this vehicle configuration being considered only as an example), $413,000 is paid just to own and operate the equipment over its lifetime while the public contributes an additional $180,000 to cover only the crash-induced costs that are borne publicly. (The author acknowledges that complete comparison of both cost types would require the factoring of a discount rate against a timetable of cost accrual for both cost streams. Unfortunately, such a process in not enabled by data available here.) Whether the public cost of $180,000/tractor lifetime should be viewed as an indirect subsidy of private enterprise (i.e., the trucking industry) or an alternative means by which the public pays for freight services is a philosophical matter. The pressing issue here is that a $180,000 crash toll is being borne by the citizenry per heavy tractor—how can it be lessened through a cost-effective change in vehicle design and configuration?

Much research has been done to help discover the aspects of truck design that could be improved by way of crash countermeasures. It is not the purpose of this paper to revisit the broad scope of these studies (although the reader is referred to two major government investigations that have given balanced treatment to the overall issue (*1,2*). As an illustration of the path toward more acceptable management of the safety component of life-cycle costs, however, one of the safety countermeasures suggested by the NHTSA investigation will be considered.

The safety agency noted that 75 percent of all fatalities in heavy vehicle accidents involve impacts with another vehicle, of which 68 percent entail strikes against the front portion of the truck. On the proposition that about 44 percent of these front strikes are candidates for resolution by means of a cushioning and underride-preventing bumper on the truck, the data show that such a device would target an accident group amounting to 22 percent of all fatalities involving trucks. In terms of the simplified analysis presented earlier, this target would appear to have a public "worth" of about $40,000 in design improvements on each vehicle, if a fully effective countermeasure were identified.

A downside of a countermeasure of this type, where a weight and length penalty appears unavoidable, is that the hauling capacity of the overall vehicle would diminish unless size and weight regulations were somehow extended in a package form of compensation. Such an observation is central to trucking economics, however, because payload-constraints show directly as constraints on truck revenue per trip. For example, using a typical freight rate of $0.0001/lb-mi, a vehicle that would spend 20 percent of its 920,000 lifetime miles operating right at the maximum allowable loading condition (where a higher tare weight directly reduces the payload weight) suffers a lifetime loss of operating revenue equal to $18/lb of excess tare weight.

If a crash-forgiving bumper weighed 400 lb, for example, $7,200 in operating revenue would be displaced. Noting that $40,000 in public crash costs could be eliminated by a 100 percent effective (400-lb-heavier) front bumper, even a 25 percent level of effectiveness for such a device would appear to yield a cost-justified package—with $10,000 in public savings available to cover the $7,200 in operating loss plus a $2,800 budget for the bumper equipment and its lifetime maintenance costs.

This example has been discussed simply to illustrate the rationale that introduces life-cycle costs into the consideration of truck designs for achieving acceptable safety performance. In the final section, an approach for implementing measures to balance public costs without mandatory standards is briefly outlined.

"Carrot and Stick" Package

The quid pro quo approach suggested in the Turner Proposal, mentioned earlier in the paper, serves as an illustration of a general strategy for managing certain public costs of trucking without mandatory equipment standards. Here this approach will be called the "carrot and stick" package (CSP), reflecting the bundling of *requirements* for equipment that has public value but will not sell on its own (the "stick"), with the *allowance* of a more productive truck configuration—one that is otherwise prevented by existing size and weight constraints (the "carrot"). The premise for using this approach for a public cost issue is that regardless of the public merit or even the best efforts of the OEM truck maker to highlight the feature, an equipment improvement that is not economically attractive to the truck buyer will not be purchased.

Further motivation for such a strategy is seen in a current case in point, shown in Figure 3. It is seen, by way of contrast with the energy-saving trends discussed earlier, that the specification of antilock braking systems (ABS) by the customers of one heavy truck manufacturer have proceeded sluggishly since the systems were introduced in 1987 (*ABS Usage in Class 8 Trucks,*

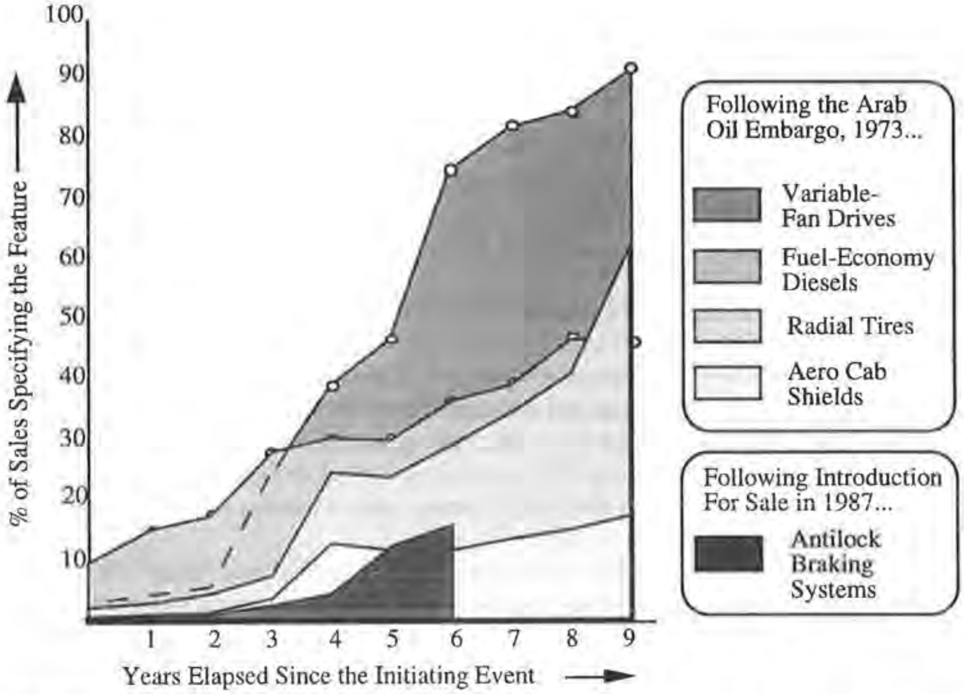

FIGURE 3 Rate of sale penetration by ABS on Class 8 trucks compared with the penetration of fuel economy–enhancing devices.

Model Years 1987–1992, a list of production data on ABS provided to the author by a U.S. truck manufacturer, Dec. 1992.).

The data show that it has taken 6 years for ABS sales to reach a 15 percent selection rate. These data support the theme of this paper: namely, that truck operators will select and specify truck equipment almost exclusively in response to the realized private costs of operation. (It is interesting to note that ABS was also introduced seriously into a number of passenger car models beginning around 1987 and is estimated to have penetrated to 40 percent of all sales by the end of 1992. Safety now appears to sell in the passenger car context where the decision to buy is much less an economic question than one of the personalization of value by each consumer.)

Moreover, it is economically understandable that equipment such as ABS for trucks penetrates the market very slowly, although its additional value for reducing public costs would probably tip the scales strongly in favor of the purchase. Safety equipment such as this is especially difficult to justify, in the truck purchase, for two powerful reasons:

1. Accidents are rare events that are also normally confused by a multitude of contributing factors (such that it is difficult for the truck owner to value an individual countermeasure in terms of safety effectiveness, per se, let alone in terms of the cost/benefit ratio).
2. The largest portion of the accident cost (perhaps 90 percent, as in the author's estimation) is borne by others and thus falls outside of a pragmatic business consideration.

By contrast, truck design improvements on behalf of fuel economy offered obvious benefits because the need following the 1973 oil embargo was inescapable—the increased fuel price was encountered every day—and the entire costs involved were borne by the business itself.

Thus, in the timid regulatory environment that this decade appears to project, it appears appropriate to consider public policies that lead to a managed, competitive dynamic within which the purchase of the safer (or less highway-abusive, or less polluting, etc.) truck is mandatory. Various examples of a CSP approach have been proposed (*13,24*) and some have been implemented, notably in Michigan (*25*) and as an interprovincial trucking policy in

Canada (*8*). If this approach is to be applied effectively at the national level in the United States, a methodical process is needed, as given here:

1. The public sector, particularly the U.S. Department of Transportation, must lead in identifying effective equipment improvements that already are, or can readily be, offered for sale on OEM trucks and that arguably ameliorate the public cost incurred over a truck's life cycle.

2. Vehicle manufacturers and suppliers must establish that the equipment can be offered, and the retail prices of such hardware must be estimated.

3. Operators must confirm, or cooperative field testing must demonstrate, that the systems are suitably functional, maintainable, and so forth; operating costs must be estimated.

4. A package of attractive weight or cubic capacity extensions must be identified as tractable from the viewpoint of highway operations and maintenance and inherently attractive for the enhancement of truck productivity.

5. A CSP proposition of requirements and allowances must be defined in terms of distinctive vehicle configurations that stand out so markedly that their identification for enforcing the requirements is straightforward.

6. The business incentive for such productivity enhancements must be analyzed by independent experts on trucking economics, developing the financial part of the equation and calibrating the numerical parameters for size and weight limits so as to make industry adoption of the CSP-defined vehicles competitively unavoidable.

7. Implementation of the North American Free Trade Agreement may suggest that a CSP proposal should also factor in the synergistic influences of Canadian and Mexican road use laws. For example, where Canadian allowances already provide for certain truck configurations carrying larger-than-U.S. payloads, it may be in the United States' interest to consider packages that approximate the same allowances but require new safety equipment and perhaps other additions. If it is imagined that some trucking segments in the United States might delay in implementing CSP vehicles because of hesitancy about capitalizing new equipment, the dynamic of ready-made Canadian (or Mexican) competition might well accelerate the pace of transition to new equipment.

8. On definition of the overall package constraints, a coalition must be built between state, federal, and industrial interests so as to support the needed Congressional legislation. If the reduction in public costs due to trucking are strong and productivity enhancement is high, support from the manufacturing community should be expected in the light of the potential for reducing freight rates and thereby improving the global competitiveness of U.S. products.

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