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ENERGY USE IN THE TRANSPORT SECTOR

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Note for the reader: This draft was completed on March 29, 1995, as part of a World Bank project to deepen the Bank's knowledge of energy issues in transport. The draft was never published because of a shift in the Bank's priorities. Although in most cases the data are now out of date, and some of the issues that were then nascent have now emerged full blown, I am putting it on this website because most of the report is still entirely relevant in 2007. More recent data would not change any of the conclusions significantly. Figures 2-16 and 2-33 provide a summary of the use of energy in transport that may be particularly interesting.

In addition, with the exception of a few typographical errors, the report is provided in its original draft form. The original report included a second section that contained a set of data files. These have been partly lost: some still exist in Excel spreadsheets; others can only be recreated from the paper copy. Questions about the annex should be directed to lou.thompson@gmail.com.

LIST OF ACRONYMS AND ABBREVIATIONS

Btu	- British Thermal Units
Cal	- calorie
Frgt	- freight
gcp/pkc	- gram equivalent of petrol per passenger kilometer capacity
gcp/pkt	- gram equivalent of petrol per passenger kilometer transported.
goe	- gram of oil equivalents
J	- Joules
kgce	- kilo gram of coal equivalents
kgoe	- kilo gram of oil equivalents
kJ/pass.km	- kilo Joules per passenger kilometer
kJ	- kilo Joules
kJ/t.km	- kilo Joules per ton kilometer
km	- kilometer
kmph	- kilometers per hour
lbs	- pounds
Max:Range	- maximum range
MJ	- Mega Joules
mph	- miles per hour
nm	- nautical miles
Pass.	- passenger
t	- ton

LIST OF UNIT CONVERSIONS

1 Btu	= 1.053 kJ
1 calorie	= 4.18 Joules
1 gallon(U.S)	= 3.79 liters
1 Giga Joule	= 10^9 Joules
1 metric ton	= 2,200 pounds
1 mile	= 1.609 kilometer
1 nautical mile	= 1.609 nautical kilometer
1 pass-mile	= 1.609 pass-km
1 Tera Joule	= 10^{12} Joules

ENERGY CONTENT OF FUELS

aviation gasoline	= 20 MJ/lb = 31,200 kJ/liter
diesel	= 128,700 Btu/gallon = 35.9 MJ/liter = 10.2 Giga calories/ton
gram equivalent of petrol	= 43.9 kJ
gram of oil equivalent	= 42 kJ
kilogram of coal equivalent	= 23,441 Btu
motor gasoline	= 115,400 Btu/gallon = 32.5 MJ/liter = 10.5 Giga calories/ton
ton equivalent of coal	= 7×10^9 calories
ton of standard fuel	= 7×10^9 calories

INTRODUCTION

1. Energy use is a major issue in modern economies. Many of the world's largest export and import flows are associated with energy products, posing the issue of national self-sufficiency for some countries, a question of ability to pay for others, and an issue of what to do about export surpluses for a few, fortunate others. Consumption of energy in all forms leads directly to various types of air, water and noise emissions, a matter of increasing concern for nearly all countries. As countries develop, access to energy supplies, for example domestic electricity, or fuel for personal vehicles, becomes deeply intertwined with quality of life and personal choice issues. As a result, potential changes in energy cost or energy policy are among the more complex that any nation faces and there are few comfortable or unimportant energy decisions.

2. In all economies transport is one of the larger consumers of energy, accounting for 30 to 60 percent of commercial energy consumed. In addition, transport is heavily dependent on petroleum sources which have often been associated with political and trade instability and price uncertainty. Transport energy use has characteristic patterns of environmental emissions, both in chemical and spatial terms (world as well as local), which often make transport an aggravated source of undesirable environmental effects, especially in congested urban areas. The interactions among transport, energy and environmental impacts focus attention on ways in which transport energy consumption can be managed.

3. This paper focusses on the linkage between transport and *energy*; the ensuing steps from energy use to emissions will not be addressed. As a broad generalization, transport energy use is directly linked to an environmental impact in the *global* arena because (subject to limited modification for fuel composition) transport energy consumption generates carbon dioxide (CO₂) which, no matter where emitted, adds to the global CO₂ burden. The localized linkages between transport energy and air pollution have an enormous number of variables which are more thoroughly discussed in a number of sources which the interested reader should consult.¹

4. As discussed in more detail below, there are many variables which influence the relationship between transport activity and energy consumption, including various physical or technical parameters (mode, load, distance, speeds, size and design of vehicle and its engine or motor, and source of power, etc) which can be specified in detail. There are other factors, including operational patterns, maintenance practices, age of vehicles and the mix in vehicle fleets, impacts of planning distortions, etc, which are much harder to specify or control and which introduce considerable unpredictability into assessments of energy use. Among the critical conclusions of this paper are *that there are very few safe generalizations to be made about which mode is energy "efficient"*, and that *the usage of single point values or general comparisons of transport energy consumption* (e.g. trucks use three times as much energy as rail") *is often misleading*. There are a number of actual circumstances in which comparisons based on single point values can be misleading. Instead: 1) appropriate ranges should be used for general transport energy consumption comparisons among modes; 2) claims based on

¹. See, for example, Faiz and Sinha.

conventional wisdom should be avoided; and, 3) where accurate values are needed to support significant policy or investment decisions, estimates can not replace an accurate and often laborious description of all of the forces and parameters at work. Even then results should be taken with a grain of salt.

5. Another critical point is that **energy is only one of the costs, often only a minor one, which influence the usage of transport which is, itself, only a derived demand.**² The total costs of transport also include vehicle ownership and maintenance, infrastructure construction and maintenance, operating labor, and many others. At the same time, the actual or perceived "prices" (costs, tariffs or fares) paid by transport users may well be more (or, unfortunately, sometimes far less) than actual costs because of misperceptions, bad information, pricing strategies, monopoly behavior, external impacts, and poorly designed government subsidies, among many other issues.

6. Perhaps more important, the competitive position and the resulting modes chosen and amounts of transport demanded by users often depend on factors well beyond the narrow issue of the cost (or tariff) of transport. The user also evaluates a wide range of quality-related factors such as travel time, time spent waiting for departure or shipment, reliability of expected travel time, passenger comfort (or freight loss and damage) of the transport, minimum shipment size or conditions of travel (fares by time of day, day of week, etc). Many of these quality factors far outweigh the mere effect of the cost of transport, and even more the cost of energy, within the overall logistics³ equation. As a result, **it can be extraordinarily difficult to measure or influence the relationship between the ultimate amounts and patterns of transport demanded in a market economy and the usage of energy by the transport sector derived from that demand; perfectly explicable market forces can make the least energy "efficient" transport mode into the most "economical" choice, both for passengers and for freight.** Attempts to influence energy usage by changes in energy costs or supply may have far from the intended effect if the market is fully empowered to make all logistics decisions and the measures do not take all of the pertinent market forces into account.

7. Nor should the present competitive balances and modal patterns be thought of as immutable. Changes in technology constantly influence the characteristics, including energy efficiency, of all of the modes of transport, affecting competition accordingly. More important, the structure of all economies changes in characteristic ways as economies develop in income per capita or make the transition from

2. A "derived" demand good is a product that is not consumed for its own sake but is, instead, used in the production or consumption of another product. By and large this is true of transport, especially freight; consumers, for example, do not care whether their soap arrives at the store by rail or by truck, or by a combination. In fact, except for tourist travel where the travel experience or "view out the window" is the objective, and exercise-related jogging or biking, there are few examples of direct consumption of transport for its own sake.

3. "Logistics" broadly includes all of the costs of bringing a product from producer to consumer. Logistics includes transport, but also includes inventory holding and management, spoilage, loss and damage, loss of "fashion" appeal, etc. A typical example of a logistics tradeoff is high fashion clothes being shipped from Far East to Europe. The cheapest transport is water, but the time in water transport can cause sellers to miss market trends: air transport is immediate and fills fashion needs, but is more expensive. The choice of air vs water (and of the resulting energy consumption) will be driven by the tradeoff between fashion volatility and transport cost.

planning to market, with a consequent evolution in the types of economic activity conducted and in the amounts and types of transport demanded.⁴ The dramatic transport developments in the formerly planned Central and Eastern Europe (CEE) and Commonwealth of Independent States (CIS) economies, where rail freight traffic has fallen by half or more during the transition to market,⁵ are a good illustration of this phenomenon. The past is at best only a rough starting point for assessing and altering the future.

8. Finally, in a number of significant cases, transport itself is only one available means to an end. An example is the tradeoff between transport and the rapidly growing capabilities in communications and information management. Some of the tradeoffs are no surprise; substitution of telephone calls, or the long-promised video conferencing, for business trips has often been discussed. What has not been as fully assessed is the impact of more recent technologies, such as Faxes, E-Mail (especially services such as INTERNET and Compuserve, but also interactive cable services), and "virtual reality" on the usage of transport, **and on the resulting usage of energy**. It is, for example, far more energy efficient to work at home and interact professionally via E-Mail ("electronic commuting") than it is to commute physically. Faxes use far less energy than moving a letter or other physical document. At the same time, some of the more energy **intensive** usages of transport, especially Just In Time (JIT) logistics systems, are possible only **because** of modern communications which permit the close integration of each of the steps in the logistics chain -- actually **increasing** transport intensity in the process of meeting a market demand. There is little doubt that these emerging communications tradeoffs could be a significant tool in the effort to improve energy efficiency within the overall economy. It should also be clear, though, that good communications can also increase the use of transport, especially the more energy intensive forms of transport.

9. Thus, this paper has several objectives. First, it attempts to discuss the richness of the relationships between transport activity and energy consumption and to quantify the spectrum of energy/transport interactions. Second, it emphasizes the fact that the relationship between transport demand and energy use (and thus environmental impacts) is quite indirect and not susceptible to easy generalization: measures meant to influence the transport/energy relationship must be carefully formulated. Finally, it briefly highlights developments in information technology, including some which could be influenced in developing countries by Bank activities, which could have an impact on the transport sector's role within the economy, and thus on energy use in transport.

⁴. See, for example, Bennathan, Fraser and Thompson, and Blackshaw and Thompson for a discussion of these issues, especially as they relate to freight.

⁵. See Fraser and Thompson (unpublished World Bank memo dated January 9, 1995) on trends in rail traffic in the CEE/CIS economies.

CHAPTER ONE

ENERGY USE IN THE TRANSPORT SECTOR

DEFINITIONS AND ISSUES

10. "Transport" means the spatial displacement of people or goods from one point to another. Displacement requires the expenditure of effort, and thus energy,⁶ for a number of reasons:

a. Friction must be overcome, either through wheels rolling on rails or road, feet walking or running on the ground, or from air (or water) resistance to movement of wings, vehicles or bodies. Other things being equal, frictional energy is related to materials (rubber on road generates more resistance than steel wheel on steel rail), speed (the power required to overcome air or water resistance rises roughly in proportion to the third power of speed but can change significantly through appropriate vehicle design), weight carried and distance travelled. While wind resistance is typically thought of as a higher speed phenomenon for vehicles, it can also be significant at much lower speeds; human dash and long jump records are not valid if there is a following wind greater than 2 meters per second and, above about 30 km per hour, most of a cyclist's effort is used just to overcome air resistance. A cycle of the best design, with streamlining, can increase the top speed of the same rider from 60 to nearly 100 km/hr, purely through reduction of air drag.

b. In order to acquire velocity, mass must be accelerated (consuming energy) and then decelerated (releasing energy, usually as unrecoverable braking heat). Acceleration energy is directly related to total mass (vehicle and cargo), and is usually much more significant in short than in long movements. For example, "stop and go" in city driving causes energy consumption per vehicle-km to be as much as 30 to 40 percent higher than the same distance in sustained speed driving on highways (at reasonable speeds, that is).

c. In changing location, mass must often go uphill (consuming energy) or downhill (usually releasing unrecoverable braking heat). The energy of elevation change is determined primarily by mass. Although elevation change is usually ignored in comparative energy figures (as will be done in this paper), it can be highly significant and can affect decisions in particular situations, especially where both mass and elevation change are significant (as in the movement of large quantities of mineral ores over mountain ranges or the pumping of liquids over long distances), where the source of energy is inherently limited (which is why cyclists and

⁶. There are many units of measure for both energy and transport output. The authors have decided to follow the recommendation of Lee Schipper and employ the Joule (actually kilo-Joules, or kJ) as the measure of energy consumption in transport. One Joule is the equivalent of 2.78×10^{-7} Kilowatt-hours or 9.48×10^{-4} British Thermal Units (BTU's). The measure for passenger transport output is one passenger moved a distance of one kilometer (the passenger-kilometer, or p-km) and for freight one metric ton (1,000 kilograms or 2,204 pounds) moved one kilometer (the tonne-km, or t-km). The resulting measures of transport energy consumption are then kilo-Joules per passenger-kilometer (kJ/p-km) or kilo-Joules per freight tonne-km (kJ/t-km). See the Conversion Table for common conversion factors into other units.

marathoners do not like hills), or where the topography limits the designer's ability to produce gentle gradients (railways do not operate well on steep gradients). Interestingly, the energy of elevation change can be significant even where the path is level: one of the reasons why cycling is much more energy efficient than walking or running is the fact that the cyclist's center of mass does not move up or down in cycling whereas the movement of the legs in walking or running repeatedly raises and lowers the walker or runner's center of mass. All of the cyclist's energy goes to forward movement; much of the runner's energy goes to lifting and lowering body mass.

Typical Energy Consumption by a Modern Automobile	
	<u>Percent</u>
Total Energy Consumed	100
Energy Available After Combustion Losses	40
Energy Available After Engine Friction	18.6
-Accessory Energy Used	(2.2)
-Transmission Losses	(1.6)
Energy Available for Traction at Wheels	14.8
Traction Energy Used for:	
-Tire Friction	(5.2)
-Air Drag	(4.9)
-Braking	(4.7)

Source: John De Cicco and Marc Ross, Scientific American, December 1994, pg. 53.

11. Measuring energy quantities requires care in definition, for example gross energy can differ from direct energy consumption. An electric vehicle may appear to be much more energy efficient than a fossil fuelled vehicle if the comparison is limited to the electrical energy used at the vehicle versus the energy content of the fuel burned in an engine. But, this ignores the fact that some kind of energy must be consumed to generate the electricity in the first place, and that energy is lost when electricity is transformed and transmitted from place of generation to place of use. Some reasonable assumptions about electric energy versus diesel traction in rail locomotives, for example, would yield the following rough comparison:

From Gross Energy Consumed to Net Tractive Output			
	<u>Percent</u>		<u>Percent</u>
Electric Locomotive Gross Energy (Coal)	100	Diesel Locomotive Gross Energy (Diesel at Refinery)	100
		Energy Used to Distribute Fuel	(5)
Net Electrical Energy Delivered to Transmission Grid (40 percent thermal efficiency plus 5 percent losses in power plant)	35	Net Fuel to Locomotive	95
Losses in Transmission (10 percent)	(3.5)		
Net Delivered to Locomotive	31.5	Net Energy Out of Locomotive Diesel Engine (30 percent thermal efficiency)	28.5
Losses in Vehicle (10 percent in transformers, motors, gears, etc.)	(3.1)	Losses in Locomotive (10 percent)	(2.8)
Net Actual Tractive Effort	28.4	Net Actual Tractive Effort	25.7

Source: World Bank Estimate.

As the example shows, when electric generation and transmission losses are taken into account, the total energy efficiency of electric traction (battery or otherwise) is often virtually the same as fuel-driven transport.⁷

12. Another issue is the sensitivity of the various modes of transport to additional increments of load (cargo or passengers). As a first approximation, the increase in rolling resistance of rail trains when more weight is added is almost nil, whereas trucking and aircraft energy increases more rapidly with increased load. Again as a first estimate, if auto or train size are held constant, the energy consumption of autos and passenger trains does not change much, if at all with each additional passenger (not true of aircraft where the energy consumption is more closely related to load). In both the freight and passenger cases, other things being equal, load factor (the ratio of passenger-km to seat-

⁷. This mis-definition is the source of the popular impression that battery driven vehicles, or electrically driven locomotives, consume less energy than their fossil fuelled counterparts. It is true that central power plants can produce less pollution emissions than distributed power sources for the same amount of fuel energy burned; it is also true that the spatial pattern of pollution emissions is different between electrically and fuel-driven vehicles. But, the total energy consumed per unit of transport actually produced is very nearly the same in both cases -- and can actually be less efficient for the electrically driven modes if the application is inappropriate.

km, or the ratio of tonnage carried to tonnage capacity) is the most important consideration; full autos and trucks are more energy efficient than lightly loaded trains, but full trains are more usually energy efficient than either full autos or trucks.

13. There is also a comparison to be made between the total energy required to produce transport service, including the energy invested in producing the vehicles⁸ and constructing the infrastructure, and the energy required solely to operate the service. For example, while it is true that a fully loaded urban metro carries passengers for less energy (kJ/p-km) than even fully loaded autos or buses, it takes more energy to build the dedicated metro infrastructure (tunneling, concrete, vehicles, rail, etc) than it does to build multi-purpose surface roads or highway vehicles. Exactly the same comparison can be made between intercity high speed rail versus air services. The result could be, in energy terms, the analog of a rate of return calculation; at what discount rate is the larger initial investment of energy in building the vehicles and the dedicated and energy-intensive fixed facilities balanced by the resulting savings over time of energy in operations? Unfortunately, very few studies have been made of this important question, and those that have been made are highly situation specific. As an example, studies in Sweden have concluded that the apparent energy efficiency rankings of some of the modes can be reordered if the energy to construct alternative systems is adequately considered.⁹ If energy impacts are significant, such total energy return calculations could and should be made when significant new, dedicated construction of transport infrastructure is contemplated.

14. Another consideration is the "renewability" of the primary energy source. Some fossil sources of energy (coal and petroleum) are considered "non-renewable" because the processes which generate them operate on a geological time scale; the current rate of mining of coal or of petroleum production far exceeds the rate at which the earth is replenishing the supply. Much the same point can be made of any "minable" energy source, such as uranium or even the deuterium to be used in future fusion power plants (even though the apparent supply of deuterium seems enormous compared with any expected need for electricity generation). This does not mean that fossil sources will ever be depleted; rather, prices should inevitably rise over a longer time frame as the best sources are used up and ever poorer sources must be exploited, with a corresponding impact on fuel prices, total demand and use of alternatives. In addition, fossil energy sources are location specific: some countries have them in abundance, others have none at all. The resulting imbalance among nations can put great pressure on trade flows, and can cause resource poor nations to add an external cost, "insecurity of supply," to their direct, cash cost of energy.

15. Other energy sources are called "renewable," meaning that they are generated by the normal daily and seasonal forces of weather and sun.¹⁰ These sources include hydropower, several types of

8. For example, the energy involved in making an automobile, including materials, is the equivalent of one to two years of the energy consumed in operating the auto.

9. See Transport Research Delegation, pages 71 and 85.

10. In a broader sense, all except nuclear energy sources are directly or indirectly driven by the sun.

direct solar energy, tides, waves, winds, and various biomass¹¹ sources such as foods, wood and charcoal, as well as methane, methanol and ethanol made from biomass decomposition or fermentation. A particular transport linkage with renewable energy is non-motorized transport (NMT) such as walking, running, rowing, sailing, swimming and cycling (and even human flight), human head and back loading, human-pulled carts and rickshaws, and various types of animal traction including donkey, horse, ox, dog, camel, and elephant power, among others.¹² The usage of renewable sources is often argued to be inherently a good thing because it appears to be environmentally benign, contributes to domestic energy independence and promotes a sustainable balance between man and nature; so long as the sun shines, these types of energy will always be available, and at low cost.

16. While the value of energy independence is not to be dismissed, some aspects of the renewable versus nonrenewable classification can violate the "no free lunch" principle. As has been painfully learned, hydropower dams may well produce clean, "renewable" energy, but they have their own related environmental costs in the scenic or historic areas their impoundment areas flood and the changes they bring to local ecosystems and habitation patterns (the Narmada Dam in India, the Three Gorges dam in China, or the Aswan Dam in Egypt are examples of both positive and negative impacts). There are also opportunity costs of renewable fuels which are often ignored, such as the fact that the food and associated land used to support and "fuel" animals could otherwise be used to house and feed people, or could be used to grow other cash crops. Sunlight captured by solar cells is not available for photosynthesis or for driving the evaporative water cycle. Land covered by dam impoundments is not available for other productive purposes. Apparently "renewable" fuels such as methanol and ethanol can actually consume so much energy in their production (because of the use of fertilizer, solar photosynthesis, and the energy of distillation) that they are far more costly (per unit of energy) than the fuel they are meant to replace; where their use is widespread, it is sometimes more an artifact of distorted agricultural subsidy policies than of underlying economic forces.¹³

17. This is not meant to minimize the significance and value of renewable energy; instead, it points out the fact that even renewable energy has costs to offset its benefits. In some cases where all costs are taken into account, the balance between costs and benefits can actually be unfavorable. Efficiency issues aside, though, some forms of renewable energy are also employed because they are readily available to the poor. Given adequate food, most people can walk, and they can do so on the most rudimentary of pathways. With the barest minimum of capital, bicycles and freight tricycles measurably improve human and small freight shipment mobility. Animals are used by the poor for power (both plowing and transport traction), not because they disdain trucks or tractors, but because

11. As the rapid deforestation around many developing country communities shows, not all biomass is "renewable." Demand for wood and charcoal as fuels often far outstrips the ability of localized environments to renew them.

12. In this paper, "motorized" transport means any form of transport in which the prime mover is mechanical or electrical, and includes all forms of fuel-driven and electrical power sources.

13. See, for example Brazil's waning use of methanol and ethanol for auto fuels, and the pressures of the US farm lobby to use corn-based ethanol for gasoline fuel additives.

animals are cheap (and reproducible -- and edible) and appear to justify the costs of fuelling them.¹⁴ Whatever the energy implications, the income distribution implications of NMT should not be ignored.

TRANSPORT AS A USER OF ENERGY

18. Modern economies use energy in a number of ways too numerous to list. Examples of energy use for personal needs include cooking, home heating, operation of household appliances, and operation of personal vehicles including autos or bicycles. Commercial use of energy is equally if not more varied, including lighting, heating, manufacturing power, agricultural irrigation, and transport of goods and people. Transport is a significant part of total energy consumption, but is by no means necessarily the predominant user.

19. As Figure 1-1 shows, transport consumes between 15 and 65 percent of total energy in a number of representative countries, with a reasonable average figure between 30 and 35 percent. Figure 1-1 suggests that the relative role of transport in energy consumption needs to be carefully approached because there is considerable variation of energy use distribution among countries and because there is no direct relationship between total energy use and the distribution of energy use by purpose among the countries listed. This paper makes no attempt to assess all of the factors involved in total energy use or use by purpose, but certain broad determinants, including total income and income per capita, geographical size and climate, and use (or lack thereof) of market prices to influence energy demand are significant. In approaching a specific country situation, there is no substitute for good local data to take these fully into account.

20. Transport also has specific patterns in its use of energy which are quite different from other consumers of energy. Almost all motorized transport operates on petroleum fuels, usually gasoline and diesel fuel or their aviation equivalents, and heavier fuel oils in the case of larger waterborne vessels.¹⁵ Transport usually does not depend heavily on solid fuels, such as coal (though there remain a sizable number of coal-fired steam locomotives in China -- and Paraguay's railway is wholly powered by

¹⁴. In fact, this may be the other end of the energy "rate of return" calculation. When all opportunity costs are computed, including the cost of food and grazing -- and allowing for the fact that animals are sometimes a source as well as a consumer of fuel -- animals may well be energy inefficient compared solely on energy grounds with motorized transport; but, their capital cost may be so low, compared to machines, and the poor person's discount rate so high, that animal power is the most rational choice. The uniform preference of the developed world for motorized transport, in whatever form, is a signal that a phenomenon like this is at work. It is also interesting to observe that another form of animal-powered transport, the conspicuous consumption of energy through jogging or cycling for exercise, is a high income characteristic. One often sees the poor in developing countries walking because that is the only affordable mode; walking or jogging, primarily in order to consume energy, is a pastime of the wealthier, primarily in developed countries.

¹⁵. The terms "gasoline" or "petrol" or "diesel fuel" are not entirely precise because the formulation of each varies country-by-country in accord with local needs (especially temperature ranges and engine designs), refining capabilities (some countries do not have the ability to produce highly-refined, higher octane fuels) and local environmental restrictions (especially limitations on sulfur or lead content of fuels). The same is true of the heavy-end fuels used in maritime power sources. They should be understood as general categories, and not as exact definitions. Estimates of the energy content of these fuels, as used in later analyses in this paper, should be similarly qualified.

wood-fired steam locomotives). Transport vehicles can also be designed to operate on compressed gaseous fuels such as butane, propane or liquefied natural gases, but such operations are not significant except in cases where the lower exhaust emissions of the vehicles can justify the cost of bulkier, heavier and more expensive fuel management systems.¹⁶

21. By comparison, electric power generation can be based on nearly any fuel, including petroleum in all its forms, but also including solids (particularly coal and lignite), hydropower, nuclear sources, and by-product heat from industrial processes. Industrial energy sources have a similar range; with (for example) steel a heavy user of coal and electricity, and aluminum heavily based on electricity. Home heating can be electric or solar as well as fossil fuelled.

22. There is sometimes a link between electric power and transport where electric energy is used to drive the vehicle. The predominant example is the use of electrically powered rail vehicles to haul either freight or passengers. For example, electricity is the normal source of traction power in urban metros in order to reduce noise and control exhaust emissions.

23. Use of electric traction in intercity railways is common in some countries; for example, Switzerland's railways are wholly electrically driven. Electric traction in the CIS countries is estimated to haul two-thirds of all rail freight ton-km and intercity passenger-km. Electric rail traction plays a major role in the railways of India, China, Japan, the CIS and CEE countries, and in Western Europe. By comparison, in the US, Canada, and most developing countries, intercity rail electric traction plays essentially no role.¹⁷

24. Electric traction is much rarer in non-rail applications, although there are examples of battery powered road vehicles (golf carts or small commuting vehicles), or of road vehicles served from a track-side power source (trolley-buses or mining trucks operated from overhead wires). Roadway electric traction has been limited because neither electric batteries nor fuel cells can store and deliver as much energy (either per unit weight or unit volume) as a much cheaper fuel tank. Advances in battery and fuel cell technology, and other forms of energy storage which are easily converted from/to electricity (such as flywheels), are narrowing the gap -- but they are not yet fully competitive, and may never be so.

^{16.} Mainly in urban areas where taxis or, for example, Bangkok "tuk tuks" have been converted to propane or LPG.

^{17.} The reasons for these differences in use of electric traction have been discussed in detail in a number of sources. See, for example, Alston, and the FRA studies of rail electrification. The primary determinants of the rail electrification versus diesel traction decision are energy costs (at appropriate world prices for both electricity and diesel fuel), locomotive maintenance, total locomotive fleet size (which is smaller in electric than diesel locomotives because electric locomotives can haul more weight per installed horsepower), relative mix of passenger versus freight (passenger services require higher acceleration and higher cruise speed, both of which are favorable to electric traction), total traffic and the traffic density over the line to be electrified. Aside from the planned economies including India, there are a few developing economies where there is some rail electric traction, including Mexico, Brazil, South Africa and Zaire.

25. As a result of the close relationship between transport and use of petroleum fuels, total national energy patterns can be heavily influenced by transport. For example, as Figure 1-2 shows, transport only consumes 36 percent of the total energy used in the US, but accounts for a much higher percentage (76 percent) of consumption of petroleum fuels. Although the percentage may fall as low as 50 percent in some countries, transport is normally the predominant user of petroleum as seen in Figure 1-2. Attempts to reduce total energy consumption would reach one type of solution; attempts to reduce consumption of petroleum in particular might well reach an entirely different solution, one which would necessarily focus on transport as a major component.

THE DETERMINANTS OF TRANSPORT DEMAND IN VARIOUS ECONOMIES.

26. Nations differ widely in the role which transport plays in their economy, and in the balance among the transport modes employed by the economy. Depending on the size of the country, its economic stage of development, and the form of its economic structure (notably the difference between planned economies and market economies), large differences appear in the amount of transport used per unit of total economic output and the relative usage of, for example, trucks versus rail to haul freight, or in the use of public or mass transport versus the individual modes to move passengers.¹⁸

27. As Figures 1-3 and 1-4 show, there can be significant variations in the transport t-km per \$ of GDP (Purchasing Power Parity adjusted) and in the way in which these t-km are distributed between rail versus road. Bennathan, et al, found that the differences in transport intensiveness among economies are largely attributable to the choice of "planning" as opposed to market-based economic structure models, with planned economies characteristically much more transport intensive than market economies. Planned economies also tended to carry a much higher percentage of their surface freight traffic by rail, both because the planned economies overproduced and overconsumed basic commodities (which are naturally rail carried) and because the lack of a concept of total logistics cost in planned economies put too much emphasis on the apparent cheapness of rail transport and undervalued the cost of inventory handling.¹⁹ Those attempting to analyze and influence the usage of energy by the transport sector in various countries will need to understand the role of the various transport modes in the particular economy in question.

THE ROLE OF MODAL SHARE IN ENERGY CONSUMPTION IN TRANSPORT

28. Transport modal balance, and the role played by each mode in the country's transport system, has a significant impact on energy consumption in the transport sector -- and on the resulting balance of fuels consumed by the transport sector. For example, countries vary widely in the usage of rail for passenger versus freight transport, as Figure 1-5 shows. As a result, there are large differences in the

^{18.} For example, see Bennathan, Fraser and Thompson for a more detailed treatment of freight transport. "Individual modes" refers to vehicles such as autos or trucks where the individual user controls their origin, destination, routing and scheduling.

^{19.} The same phenomenon appears to have been at work in passenger transport: see Blackshaw and Thompson, and Blackshaw. In the case of passenger transport, the planned economies suppressed individual modes in favor of public or mass transport.

portion of transport energy which is consumed by each mode, as Figure 1-6 shows for the US. Energy consumed in transport is not a simple function of t-km and p-km; it is, instead, the result of a number of complex considerations. As a result, there is no easy relationship between policy or tax interventions at the level of fuel cost and availability, and the way in which the economy will react. It is as easy for measures to be self-defeating as successful.

THE SIGNIFICANCE OF NON-MOTORIZED TRANSPORT

29. There are few issues in transport that are more interesting or more varied than those of non-motorized transport (NMT). Non-motorized "modes" cover an enormous range of purposes and vehicles, and seem to have infinite ability to adapt to local circumstance including personal income, cargo, terrain and condition of infrastructure. There are two fundamental divisions of non-motorized transport -- human powered and animal powered, both of which can be found in passenger as well as freight transport.

NON-MOTORIZED PASSENGER TRANSPORT

30. Human powered passenger transport starts, of course, with walking which, however unglamorous to transport engineers and economists, is the fundamental mode of human transport in many economies, especially in the urban, lower income context. Probably the next step up is cycling (two or three wheels) in its many forms (self-cycling, hauling someone in a passenger seat, or for-hire operation of pedal-rickshaws). Cycle power is an important mode of human transport in many countries. Other forms of human "transport", such as recreational jogging, running, biking and swimming (and even human powered flight), are also well known, although they should probably be thought of as deliberate, exercise-related activity rather than "transport."

31. Animal powered human passenger transport also exists, both on the back of animals (horse, donkey, camel), and in various forms of cart-pulled transport, with the human movement often incidental to cargo movement. There are relatively limited statistics as to the importance of animal drawn passenger transport, but there are certainly countries (India, Southeast Asia, Saharan Africa) where it is significant²⁰.

NON-MOTORIZED FREIGHT TRANSPORT

32. Human-powered freight transport such as head loading, back loading and in handcarts, is well known in many developing countries throughout Africa, Asia and Latin America: it is especially important where adequate roads do not exist to use cycles, cars or motorized modes.²¹ Cycle driven

^{20.} See, for example, N.S. Ramaswamy and C.L. Narashiman, India's Animal-Drawn Vehicles, Indian Institute of Management, Bangalore, 1984.

^{21.} See, for example, David de Leyser, Case Studies on Intermediate Means of Transport and the Role of Women in Rural Transport, working paper No 2, I.T. Transport Ltd, Ardington, U.K., March, 1992. See also, Ian Barwell, Local Level Transport in Rural Sub-Saharan Africa, World Bank, SSATP, forthcoming. See also, Thamphil Pankaj,

freight transport (usually as three wheelers, but also as two wheelers) plays a major role in smaller, shorter-haul freight movements in many cities and rural areas.²² Although the data are episodic, cities such as Beijing are heavily dependant on human power for a significant share of their intracity goods and services movement. Human powered hand carts are also well known in many countries (India or Madagascar). In fact, human powered, cycle-based messenger transport (clearly a kind of freight transport for high priority letters, documents and packages -- an intracity Federal Express or DHL) is well known in developed countries as anyone who has been nearly run over by a messenger cyclist on a crowded Washington, DC sidewalk can testify.

33. Animal powered freight transport also plays a role in many countries, especially at the first step of agricultural transport from farm to initial market where the animal is also the source of power for the agricultural implements.²³ Almost all larger animals have been used for back-haulage or pulling a cart, including donkeys, cattle, oxen, horses, mules, camels, elephants, llamas, and even dog carts or sleds. Quantitative information on the role of animal powered freight transport is also scattered, but there is no doubt that it plays an important role in many countries.

34. It may seem surprising that the issue of energy consumption would be linked to NMT but, as discussed above, there is a connection. The concept of non-motorized transport as "renewable" has obscured the linkage because the energy consumed in non-motorized transport is not seen as directly related to the transport services performed.

35. But, there is a connection both because of the opportunity costs of using non-motorized modes (the land used to feed the animal could be used to feed humans or grow non-food crops, etc, and there is an energy investment in raising the animal from infancy) and because NMT does in fact consume energy in the form of food, which itself requires energy (fertilizers, sunlight, cultivation effort) to produce. Human power and animal power sources are "engines", and their energy usage in producing transport services should be analyzed accordingly.

36. Basic energy (in the form of fossil fuels, or sunlight, or nuclear sources, or hydropower) is useless by itself; it must be converted into a usable form through a secondary process. The secondary process can be direct, mechanical, heat-based, or biological.

37. Direct sources include solar cells, nuclear-electric generators, and fuel cells (leaving aside the questions of where the source of the fuel cell's fuel comes from). Mechanical sources include hydropower (for example, water falls through a turbine which drives an electric generator, or water

Designing Low Cost Rural Transport Components to Reach the Poor, World Bank Infrastructure Note No. RD-3, March, 1991.

^{22.} See, for example, Padeco Co. Ltd, Non-motorized Vehicles in Asian Cities, World Bank, June, 1993, or Xiaoyang Wu and Louis S. Thompson, Freight Cycles in Beijing, World Bank, forthcoming in 1995, among others.

^{23.} In fact, when the "mechanical ox" was developed, it often took over exactly the same functions, tilling and farm haulage, and haulage from farm to first market that the ox had previously performed.

drives a mill wheel directly), or wind power (a windmill which drives an electric generator or a mill wheel). Neither source necessarily involves the generation of heat, and either can, in principle, convert a very high percentage of its potential energy into usable energy subject only to losses of friction and electrical generation and transmission. Except in the usage of hydropower to drive electric railways, neither is currently a significant source of transport energy (sailboats used to be a primary source of long-distance transport).

38. Heat engines are by far the most important source of energy, particularly for transport. "Heat engine" refers to all prime movers which are driven by the exchange of heat from a higher temperature source to a lower temperature sink. These engines are inherently limited by the laws of thermodynamics which define a fundamental limit of efficiency of the engine based on the relationship between the higher temperature and the lower temperature.²⁴ Typical examples of heat engines are the gasoline engines in most automobiles, motorcycles and many trucks, the diesel engines in larger trucks, rail locomotives and many maritime engines, and all forms of heat-driven turbines (steam as well as fuel driven). Although a bit of a misnomer in this context, heat engines are the "workhorse" of the transport systems in all countries.

39. Biological power sources (and fuel cells) are not heat engines because they are not driven by the exchange of heat between high and low temperature sources and sinks. The chemical process whereby food sugars are converted into energy-generating chemicals within the body is thus not thermodynamically limited in its efficiency.²⁵ The succeeding process whereby the body (be it animal or human) produces power and work is, however, rather inefficient, because of friction within muscles and joints when muscles contract to produce motion. Muscle friction generates heat which must be expelled (a phenomenon well known to all athletes), and heat expelled is energy not used. One of the limiting factors on the biological mechanism's ability to produce sustained amount of power is the need to avoid overheating, which explains why cyclists can generate more sustained power than runners (higher speed air flow carries away more heat) or swimmers can generate significantly more sustained work than cyclists (because cold water is the best heat sink of all -- and even though the swimming energy is rather inefficiently transformed into forward motion). As a result of these factors, non-motorized energy sources ultimately show about the same total energy efficiency (ratio of useful work to total input energy consumed) as motorized energy sources. They are neither "free" nor necessarily "efficient" by comparison with their competitors. Instead, in the transport equation, their primary niche seems to be in operating at the small end of the scale for very short trips, or in facilitating transport access by the poor who cannot afford the investment required to employ mechanized transport.

^{24.} The maximum percentage of gross energy which can be converted into usable energy is defined as $1 - (T_l/T_h)$ where T_l is the lower temperature of the heat sink, and T_h is the higher temperature of the heat source, both temperatures being expressed in degrees above absolute zero (-459 degrees Fahrenheit or -273 degrees Celsius). Thus, a steam turbine which operates with steam at a temperature out of the boiler of 1,200 degrees Fahrenheit, and condenses the steam using cooling water at 70 degrees Fahrenheit, could at most have an efficiency of $1 - ((459+70)/(459+1200)) = 68$ percent. In practice, this thermal efficiency rarely exceeds 45 percent for steam turbines. For other heat engines, such as gasoline engines or diesel engines, the maximum efficiency is quite a bit lower, ranging from 20 percent or less to as much as 35 percent under optimum conditions (primarily because there is no good way to recover the waste heat in the hot exhaust gas).

^{25.} See, for example, Kleiber for details.

CHAPTER TWO

DETERMINANTS OF ENERGY INTENSIVENESS IN TRANSPORT

40. The modes of transport use widely differing amounts of energy to produce the standard measure of transport output -- the movement of one metric ton over a distance of one kilometer (t-km) for freight service, and the movement of one passenger a distance of one kilometer (p-km) in passenger service. The reasons for these differences are complex, resulting in a wide range of reports of transport energy use by mode depending on the assumptions and circumstances on which the estimate was based. In a number of cases, the range of variation is wide enough (a factor of two to four, or more) to call the usefulness of the estimate into question. In other cases, certain tenets of widely-held transport conventional wisdom -- for example that rail freight is necessarily more energy efficient than truck, or that rail passenger service uses less energy than automobile or the bus -- are valid for some specific conditions and invalid for others. Actual conditions can and do produce circumstances where the conventional wisdom is inaccurate and where policy and investment decisions based on conventional wisdom would also be invalid. The purpose of this chapter is to present the reader with a summary analysis the data in order to show what is, and is not, known, and what generalizations can be made about transport energy use.

FUNDAMENTAL DIFFERENCES BETWEEN DESIGN OR ENGINEERING DATA AND REAL DATA.

41. The energy consumption of a transport mode is related to a number of definable physical and engineering parameters which can be specified and analyzed as discussed in some detail below. Energy performance is also often influenced by forces outside the control of the designer, including maintenance practices, operating practices, and regulatory policies and subsidies, among many others, which can have a significant impact on energy use. Also, transport systems operate as fleets of "vehicles", on networks of widely varying quality. A fleet will often include a broad mixture of vehicles -- new and old, well or poorly maintained, small or large, variously fuelled, private and public - - which performs as a loosely defined amalgam of the individual vehicles. A network can include new and old infrastructure, rough or smooth, which carries uphill loaded and downhill empty movements (or vice versa), in widely varying, seasonal climates.

42. The data below accordingly fall into two types, engineering-based and experience-based. The engineering analyses are design-related and assume that variables outside the ones under consideration are known and controlled. Engineering-based data tend to fall within narrow, mathematically determined ranges: they are often based on computer models, and they are precise within their limits. The experience-based data usually include actual, broad average results taking all known and unknown factors (including errors in measurement) into account. They are inherently ranges, and the range they comprehend is often surprisingly wide. Both types of data have their uses: engineering data help explain the impact of the individual forces impacting on energy consumption; experience data show how all of the forces work together. Both also have their disadvantages: engineering data can mislead by their apparent precision, while experience-based data often are so undefined as to make interpretation, and use outside the direct area of experience, difficult. Fortunately the two types of data are not mutually exclusive: one brings understanding, the other caution.

43. The discussion below is organized by freight and passenger sections which are further divided into the various modes, including motorized and NMT options. In each section, the discussion first focuses on engineering factors, then presents results of experience. We do not include discussion of one major factor, the effect of uphill versus downhill movement, because, for any given application, it does not differ much among alternatives. This said, elevation change is important in actual energy consumption. In some cases it can be the most important factor which causes experienced-based averages to vary widely.²⁶ However, in any given situation elevation change will not have much influence on the choice of the most efficient mode. Some of the impacts of gradient are included in the detailed data shown in Annexes A and B, and there are models of energy consumption available which can take gradient into account when it is important in a particular case.

44. The objective of this chapter is to discuss how and why transport energy consumption varies, and then to present as much of the actual experience-based data as is useful in order that the reader can place the parametric discussion into the best operational context. Because of the large amount of information and variables, the presentation is divided into a conceptual discussion section below, and a series of more detailed, separate Annexes A and B. The reader should follow the conceptual discussion, and then may wish to look at the Annexes to see how much the reported numbers can vary according to location and other circumstances, many of which are not reported or defined in the underlying data.

DETERMINANTS OF ENERGY INTENSITY IN FREIGHT TRANSPORT

Trucking

45. Trucking is the most ubiquitous of all freight transport modes. Trucks are commonly used across the entire spectrum of freight transport, from local pick up and delivery to international haulage. As a result, trucks vary from very small, light utility vehicles carrying 500 kg or less over local distances to very large and heavy, long haul vehicles carrying 20 tons or more over distances of 5,000 km or even further.

46. The primary engineering determinants of trucking energy consumption are the size and type of truck (light utility, van, tractor/trailer, articulated), type of fuel (especially diesel versus gasoline), load factor, speed, and roughness of road surface. Figures 2-1 to 2-3 use one of the better sources of engineering data (the World Bank's Highway Design and Maintenance Standards Model, often called the "HDM") concerning trucking energy consumption. Figure 2-1 shows that energy consumption is quite sensitive to truck size, speed and fuel. Figure 2-2 shows the relationship between energy consumption and load factor for various truck types, and Figure 2-3 shows the relatively small effect of road roughness on energy consumption for the same types of trucks.

47. Taken together, Figures 2-1 through 2-3 show that larger trucks are considerably more fuel efficient than smaller trucks, an advantage that is compounded for diesel versus gasoline trucks. As

^{26.} In the case of cycling, the need to climb (or descend) steep hills can be a significant factor in deterring cycle use.

Figure 2-1 shows, countries that have restricted the availability of larger trucks (e.g. India, Pakistan and the CEE/CIS economies), especially when those trucks are gasoline fuelled as in CIS countries,²⁷ have paid a considerable fuel penalty for doing so -- as much as doubling the fuel consumption. Arbitrary limitations on truck sizes and fuels are probably only tenable when there is no competition in the transport market and when fuel is priced well below border levels: such limitations are certainly not typical practice in the more open, market economies. There is also a characteristic speed, depending on the truck's gearing, at which the truck is most fuel efficient: speeds both faster and slower will reduce fuel efficiency. This emphasizes an often hidden cost of traffic congestion: not only does the utilization of a truck fall at speeds below the optimum, but its fuel consumption, and resulting emissions, worsen as well. Figure 2-3 shows that rolling resistance and fuel consumption go up slightly on rough roads, adding another penalty to transport costs in those countries that have inadequate, and inadequately maintained, road systems. Figure 2-2 illustrates the effect of load factor on trucking energy consumption: notable is how energy efficient a large truck can be under optimum conditions. Finally, Figure 2-4 shows that truck energy efficiency has been a moving target, improving by about 0.5 to 1.5 percent per year between 1970 and 1990 in the US, for example.

48. Figure 2-5 shows the range of actually reported data. Since most of this data lacks information about most of the values of the independent variables involved, it can only be reported as a frequency distribution.²⁸ The information that is available indicates that the numbers at the lower end of the consumption range pertain to large trucks, and to countries in which there is a sizable fleet of larger trucks with longer hauls available operating under more nearly optimum conditions. The reports at the high end of the range probably apply to cases of small truck energy consumption, or to countries in which the trucking fleet is dominated by smaller, shorter haul or gas-powered trucking. The influence of factors such as type of fuel or road roughness is mixed into the noise of the data. This said, it is encouraging to note that the ranges taken from the HDM estimates are quite consistent with the reported data based on experience.

Rail

49. The most important variables affecting freight energy consumption in railways are locomotive fuel type, wagon loading and train makeup and, to a much lesser extent, speed (rail freight usually does not move at speeds at which wind resistance is significant).

50. The net fuel efficiency of steam locomotives is about one-third (or slightly less) that of diesel locomotives, although there have been experimental steam locomotive designs that were capable of coming much closer to diesel efficiency levels. Although the overall thermal efficiency of electric locomotives is roughly the same as for diesels (see Chapter 1), electric locomotives can still enjoy a

^{27.} The standard truck in the planned economies was a 4 to 8 tonne, gasoline powered vehicle. There were very few large, diesel combination trucks.

^{28.} The purpose of these "frequency" distributions is to give the reader a general idea of where the reports of energy consumption tend to be grouped in the data which we were able to collect. No claim is made that the data set is complete or that the frequency distribution of a totally complete data search would be identical to that presented.

considerable economic advantage over diesels, but the advantage is only partly in the somewhat lower price of coal vis-à-vis oil (per unit of energy content) for use in electric generation. In addition, the simplicity of maintenance of electric locomotives, and the facts that electric locomotives are higher in horsepower and can be temporarily overloaded so that the same amount of work can be done with fewer locomotive units are also significant.²⁹

51. With similar locomotive technology, the most important determinants of rail fuel efficiency are wagon loading and train length, as Figure 2-6 shows. Long, heavily loaded trains moving at optimal speeds can move large amounts of freight with very low fuel usage, providing a basis in fact for the perceived energy advantage of rail in freight movement. Figure 2-7 also shows, however, that there are conditions (movement of general freight, at low load factors, in short trains) in which the potential for rail energy efficiency can be significantly eroded, or even lost, vis-a-vis trucking at optimum efficiency.

52. Figure 2-9 displays the range of actual average fuel efficiencies reported by operating railways. Unlike the comparison of highway practice with highway engineering data based on the Bank's HDM modeling work, the actually reported rail energy consumption levels often occur well above those derived from rail freight energy models based on US rail practice. There are many reasons why this should be so:

a. Most of the rail modeling work focuses on line-haul movement, ignoring fuel which is consumed while the locomotive is idling or performing switching operations. These factors are included in industry-wide, or company-wide reports.

b. There is considerable variation in the types of traffic and operations among railways. As Annex A-3 shows, there is a wide range of average fuel consumption experience even within the US rail freight industry because companies differ in their typical train makeup and operating conditions: the Burlington Northern (BN) railroad in the US has significantly better energy efficiency than the Denver and Rio Grande (D&RGW) because BN hauls so much coal in relatively level terrain whereas the D&RGW operates more mixed trains in mountainous territory .

c. US practice has been optimized for freight, not passenger, service and thus has routinely employed strong track (which permits large wagons and high axle loads), long trains, and train schedules which allow freight trains to operate at maximum efficiency. Many national railway systems are optimized for passenger services (see Figure 1-5) and not designed to take advantage of optimum efficiency practices for freight services alone.

53. Only China and the CEE/CIS countries, and to a lesser extent India, operate freight trains under conditions similar to those in North America. As the range of variation in Figure 2-8 shows, many of the Bank's borrowers operate rail freight under conditions which do not take full advantage of rail's potential freight energy efficiency. If a railway runs short, lightly loaded freight trains and stops them

²⁹. In particular cases, the maintenance and investment savings of electric locomotives can equal or exceed their savings due to lower energy costs. See, for example, Alston and the USDOT, Federal Railroad Administration studies.

frequently to allow passenger trains to pass, fuel efficiency suffers accordingly and (if there is an adequate highway system) rail's competitive advantage can be seriously undermined.

54. It should also be noted that the actual length of a rail line between two points is almost always significantly longer than by road, sometimes by 20 to 50 percent, because rail locomotives cannot climb gradients as steep as those which trucks can climb.³⁰ This means that, for a given tonnage to be moved between two points, rail may need to generate significantly more ton-km than trucks, a fact which further reduces the actual fuel efficiency of the rail movement.

55. As with trucking, rail fuel efficiency has been very much a moving target over time, as Figure 2-9 shows. Although a part of this improvement is unique to North American conditions, a significant part is directly related to locomotive efficiency which has in turn influenced developing countries because many of the world's diesel locomotives are based on North American technology. In the US between 1960 and 1990 the total rail industry average fuel efficiency roughly doubled while specific locomotive fuel efficiency improved by only 30 percent: the remaining improvements were due to changes in loading, train length and length of haul.

Air Freight

56. If energy consumption alone were a governing consideration, there would be no movement of freight by air. Because of their speed, airplanes generate much more air drag than any of the surface modes. Because they typically climb as high as 10,000 meters to cruise, airplanes usually consume a significant amount of fuel on elevation changes. Finally, generating lift over an airplane wing (which is needed to keep the aircraft in the air) requires continuous power, unlike the surface modes which are concerned only with drag, and not lift. The result is that air freight consumes a high amount of energy per unit of output, as Figure 2-10 shows. Because of the importance of fuel consumption in climbing, trip length plays a much more important role in air than in surface transport. Aircraft type and size also play a significant role. Data on the importance of load factor can be seen in Figure 2-11 which shows that aircraft fuel consumption is quite sensitive to load factor, possibly more so than for the surface modes. Unfortunately, it is difficult to calculate the fuel consumption of air freight directly because most air freight is carried in combination with passenger service and it is hard to separate the effect of freight from passenger on fuel consumption. Figure 2-12 contains the available experience-based data.

Pipelines

57. Pipelines are the most specialized and restricted modes of transport. They only move fluid or fluidized cargos in high volumes between a limited number of points. If volumes are high enough, as Figure 2-13 shows, liquid pipelines are among the most energy efficient modes of transport. It is

³⁰. Because of the low friction of steel wheel on steel rail, rail operations begin to encounter difficulties with traction wheel slippage on loaded gradients of more than two percent. The much higher friction of rubber tires on road means that highways routinely operate with gradients of greater than 5 percent, and can go as high as 10 percent or more. Thus, the railway energy savings from lower rolling friction can sometimes be partially surrendered by a need for longer trips on less steep routes.

significant to note that the energy consumption of pipelines is highly dependent on the nature of the liquid, especially its resistance to flow (viscosity), and on pipe diameter. Under optimum conditions, water could be moved for as little as 10 kJ/t-km, and crude petroleum for as little as 200 kJ/t-km. By comparison, coal slurries appear to require about ten times as much energy -- in the range of 2000 kJ/t-km -- because the effective viscosity of coal slurry is so high. Because of their low energy consumption for liquid cargo, and low operating costs, pipelines are usually the most efficient method for moving large volumes of liquid products between a limited number of origins and destinations. Gaseous products are somewhat more energy intensive than liquids to move by pipeline, consuming between 1,000 and 1,500 kJ/t-km.³¹ Despite their higher energy intensity, gas pipelines have very low operating costs and are usually the most efficient way to move gases overland if the volume is high enough to justify construction of the pipeline.

Water Transport

58. Water transport is also a specialized mode. For ocean shipping of large amounts of bulk commodities there is no effective substitute for ocean transport. Most countries have limited or no access to inland water transport, the US and the countries of Western Europe, and to a lesser extent Russia and China, being the exceptions. Coastal and inter-island water transport plays a significant role in many countries, particularly Japan and the Ocean Pacific countries. Though the distances are often quite short, coastal water transport often enjoys an effective monopoly over this type of movement as well.

59. Water transport has the unusual characteristic that there are never any hills.³² Depending on hull design, water drag on the hull can be quite small and, of course, at typical water transport speeds, air drag on the ship is minimal (not necessarily true of hydrofoils or air-cushion vehicles). Although energy consumption for a particular hull is sensitive to speed and rises exponentially when speed rises above design levels, most ships can be operated close to their design point. As Figure 2-14 shows, ship size and type are the primary determinants of energy consumption, and there is significant variation among types. Overall, reported energy consumption levels for water are among the lowest of any transport mode: nothing carries more ton-km for fewer kJ than a fully loaded supertanker at its optimum cruise speed. But, lightly loaded small ships are not much more energy efficient than the other surface modes.

Non-Motorized Freight Transport

60. Traditional transport analysis has rarely looked at NMT freight in terms of its "fuel" consumption. Explicit calculations of NMT freight energy consumption in kJ/t-km have been rare,

^{31.} World Bank calculation. See also Jacques Vincent-Genod, Fundamentals of Pipeline Engineering, Institute Francais du Petrole, Gulf Publishing Co, Paris, 1984 page 40: "All in all, for the transport of the same amount of energy, the pipe must be 50% larger and the power must be 5 to 6 times as high for gas as for liquid fuel."

^{32.} Locks do move traffic "uphill" but they do not affect the energy consumption of the water transport. However, river boats do have to go upstream occasionally, a fact that is quite important on the Rhine river, for example.

perhaps because freight NMT has been treated as a marginal, almost invisible issue for most traditional transport analysis. This lack of attention to NMT is unfortunate because NMT is not a marginal mode of freight or passenger transport in many Bank countries. While few countries have adequate estimates of the percentage role of NMT in their overall national freight transport, it is clear that NMT cannot physically play much of a role in total ton-km, or in long-haul freight. It is equally clear, however, that NMT plays a significant role in a number of local freight transport systems in Asia and Africa (and a few cases in Latin America), especially for the poor who cannot afford trucks and do not ship enough cargo to justify access to the railway.³³ The Bank is moving to improve its information about NMT in recognition of its importance in local transport by the poor.

61. Another reason why NMT energy consumption has not been as fully reported as that of motorized transport is that NMT "fuel" is food, a renewable resource which is not placed in quite the same category as nonrenewable, fossil fuels. As discussed earlier, this treatment is debatable; aside from the fact that fossil fuels are often used in significant quantity to make "renewable" foods, there are definite opportunity costs associated with use of resources such as land, water and sunlight in food production rather than alternative uses.³⁴ Even though, as discussed below, NMT is quite energy efficient within its normal range of operations, the Bank should at least be aware of its energy consumption implications.

62. The diversity of sources of NMT traction effort is incredible. There are many cases in which humans are the prime mover as well as providing the platform, including head loading (a very significant mode, especially by women, in Africa and some parts of Asia), and back loading in many congested urban areas. Although most head and back loading is for private purposes (the NMT equivalent of "private", or "own-account" carriage), there are well documented examples of humans as public ("common") carriers.³⁵ It seems probable that the actual amount of this type of carriage is significantly greater than has been reported to date, but has never been fully recognized as such and therefore has not been fully profiled except in a few cases.

63. In addition to the human as platform, there are a number of important examples in which the human is the power source, but the freight platform is a bicycle, a tricycle bed, or a rickshaw. Saddle bags or other forms of freight management (back packs, or animal cages) are often seen on bicycles. Freight tricycles encompass virtually every form of contraption known to human ingenuity, and are commonly encountered in many urban areas in Asia, such as Beijing.³⁶ Human-drawn freight

^{33.} The limited existing data on tariffs for NMT suggest that, while it is the only mode accessible to the poor in many instances, it is extremely expensive. See, for example, the Pankaj, Barwell and Riverson/Carapetis sources which cite tariffs for NMT of up to \$2.80 to \$3.00 per t-km for cycles and \$3.00 per t-km for head loading in Ghana, at least ten times the comparable costs by truck.

^{34.} The tradeoff between water for agriculture and water for drinking is particularly clear, for example, in competition for water resources between Southern California (people) and Central California agriculture.

^{35.} See Pankaj.

^{36.} See Padeco and Wu and Thompson.

rickshaws are occasionally seen in urbanized areas (Antananarivo) where maneuver is difficult and labor is cheap.

64. Because NMT energy is often not analyzed as such, we have had to develop estimates from sources that were intended for other purposes. The results presented should be understood as the best available estimates, and reasonably indicative. Even less is readily available on the freight energy consumption of animals, for which there is perhaps an even wider variety of options involving animal-back, or animal-drawn cart arrangements, ranging from dog sled to camel cart to elephant back. For the information available, and subject to the qualifications noted, Figure 2-15 shows the relationships between energy consumption and speed (which appears to be the primary independent variable), though speed is only weakly related to energy consumption within the normal speeds of sustained human and animal freight traction.

Summary of Freight Transport Data

65. Figure 2-16 summarizes the overall energy efficiency ranges of the various modes of freight transport. We have presented the results as ranges since no point values are possible given all of the variables involved. There are some significant conclusions within these ranges:

a. Depending on the circumstances, the energy efficiency range for a mode can be quite wide. "Trucking" in the US with large, full diesel trucks moving long distances at steady speeds over relatively smooth roads can move freight for 500 kJ/t-km, whereas "trucking" in CIS countries using partly loaded, small to medium gasoline trucks over rough roads could consume as much as 5,000 kJ/t-km. A very heavy, unit train carrying 10,000 tons of coal at optimum speeds might need only 100 kJ/t-km, whereas the railways of the US and Malawi actually average 260 and 1,038 kJ/t-km, respectively. Imprecision in specifying conditions can result in misleading estimates of the energy performance of the modes.

b. Again depending on the circumstances, the ranges can readily overlap. While unit trains of coal do move at energy consumption rates which are far below those of small trucks, very large trucks under optimal conditions can move freight for less energy than some average railways. The comparison of actual railways with actual trucking in a particular country is hard to predict in advance.

c. NMT freight transport is not particularly "fuel" efficient. Human powered freight transport falls within the range of a small truck, as does animal freight transport. This should not be surprising as the underlying physical forces at work are the same for all of transport: force must be exerted through a distance to overcome elevation and friction and, although the mechanism is somewhat different, the process whereby animals turn food into tractive effort is no more fuel efficient overall than the process whereby heat engines turn fuel energy into power for traction.

DETERMINANTS OF ENERGY INTENSITY IN PASSENGER TRANSPORT

Automobile

66. Autos are to passenger transport as trucks are to freight: autos are the most pervasively available method for motorized movement of people. In the developed world, they carry the lion's share of local as well as intercity passenger-kilometers.³⁷ Autos are unusual in that they are often both a private and a public mode of transport (taxis). In the developing world, the rush toward auto (and motorcycle) ownership is one of the most striking, and environmentally threatening, trends now occurring. As a number of studies have indicated, predictions of energy consumption in transport are largely driven by forecasts of the auto fleet and its use (and, secondarily, trucking).³⁸

67. Even more than trucks, autos come in all sizes, types and ages. Depending on personal income and government policies relating to auto and fuel taxation, the automobile fleets in specific countries will have widely differing mixes of auto types and usage patterns. Taxi fleets and autos, in particular, are sensitive to the availability of spare parts. The result is that it is difficult to analyze auto energy usage without detailed studies of the situation and trends in each country.

68. The predominant determinants of auto fuel efficiency are size of auto, speed, fuel type, load factor and, to a lesser extent, road surface roughness. Figure 2-17 displays auto fuel economy under standard conditions for various sizes of autos at various speeds. Fuel economy is heavily dependent on auto size, and is affected by speed. As with trucks, autos have an optimum speed for best fuel economy -- slower speeds caused by congestion reduce fuel efficiency, higher speeds cause rapidly decreasing fuel economy. Figure 2-18 shows how fuel economy varies with load factor (the number of people in the car) for various autos: because total fuel consumption is essentially independent of passenger occupancy, energy intensity per p-km is wholly driven by occupancy, *ceteris paribus*.³⁹ Figure 2-19 adds the dimension of road surface roughness in the energy calculus.

69. Figure 2-20 shows the rate at which new car fuel economy has improved over the past 15 years in Europe, the US and Japan. Changes in the technology of auto design account for part of the improvement, while another part is embedded in a highly complex series of changes in the fleet mix in these countries. Autos have become somewhat smaller in response to fuel economy standards and changes in fuel prices (fuel prices have risen in Europe, and are slightly down in real terms in the US). At the same time, and offsetting the trend toward more fuel efficient vehicles, autos have gotten

^{37.} To be sure, walking is the most pervasive mode of transport on the basis of percentage of passengers.

^{38.} See World Energy Council/Statoil, Transport Sector Energy Demand Towards 2020, World Energy Council, Final Draft Report, Stavanger, Norway, June, 1995. [This is to be transferred to the Bibliography]

^{39.} For taxis, only the passengers (and not the driver) count in determining p-km. With two passengers, the taxi is only half full and, because taxis often cruise empty looking for passengers, actual taxi energy efficiency would be below optimum levels.

somewhat more luxurious and higher powered in response to increases in personal income. The energy efficiency of the overall fleet has lagged the performance of the new vehicles.

70. A comprehensive picture of all of the forces at work in the auto demand and usage equation is simply not available, even in the developed markets where the most detailed information exists. Where the past and present are not well understood, the future is difficult to predict with any confidence. Predictions are even more problematic in many developing countries where the basic data is non-existent or questionable at best.

71. Keeping these caveats in mind, Figure 2-21 shows the range of auto energy intensity which has been reported in the literature. It has been shown as a frequency distribution because many of the underlying parameters are not reported with the overall data. Given that age and technology, average speed, auto size and occupancy, and the balance of urban versus rural driving are likely to be different in many of the reports, it is difficult to analyze the data in detail. It is likely that the lower numbers are based largely on more favorable assumptions about vehicle size and occupancy ratios, while the higher numbers relate to larger autos with low occupancy ratios. It is reassuring that the levels reported in the HDM models are consistent with the reported data.

Rail

72. The very low rolling resistance of steel on steel versus rubber on road gives rail passenger transport the same potential advantage over autos as it does rail freight over trucks. But, as with rail freight, there are a number of forces at work in rail passenger energy consumption which can strongly affect the actual results.

73. The main determinants of the energy efficiency of rail passenger activities are the types of service and their related technology, speed and occupancy. As a broad generalization, rail passenger services can be divided between urban (metros and trams or trolleys), relatively short-haul suburban services (usually diesel or electric multiple-unit coaches, but also short, locomotive-hauled trains) and longer-haul intercity services (mostly locomotive hauled). While this is not an absolute distinction because a spectrum of services exists, it is a useful general classification. There is also a distinction between electric and diesel traction but, as with rail freight services, there is not a great difference between the total energy efficiency of electric and diesel traction. In fact, the preference for electric traction in metro and suburban services is not strongly based on fuel efficiency but is instead based on restrictions on combustion in tunnels (both to guard against fire and to avoid consuming the oxygen in the tunnel) and on the greater acceleration capability of electric vehicles.

74. The speed of the train has little influence on the energy consumption of "conventional" passenger trains (speeds below about 100 to 110 km/hr). Air drag becomes important at speeds above these levels and, for the true "high speed" trains (the TGV in France travels at more than 300 km/hr), air drag becomes the major consumer of energy.

75. Since the weight of the passengers in a 70 to 90 ton rail passenger coach is at most 10 tons, the total energy consumption of a full train is almost the same as that of the same train if it is empty: the energy intensity in kJ/p-km is thus very strongly dependent on occupancy rates.

76. Figure 2-22 shows the relationship between speed and energy consumptions for several selected types of trains, and Figure 2-23 shows the impact of train occupancy on rail passenger energy intensity. Figure 2-22 supports several significant conclusions. First, the very bad aerodynamics of the Amtrak high speed trains (one AEM-7 locomotive with six Amfleet coaches) means that, at higher speeds, the TGV or X-2000 (Swedish technology) actually use half or less the energy per p-km used by Amtrak in their Northeast Corridor. Next, many long haul trains, such as the Amtrak Superliners, carry a significant amount of rolling stock in the train which is not producing seat-kms: diners, sleeping cars, and baggage cars are all part of a long haul train consist, but have relatively few seats. Also, seats cannot be placed as close together on a long haul train as on a short haul train. The higher-density, shorter haul Amtrak conventional train shown in Figure 2-22 gives a better idea of what passenger energy consumption could be if operated for maximum energy effectiveness. Finally, Figure 2-23 adds emphasis to the importance of load factor; half full trains lose a lot in energy efficiency.

77. Figure 2-24 displays the actual data reported for rail passenger operations. One important conclusion is that the higher energy consumption numbers probably relate to shorter haul rail services which tend to have surprisingly high energy consumption intensities because of their typically low load factors. Another striking point is the divergence between the commonly reported engineering estimates of rail energy intensity and the levels sometimes experienced in practice. Although the data are not sufficiently detailed to be sure of the reason, it seems likely that the primary force at work is low load factors: many commuter agencies run relatively empty trains,⁴⁰ and empty trains are fuel inefficient, no matter how well run or designed. Low load factors are a particular problem for urban transit authorities because of the highly peaked nature of commuting demand: efficient, full trains during the rush hour become inefficient, empty trains in the off-peak hours.

Bus

78. Measured by passengers handled, buses are by far the most important form of short-haul public passenger transport in the world. Buses are also important in longer-haul public transport in developing countries, but occupy a lesser role in many developed countries. The fuel efficiency of buses is related to bus size (from 15 passenger jitneys to 100 passenger articulated buses), operating cycle (urban versus long haul), speed (stop and go versus highway), road roughness, and occupancy (the key factor). Figure 2-25 displays the HDM-based relationship between bus speed and fuel economy.⁴¹ Figure 2-26 shows the impact of changes in occupancy: road roughness is not shown, but can be inferred from Figures 2-3 and 2-19. Figure 2-27 then displays the reported bus fuel economy data in a number of

^{40.} Amtrak's overall average load factor in 1994 was slightly below 50 percent. Since the average long haul train carries about one gross ton of weight for each passenger, it is not surprising that half-empty trains consume large amounts of energy per passenger-km.

^{41.} The HDM does not yet have the capability to estimate fuel economy for smaller buses, nor for gasoline-powered buses. Comparing Figure 2-17 with Figure 2-25, the energy consumption per p-km of a fully loaded large automobile is about 4 times that of a fully loaded large bus. Small buses will probably fall somewhere between the two curves in Figure 2-17 and 2-25, and gasoline-powered buses would probably have about the same relationship to diesel buses as do gasoline trucks to diesel trucks of the same size.

countries. We have not been able to distinguish urban from intercity buses in this Figure, but the impact of start/go operations and peak/off peak on load factors on urban buses no doubt accounts for some of the points at the upper end of the range. Note, for example, in Annex B-3, pages 2 and 3, that urban buses can be much less energy efficient than the average levels often reported for intercity buses. Figure 2-27 and Annex B-3 help to underline both the very high potential fuel efficiency of long haul buses under appropriate conditions, and the considerable gap between optimum long haul operations and typical urban operations.

Air

79. As with air freight, passenger air travel represents the higher end of the tradeoff between speed and energy consumption. Aircraft carry passengers quickly over long distances but air drag and the energy of climbing cause energy consumption to be high. In general, as Figure 2-28 shows, larger aircraft can be somewhat more fuel efficient than smaller aircraft, and there is an optimal length of haul for each type of aircraft. Load factor is also critical, as shown in Figure 2-29. Figure 2-30 then displays the reported airline fuel economies across a wide range of aircraft types, stage lengths and load factors.

Motorcycles and Mopeds

80. In many countries, motorcycles and mopeds represent the first step in motorization: they are the poor man's auto. Motorcycles and mopeds have gained a rapidly growing share of a number of transport markets as a result.⁴² They have brought in their wake a serious air pollution problem in many cities in Asia because many motorcycles in developing countries use a two-stroke cycle engine which is quite dirty in its emissions (US motorcycles above 50 cc engine displacement were required to change to four-stroke cycle engines in 1978).⁴³ However, because of their relatively small size it might at first appear that they should at least be quite fuel efficient.

81. There is not a lot of available parametric information about motorcycle fuel efficiency, but the limited data shown in Figure 2-31 suggest that motorcycles and mopeds are not greatly different in their fuel efficiency from other forms of road transport.⁴⁴ As with other forms of transport, the smaller engines on light weight mopeds tend to yield higher efficiency, while larger engines on heavier motorcycles are less efficient. The speed relationship that holds for autos, buses and trucks would apply even more strongly to motorcycles and mopeds because they are less streamlined; but

^{42.} Motorcycles and mopeds have not been analyzed as a mode of freight transport. There are some types of cargo (dispatched mail or messages) and some locations in which motorcycles are likely to have a small share of the freight market, but we have no examples of cases in which the share is large enough to deserve separate attention.

^{43.} See Lit-Mian Chan and Christopher S. Weaver, Motorcycle Emission Standards and Emission Control Technology, World Bank, Asia Technical Department, September, 1994, pg 14. [reference to be transferred to bibliography]

^{44.} Given the importance of motorcycle and moped transport, it may be desirable for the Bank to add them to the parametric equations in the HDM.

motorcycles may be somewhat less affected by urban congestion than other modes because they can drive between lanes and thus keep moving while other traffic is stopped.

Non-Motorized Passenger Transport

82. Certain forms of NMT passenger transport, such as walking, are so thoroughly taken for granted (except by the lazy) that they are often not fully recognized as a real and important form of passenger transport. The poor have long known otherwise, however, and the Bank is now focussing on human NMT, particularly walking, because of its importance to this segment of the population. Running, swimming, and rowing are probably more properly defined as "exercise" than transport, and yet they are interesting in outlining the limits of energy intensity. Although it also occupies an area at the margin of "transport", animal-back passenger transport is also a well known activity, and is another boundary to be examined. Figure 2-32 shows the range of energy intensities for these types of passenger transport.

83. Human pedal-powered transport is certainly not a marginal mode, as any visitor to many Asian countries (or The Netherlands) can testify. Cycling, like the progression from walking to running, offers the opportunity for both efficient transport and exercise, depending on purpose. For the poor, cycles offer the opportunity to expand their range of employment opportunities at minimum cost of both money and energy; for the urban dweller, cycling offers an effective and environmentally friendly way of getting around on congested streets. For those so inclined, cycling can also be a way of rapidly burning off excess calories. In a few cases, cycle rickshaws also offer a way of moving people around in urban areas.

84. The primary determinants of energy intensity in cycling are design and speed. Cycle designs vary over a wide range:

- a. The fat-tired, coaster brake bicycles of years ago;
- b. The rugged, simple, single speed bicycles produced by the millions in many Asian countries (and The Netherlands) for use in urban traffic on essentially level terrain;
- c. Simple, three speed utility bicycles with tread brakes;
- d. High performance bicycles including "mountain" bikes, "hybrids" and "road" bikes. These bicycles have a range of tire widths and frame sizes, are typically equipped with 10 to 24 speeds, have tread brakes, and weigh as little as 10 kilograms. They are designed for specialized conditions from rugged, off-road use (large tires, small frames and upright riding position) to sustained high speed cruising (small tires, larger frames and streamlined riding position), and cost from as little as US\$ 200 to as much as US\$ 3,500 or more.

85. As Figure 2-32 shows, energy consumption on bicycles and rickshaws is highly dependent on speed (assuming level ground and no wind). The influence of streamlining at higher speeds is evident since, for a typical bicycle, air drag begins to exceed rolling friction at speeds greater than about 15

km/hr. The influence of air drag is so great that streamlined fairings on cycles can increase human powered cruising speeds by as much as 50 percent.⁴⁵

Summary of Passenger Transport Data

86. Figure 2-33 summarizes all of the passenger transport data in ranges, as was done for freight. Many of the conclusions from this Figure are similar to those for freight:

a. The range for each mode is quite wide. Speed and luxury are expensive in passenger transport, but the critical issue is occupancy. Most passenger modes are strongly affected by load factor (except walking and cycling which by definition have a load factor of at least 100 percent, but can be greater). Underutilized modes suffer greatly in energy efficiency no matter what their technical capabilities might be.

b. It is fair to say that cycling is, under normal conditions, the most energy efficient (though not energy free) mode of passenger transport. Walking is not far behind. Beyond this, there can easily be overlap among the ranges of efficiency of the modes. Of the motorized modes, full buses are hard to beat, although full trains can equal them. Empty trains can burn more fuel per p-km than full airplanes, and a full automobile is a highly energy efficient mode of personal transport when there is a way, such as trip sharing or HOV lanes, to increase auto loading.

c. It is particularly important to distinguish between urban versus intercity transport because of the impact of congestion which causes slow, stop-and-go traffic and because of the impact of time of day and day of week peaking on load factors. The most efficient mode for intercity trips may not always be the efficient choice for urban travel.

^{45.} An example of the influence of distance and speed on human energy consumption in cycling is the estimate that racing cyclists on multi-day races, such as the Tour de France, consume up to 10,000 calories per day -- versus a normal bodily requirement of around 2,500 calories per day. The 7,500 calories of "fuel" moves the cyclist a distance of up to 200 km per day at speeds of up to 60 km/hr, or more.

CHAPTER THREE

THE ROLE OF ENERGY CONSIDERATIONS IN MODAL CHOICE

87. Transport system users often do not choose either the most energy efficient mode or the most environmentally friendly mode. This happens for two reasons: first, energy is only a small part of the cost of producing transport; and, second, transport is only a part of the total cost which the transport user experiences in managing freight logistics costs, or in making personal travel decisions.

Energy Costs as a Share of Transport Production Costs

88. While energy is needed to produce physical movement, labor, vehicles and infrastructure are required as well. Transport providers must cover the cost of all of these resources if the transport services are to be sustainable. Though it is not usually expressed in these terms, this statement applies to NMT as well as motorized modes. Although there is considerable variation in the cost categories below, reasonable estimates of the percentage of total costs of transport by mode and by type of cost category would look roughly as follows⁴⁶:

	Fuel	Labor	Other Operating	All Other	Total
Freight:					
Truck	11.9	36.4	41.0	10.7	100
Rail	6.4	47.3	36.8	9.5	100
Air	5.7	50.8	36.0	7.5	100
Freight Cycle (Beijing)	1.4	97.2	0.8	0.6	100
Passenger:					
Auto	5.5	57.3	21.2	16.0	100
Rail	10.4	58.2	25.6	5.7	100
Bus	4.9	16.3	73.5	5.3	100
Air	11.9	35.0	47.7	5.4	100
Bicycle (commuting)	7.9	84.8	3.4	3.8	100

89. In fact, as these numbers suggest, transport actually is based on a rather complex tradeoff among several factors of production, of which energy is only one -- and energy is at most 10 percent of total transport costs at that. It is possible to influence these tradeoffs by changes in factor prices or tax policies but, because energy is such a small part of total cost, energy prices would have an effect only at the margin. Railways do like to save fuel, of course, but not at the cost of inefficiencies in labor or usage of their capital investment. Trucks are more sensitive to fuel costs than rail, but trucking companies have generally not been willing to save fuel by slowing down their trucks because slowing

^{46.} Source: World bank calculations based on annual reports of the carriers involved, and estimates for the NMT modes.

down also raises labor costs, reduces capital utilization, and reduces the quality of service to the customer. A comparable example is the relatively similar auto usage and fuel economy among the US, Europe and Japan despite the fact that auto fuels cost about three times as much in Europe and Japan as the US: clearly European and Japanese drivers do not see fuel as the determining important cost of owning or operating an auto.

90. The important point is that programs to influence energy efficiency in transport through energy price or taxing incentives often miss their mark because the operator/user is optimizing the sum of all costs, including transport, and not just that of transport energy. A less obvious, but possibly more important point is that programs which intervene directly in energy usage (for example mandated fuel economy standards) often significantly decrease the overall economic efficiency of transport, even though they may reduce the usage and apparent cost of energy by itself: when this happens, the economic cost of "saving" energy can be far above the cost of the fuel in the first place.

What is the User Optimizing?⁴⁷

91. Consumers of transport services are clearly optimizing something beyond just the cost of transport. In freight, the shipper minimizes total logistics costs, including inventory management costs (which are related to shipment size and time of transit), loss and damage, and Just In Time (JIT) considerations including the reliability of promised shipment time -- in addition to the cost of transport. In passenger services, the user is optimizing a personally determined combination of trip time (which includes speed and frequency of service), comfort, perceived prestige, and perceived safety -- over and beyond the cost of the ticket or the perceived cost of the trip.⁴⁸ It is the balance of these factors which ultimately determines modal choice.

Freight Modal Choice

92. Although the input factors could in principle produce an almost unlimited range of outcomes in modal choice for particular shipments, modal choice tends to simplify itself in practice into broad domains where one or the other modes generally dominates, with domain boundaries along which the modes compete. The quality-related competition between rail and truck can, for example, be seen in concept in Figure 3-1 which shows that the areas in which rail's low cost, relatively low quality of service characteristics generally appeal to shippers of low value, bulk products which are shipped in

^{47.} Much of the discussion in this Chapter, including Figures 3.1 and 3.2, is drawn from Gwilliam, Shalizi and Thompson, Railways, Energy and Environment.

^{48.} We use the word "perceived" here because studies have repeatedly shown that the actual costs of auto travel, for example, are often quite different from those on which the traveller apparently makes travel and modal choice decisions. The same is true of safety: while the actual risks of auto travel are far higher than those of air travel (on scheduled airlines, at least), travelers are far more aware of and sensitive to airline risks than when they drive on the highway. Prestige is, of course, inherently a matter of perception.

large quantities between a limited number of points.⁴⁹ The road domain includes the high value, shorter haul and highly reliable transit time, end of the spectrum. Water is not shown on this chart but would overlap rail from the left hand side (i.e. from the low value, lower quality end of the scale). Air would overlap road somewhat and extend to the right side of the chart (i.e. even faster shipments and higher value commodities).

93. Another perspective on modal domains is shown in Figure 3-2 which focuses on shipment size and trip length. Rail is unable to compete with trucks for small shipments over short distances, while trucks cannot compete with an effectively managed railway for large shipments over long distances; mid-sized shipments over medium distances are the only area for competition. Air freight is not shown on this chart but its "reserved" area would be slightly on, and mostly below, the left-hand side of the Figure. Water's domain would be on the lower right-hand side and beyond and below; pipelines would fall roughly in the same area, but would be restricted to surface movement of liquid cargos. NMT freight is confined to the extreme upper left-hand corner (at most about 15 miles (25 Km), and up to at most 1,000 pounds (500 Kg)).⁵⁰

94. Figures 3-1 and 3-2 are based on analyses in a developed country context, and might not have quite the same shape in some developing countries. Where highways are poor, and the size of trucks arbitrarily restricted, rail's domain might expand, as would the competitive overlap. Extremely cheap labor to load and unload rail wagons would also have a positive effect for rail. However, in countries where trucking is private and market-driven whereas railways are very poorly managed and in the public sector, rail's domain has shrunk to the extreme lower right-hand corner of Figure 3-1 -- and consists mostly of government controlled cargoes. Also, while Russia, India and China offer the full range of distance and shipment size shown in Figure 3-2, there are also countries (Costa Rica) in which the longest shipment geographically possible is less than 500 km (300 miles), and others in which all shipments are small: these are not natural domains for rail freight.

95. Thus, transport modes are not necessarily interchangeable: in most cases, shippers can change modes only at a significant increase in their total logistics costs. Therefore even significant changes in the cost or availability of fuels or energy sources, or in the efficiency with which energy is used, may have little effect on actual modal choice (though such changes might marginally change the total amount of transport demanded).

Passenger Modal Choice

96. It is much more difficult to represent the domains and competitive interfaces among the passenger transport modes because the dimensions of the modal choice decision are more complex.

^{49.} An emerging and partial exception to this generalization is in containerized freight where, if volume is large enough to permit unit trains of trailers or containers, service quality can be delivered which is comparable to that of trucks.

^{50.} See Wu and Thompson.

Overall, passenger modal choice falls into two broad categories: urban versus intercity, and is subject to the broader influence of the choice of personal versus public transport.

97. Urban passenger choices. Figure 3-3 conceptually illustrates the domains of the urban passenger modes based on the distance to be travelled and the income of the traveler. It is based on the assumption that time has at least some value for all: almost everyone will walk very short distances; only the poor will regularly walk long distances to work; bicycles offer an interim choice, where terrain and weather permit, for those who are younger or sufficiently agile. Figure 3-3 also shows how the distance curve might actually bend backward for those whose income has risen high enough that they deliberately seek exercise.

98. The smallest towns tend not to offer public modes, so the only choices are NMT (walking or bicycles) and driving. As the town becomes a city, public modes become feasible, starting with buses for smaller cities and graduating to high capacity busways and rail-based modes as the city becomes even larger. It is difficult to show the bus domain graphically because bus has no solidly exclusive competitive advantage. In principle, bus would compete in an area roughly within the dotted lines on Figure 3-3. The high capacity mass transit modes in major cities would generally overlap the bus area but, if well designed and operated, might extend the domain slightly to the left, and more significantly to the right. In this urban context, "auto" and taxi might be thought synonymous, with the taxi behaving as an expensive, but more widely available auto: if so, the taxi curve would be somewhat above and to the right of the total "auto" curve.

99. These are, of course, broad generalizations meant to explain, not define: the boundaries of each competitive domain are less clear for urban passenger than for freight transport. Fuel prices do eventually affect urban transport costs and a change in energy costs might favor the most energy efficient mode slightly. However, most urban public transport modes are subsidized, some significantly so, and public subsidies often offset other factor cost changes. Of course, subsidies are not confined to public modes and employer-based devices such as subsidized auto parking can far outweigh the effect of public policies attempting to encourage use of public modes.⁵¹

100. Other things also affect the shapes of the modal domains shown. Potholes in the street can make both auto and bus travel more expensive (in time and cost) and could extend the walking domain - - but only if there is room to walk or ride a bicycle. Policies of providing free public transport have also been tried with some success but, without easy access and frequent service by public modes, people will still use their autos or walk because public transport is not a full competitor -- no matter what happens to energy efficiency or energy cost.

⁵¹. Consider, for example, the case of a World Bank employee with a 20 mile round-trip commuting trip each day in an automobile with 20 miles per gallon fuel consumption. Each month, this employee would consume 22 gallons of gasoline (22 days/month X 20 miles/day divided by 20 miles/gallon) costing about \$28.60/month at \$1.30 per gallon. The Bank parking subsidy to each employee of about \$70 per month is the equivalent of a subsidy of roughly \$3.18 per gallon, which is far beyond any likely changes in fuel taxes in the US. In effect, removal of the Bank subsidy ought to have the same effect on employee driving behavior as an increase in the fuel tax of \$3.18 per gallon.

101. Intercity non-leisure passenger choices. "Intercity" implies a longer trip than "urban". Under some conditions (high urban density, very low inter-urban density) intercity travel might be as short as 50 Km; a trip length of at least 100 Km would be more typical, though certain commuter operations occasionally extend to 120 Km (Bombay, London, or New York City, for example). A simple way to think of the competitive modal domains is the two mode autos versus air case which would be typical of some developed countries, as in Figure 3-4. There is a minimum distance below which the auto is faster and cheaper than air because of the minimum access time to the airport and waiting time for the airplane. Beyond the minimum, air has a travel time advantage which increases with distance, making it easier for air to compete for travelers with lower and lower values of personal time. Extremely wealthy travelers have corporate or private airplanes and sometimes fly over distances as short as 150 Km. Commercial airlines have to offer very low discount prices to get the lower income employees to travel long distances. The location and shape of the interface can move slightly if air's cost, comfort, frequency or perceived safety change, but the basic tradeoff is well established.

102. The case can be made more relevant for developing countries by adding rail to the picture, as has been done with the dotted lines on Figure 3-4. Cheap and reliable rail service may lure passengers from autos (the area below the auto/air interface), and high speed rail can take passengers from air up to distances of 1,000 Km under ideal conditions (the area above the auto/air interface). It is more difficult to add bus to the picture because the bus role in non-leisure intercity travel is less clear and the bus and auto areas largely overlap. Travelers without access to an auto would compare bus with air (or rail) while those with access to an auto would compare bus cost and frequency with auto costs.

103. Leisure travel is a partial exception to much of the above discussion. There are circumstances in which travel, itself, is the commodity being purchased. For autos and trains (and, to a lesser extent buses), the traveller is sometimes paying for the view out the window, and speed is actually a negative attribute. For long haul trains, such as the "Orient Express", the product may be a combination of experiences inside and outside the window. Cruise ships are much the same.

104. Personal versus public transport. Although the auto has been listed as a competitor with other modes above, this is not a fully accurate description of the situation because personal autos serve functions which are well beyond simple transportation. "Autos" as a mode of transport are more energy efficient than has usually been recognized (according to Figures 2-17, 2-18 and 2-27, a full taxi can be more energy efficient than many average bus systems). But autos have other characteristics that go far beyond pure energy efficiency, or even transport economics; they offer a high degree of personal flexibility and freedom of expression.

105. No public transport mode can compete with the flexibility of the auto -- the ability of the personal auto to move the traveler any time, anywhere, at the traveler's demand and on the traveler's terms. Permission need not be asked, tickets are not necessary, schedules need not be consulted, peak/off peak frequencies do not cause a problem, thieves and thugs need not be encountered, sweaty masses of people do not intrude, and the traveler is protected against hot, cold and rainy weather; the auto owner can just go as and when he or she wants. Real world experience has repeatedly shown that the value of the on-demand, instantly available characteristic of auto service is so high that the push toward auto ownership is occurring even in the poorer developing countries at a rate that is

overwhelming efforts to provide road capacity and maintain clean air. The issue of "motorization" (or, more accurately, "auto-ization") is one of the most important transport issues the Bank faces.⁵²

106. There is also a very real and important characteristic of self expression in auto ownership. In many countries, mere ownership of (or access through professional or political activity to) an auto marks the owner as having "status." As individual wealth increases, the opportunity for auto ownership to make a personal "statement" grows; a US\$ 200 jalopy, US\$ 2,000 used car, a US\$ 20,000 mid-sized auto, a US\$ 80,000 luxury auto, and a US\$ 200,000 Rolls Royce provide nearly indistinguishable levels of transport service, and yet individuals see enough difference in other attributes to pay these enormous differences.⁵³ As with any other product, auto manufacturers have been quick to analyze the motivations for auto purchase, including transport as well as status consciousness, and design and market autos accordingly. While it has been argued that the large auto makers create as well as serve demand, there is no arguing with the power of the self-expression motive for auto purchase.

107. In addition, many developed and developing countries (Korea, China and Malaysia) believe that domestic auto manufacture has the potential to improve the macroeconomic health of the country. There may be some developing countries where the right combination of labor costs and skills and the opportunity for economies of scale make this belief valid. Other developing countries may be in a position (size, local skills and costs, location) that domestic auto manufacture will convey no benefit that many other types of manufacturing would not also generate.

108. The combination of the flexibility and self-expression motivations for auto ownership and use has considerable significance for transport policy, including attempts to influence energy efficiency in transport. For example, part of the fervent political opposition to increases in gasoline taxes, or imposition of congestion prices, in the US and elsewhere, is because cheap fuel and low cost of access to the transport system are seen as an integral part of personal liberty. At the other end of the issue, the continued high use of auto fuel in Europe (often driving large autos at much higher, less efficient and less safe speeds than in the US) even though fuel prices are three times US levels is evidence of the economic foundation of the demand for transport flexibility.

109. The most interesting issue from a transport energy (and pollution emissions) viewpoint is whether the emotional and political aspects of the ownership decision can be separated from the economically-driven issues of auto use. While it is clear that, for powerful reasons, everyone would like to own an auto, it may not be a vital transport issue to try to influence this ownership: the real transport, energy and pollution question is whether owners will insist on being able to use their auto

^{52.} See World Bank, Sustainable Transport: A Sector Policy Review, Transport, Water and Urban Development Department, forthcoming.

^{53.} The "personal statement" phenomenon is not unique to autos as an inspection of any guarded bicycle parking area or a bicycle shop in the US will demonstrate. For all but the most extreme uses, a US\$ 400 road bike is as good as a US\$ 4,000 road bike. As with prestige autos, the individuals who own the expensive bikes are not always the ones capable of using them to their fullest performance limits. A similar phenomenon can be seen in hiking and jogging shoes.

everywhere, at all times and in all conditions, or whether they can be encouraged to make more efficient use of the auto through an appropriate system of prices and taxes.

110. A great deal is riding on the answer to the question, and the outcome is not clear. While there is some evidence that auto use can be influenced by prices and taxes, the fuel price/usage elasticities experienced, especially in the short term, can be quite low. There is also clear evidence that auto users are not fully aware of either their personal costs of auto ownership or the costs their use can impose on others and, lacking understanding, can bitterly oppose measures which would offer them choices that would actually have large and direct benefits to them. Naive interventions in this equation, whether based on a desire to reduce energy consumption, pollution emissions, or transport congestion, have often come to grief, at least partly because they have confused the issues of why autos are purchased with the way in which owners choose to use them.

CHAPTER FOUR

SUBSTITUTES FOR TRANSPORT: ENERGY IMPLICATIONS

111. Transport is defined as the physical movement of goods or people from the place they are available to the place they are needed. As such, while there is clearly scope for competition among modes of transport in the transport market, there might appear to be no substitute for at least some form of transport to support economic activity.

112. But transport (always excepting the view out the window) is also a derived demand; that is, transport has little value, per se, but is instead used in the production of a related good or service for which transport is an input, or transport is useful in moving labor from home to work place. As a result, competition and substitution among goods and services can readily change demand for both the amounts and the modes of transport. When transport demand changes in amount (ton-km or p-km) or modal balance (e.g. rail versus road), energy consumption can also change, sometimes significantly. Although the potential for substitution has been discussed in detail in a number of sources,⁵⁴ it will be useful to touch on the possibilities, and the issues, in order to have a more complete picture of the tools available in the future to influence energy usage by the transport sector.

The Energy Implications of the Interactions Among Transport and Communications

113. At the most basic level, transport involves movement of either information or a physical commodity. In this formulation, the word "information" has both direct and indirect aspects. Information clearly includes communications in all forms; but, there are different ways to package and move the information, and there are ways in which communications in one form can substitute for transportation in another form.

114. Perhaps the simplest example of the tradeoff is a letter versus a phone call in order to transmit information. Although exactly the same "information" would be included, sending a letter involves the physical movement of paper from sender to receiver whereas the telephone call involves only the movement of electrons. A typical three page letter would weigh about 30 grams which, for a 1000 km trip, would generate about 0.03 ton-km and consume between 90 and 360 kJ depending on whether it is sent by truck, incremental air cargo, or dedicated air cargo. If the same letter is read over the phone, it would take about 6 minutes and consume at the very most .001 kw-h, or about 3.6 kilojoules -- from one to five percent of the energy of the letter.⁵⁵ This ratio would be more favorable to phone at longer

^{54.} See, for example, USDOT, Transport Implications of Telecommuting

^{55.} Source: World Bank estimate. The calculation has been performed to overestimate the energy of a phone call. If anything, the ratio of energy in communications to energy in transport is more favorable to phoning than these numbers would indicate. In this and all other calculations of transport and communications usage of energy, the estimates are rough, and are subject to considerable change depending on assumptions as to specific conditions and equipment. Numbers for energy use by communications in this paper are intended to be reasonable estimates only: this said, the relative magnitudes of transport versus communications use of energy are such that it is unlikely that any defensible set of assumptions would suggest that communications would ever use as much energy to transmit the same amount of useful information as any transport mode.

distances, and slightly less favorable to phone if the letter went by rail (which sometimes is the case in Europe, but is not common in the US).

115. This is a simplistic comparison, of course, because more than the pure information may be at stake. A phone call will not replace the prestige of fine stationery, nor is it a substitute for handwriting or the perfume on the envelope. At the same time, letters do not convey the sound of the human voice, an important part of "communication". Purely on information content, though, any reasonable calculation will show that electrons are far more energy efficient (and much faster) than physical movement of an envelope and its contents.

116. More modern techniques, such as the FAX machine, can convey the appearance of the handwriting as well (along with pictures) at a reduction in energy consumption of somewhere between 10 and 20 (or more) to one, depending on the distance of the communication, the size of the message, and how intensively the FAX machine is used and whether it is turned off between messages, or at least turned off at night. FAX machines have rapidly become the method of choice for much of the modern communications traffic, especially where the information is needed quickly and is complex or needs to be used repeatedly -- and FAXes have the added benefit of saving energy in transport under the right conditions.

117. Rough calculations indicate that electronic mail (E-Mail) has the same advantages as FAX machines for energy savings vis-à-vis letters, depending primarily on the at-rest energy consumption rate of the computer which supports the E-Mail message. As E-Mail becomes more prevalent, it will displace the FAX machine for almost all information transfer, unless the information must be copied from another hard-copy source and then re-transmitted: this is especially true when E-mail is used to transmit the document in processable form and not just as a visual copy.

118. "Information" can displace transport in another sense, at least for those whose jobs primarily involve the acquisition and processing of information. This option, "telecommuting," describes the practice in which an employee stays at home and works and communicates with the office via E-Mail, FAX or phone rather than going in to the office. If the choice is between keeping a phone line open continuously between home and work place, or driving to work, an 8 hour phone call would consume about .08 kw-hr, or about 300 kilojoules.⁵⁶ A 50 km round trip to work would consume at least 75,000 kilojoules by auto and at least 12,500 by rail, a reduction by telecommuting of at least several hundred times. This reduction could be even greater if the choice were being made between, for example, a phone call (or FAX or E-Mail) to Africa from the World Bank, or an air trip to do business in person.

119. The potential for energy savings, and the potential for pollution and congestion reduction is significant. There are a growing number of examples where employers, including the US Government, are beginning to allow or even encourage telecommuting. This is true even when the employee cannot

⁵⁶. The energy used in keeping the home computer turned on is not relevant since the employee would have the computer on in the office if he or she had commuted to the office. Note also that the comparison assumes that the phone line would be kept continuously open. More likely would be that the employee would call several times per day, but not keep the connection open all of the time.

work at home all 5 days per week: just staying home one day per week could represent a 20 percent saving in auto traffic and in the resulting congestion and pollution. Many Bank employees could readily work from home one day per week, and there are probably a lot of workers elsewhere in similar job categories, even in developing countries. Congested cities such as Bangkok might find the various forms of telecommuting to be at least a partial approach to relieving traffic delays and air pollution.

120. In fact, the ability to function productively in modern, transport-intensive urban areas may be strongly dependent on the availability of an adequate percentage of the urban surface area for transport facilities. For example, although precise and comparable numbers are not available, it appears that typical, developed Western cities use around 20 percent of their land for transport whereas typical Asian developing megalopoli have dedicated only 10 percent (or less) of the urban area to transport (African and Latin American cities are more on the Western than Asian model). This is one of the reasons why Asian developing cities are already congested, even though their rates of automobile ownership are far below those of Western cities. In trying to solve the problems of growing motorization, there may well be a balance point in developing Asian cities which already have restricted area for transport, where it would be cheaper and more environmentally benign to invest in communications as a replacement for urban transport capacity rather than in tunneling below the surface or condemning and paving over surface land that is currently occupied for other purposes. It is clearly going to be imperative that transport strategies for these cities look both at transport and communications in order to find the right balance of infrastructure investment.

121. Telecommuting is not, of course, a perfect substitute for being there. Employees at home are sometimes thought to be hard to supervise (although there is some evidence that many employees work as well or better at home than in the office, especially when the employee only wants to work part-time). Business interactions sometimes require face to face discussions which neither phone calls nor E-Mail will fully replace (but tele-conferencing is a partial substitute for face-to-face contact, and "virtual reality" may go even farther toward creating the feeling of physical presence). "Tele-shopping" is also beginning to emerge as a way to combine many short trips to separate stores into one trip to pick up the goods which have already been selected via the communications link.

122. To be fair, it should also be said that the employee who "saves" energy by not commuting to work could well waste the energy by making more trips for errands or personal purposes than might otherwise be made. If these trips are short, and made from a cold start, the result could, under some circumstances, be a net loss rather than a gain in energy and environmental emissions. As elsewhere in the analysis of energy in transport, generalizations can be risky.

123. Overall, there are clear prospects for several more orders of magnitude of improvement in the effectiveness of communications in replacing the need for physical movement of people or packaged information, especially if ways can be found for FAXed or E-Mail documents to stand in place of signed originals. By contrast, there is nothing on the immediate horizon in the technology of physical transport that appears to offer the same degree of improvement in either effectiveness or efficiency. Autos, trucks and trains will continue to evolve in performance and efficiency, but will not improve by even one order of magnitude in their energy efficiency within the foreseeable future. With appropriate caveats, there is clearly a potential for using communications to reduce transport usage of energy.

124. Conversely, though, in at least one respect communications can actually act to increase the energy consumption of transport. Modern logistics systems place great emphasis on reducing inventories at all levels in the production cycle. This has the benefit of reducing investment in inventories, and it reduces the costs of spoilage and out-of-fashion goods. By their nature, though, just in time (JIT) systems also inherently require smaller and faster shipments in order to keep the production and market lines open, a characteristic which shifts transport demand to truck from rail and to air from truck or sea. In all cases, these shifts increase transport energy demand. JIT systems, because they connect shipper and customer directly, cannot work without good communications among shipper, receiver and the transport modes involved. JIT systems vastly increase the total efficiency with which the needs of the ultimate customer are served, of course, but they do so by increasing transport costs in order to reduce total logistics costs.⁵⁷

Examples of Product Tradeoffs Which Affect Transport

125. A final issue to be aware of is the ways in which manufacturing processes can be changed in response to changes in the technology and efficiency of both production and transport. A good example is the decision to ship fuel (coal) from point of production to dispersed power plants for electric generation, or using mine mouth (or well head) power generation and then "shipping" the power over transmission wires.

126. In purely energy terms, under typical conditions the output of a 1,000 megawatt coal-fired electric power station could be transmitted 800 km with a loss of around 2.5 percent of the total power generated, a total energy cost of around 208 million kwh of energy. The rail transport of coal needed to fuel the station would consume the equivalent of 83 million kwh of energy if the coal were typical bituminous coal (about 3 million tons needed), and 140 million kwh of energy for typical lignite (about 6 million tons needed). The energy saving is not, of course, the whole picture because a power line is much cheaper to operate than a railway. That this is an active tradeoff can be readily seen in the fact that while bituminous coal is often shipped long distances for subsequent electric power generation, lignite is typically burned at the mine mouth and the electric power is moved by transmission wire: increases in the cost of coal transport, or improvements in the technology of electric power transmission, or congestion on an existing rail line, or differences in the quality of coal can well shift the balance toward transmission rather than transport, or vice versa.

127. Another pertinent example is the impact which changes in economies of scale in production can have on the amount and modes of transport demanded. In the formerly socialist economies, where transport (and energy) costs were often underestimated or even excluded entirely from production planning, production often took place in giant factories which wrung out the last few percentage points in production economies of scale, but at the cost of vastly increased transport of large quantities of raw materials over long distances inward and finished products outward. Market economies did a much better job of locating manufacturing activities at the point between raw materials production and finished goods consumption which minimized the total cost of supplying the final customer. As Figure

^{57.} Business travelers have also observed that good communications make it possible to travel in circumstances when they would otherwise have to stay in the office.

1-3 showed, the net result was that socialist economies consumed far more ton-km of freight transport per dollar of GDP than do the market economies. Even though socialist economies tended to make more use of rail than market economies (which are more truck dependent), the apparent energy efficiency of rail was more than offset by the over-consumption of total transport. As a result, the advent of market forces in the CEE and CIS economies will actually lead to a significant reduction of energy consumed in transport even though more use will be made of less "efficient" trucking and air modes.

128. There are also cases in which the product itself is information, as in the case of the computer software companies that have been formed in Bombay which both communicate and ship the "product" (computer software) back and forth between India and the US by E-Mail. Even one decade ago this trade would not have been feasible (because it would have taken too much time and money to transmit the software by paper and laboriously re-enter it into machine form, with consequent errors), and it would have consumed considerably more energy to ship as hard copy (or floppy copy) rather than as purely electronic information.

129. More examples are available, but these are enough to make the point that, while changes in transport costs and services can affect the demand for transport and the resulting efficiency of the use of energy by transport, transport is normally in the position of responding to these forces, not driving them. In general, the more important question to the overall economy is how to reduce the total cost of activity involving transport, of which transport and energy are usually only a small part of the total. Because transport is only a part of the picture, if (for whatever reason) there is an objective to reduce energy consumption in transport, or to increase energy efficiency in transport, it is often necessary to look well beyond the transport sector both to measure the effects of, and to implement the desired change.

BIBLIOGRAPHY

- Asian Development Bank. 1991. *Environmental Considerations in Energy Development*. Manila.
- Asian Development Bank. 1987. *Energy Policy Experience of Asian Countries*. Manila.
- Anderson, David and D. Mattoon. 1993. *Train Operation and Energy Simulator(TOES) Technical Manual*. Association of American Railroads, Research and Test Department, Chicago.
- Anderson, David, D. Mattoon and S. Singh. 1992. *Revenue Service Validation of Train Operation and Energy Simulator (TOES), Version 2.0*. Association of American Railroads, Research and Test Department, Chicago.
- Association of American Railroads. 1990. *Locomotive Improvement Program, Eleventh Research Phase Final Report*. Washington, D.C.
- Balen, Peter. 1987. "The Bicycle in Nicaragua: A Field Experience." Presented at the *67th Annual Meeting of the Transportation Research Board*, January 1988 in Washington, D.C. Delft, Netherlands: Delft University of Technology, Centre for International Cooperation and Appropriate Technology.
- Barwell, I.J. and G.A. Edmonds. 1985. *Rural Transport in Developing Countries*. London: Intermediate Technology Publications
- Bester, C.J. 1981. *Fuel Consumption of Highway Traffic*.
- Bowyer, D.P., R. Akcelik and D.C. Biggs. 1986. *Guide to Fuel Consumption Analyses for Urban Traffic Management*. Australian Road Research Board.
- Bryceson, Deborah and J. Howe. 1992. *African Rural Household and Transport: Reducing the Burden on Women*. IHE Working Paper IP-2. International Institute for Infrastructural, Hydraulic and Environmental Engineering, The Netherlands.
- Carapetis, S., H. Beenhakker and J. Howe. 1984. *The Supply and Quality of Rural Transport Services in Developing Countries: A Comparative Review*. Staff Working Paper 654. World Bank, Washington, D.C.
- Chester, Andrew and R. Harrison. 1987. *Vehicle Operating Costs: Evidence from Developing Countries*. The Highway Design and Maintenance Standard Series. Baltimore: The Johns Hopkins University Press.
- Conrad, H.R. 1964. *Symposium on Factors Influencing the Voluntary Intake of Herbage by Ruminants: Physiological and Physical Factors Limiting Feed Intake*. Ohio Agricultural Experiment Station, Wooster.
- Cyprus. 1985. *Transport Statistics*. Department of Statistics and Research, Ministry of Finance.

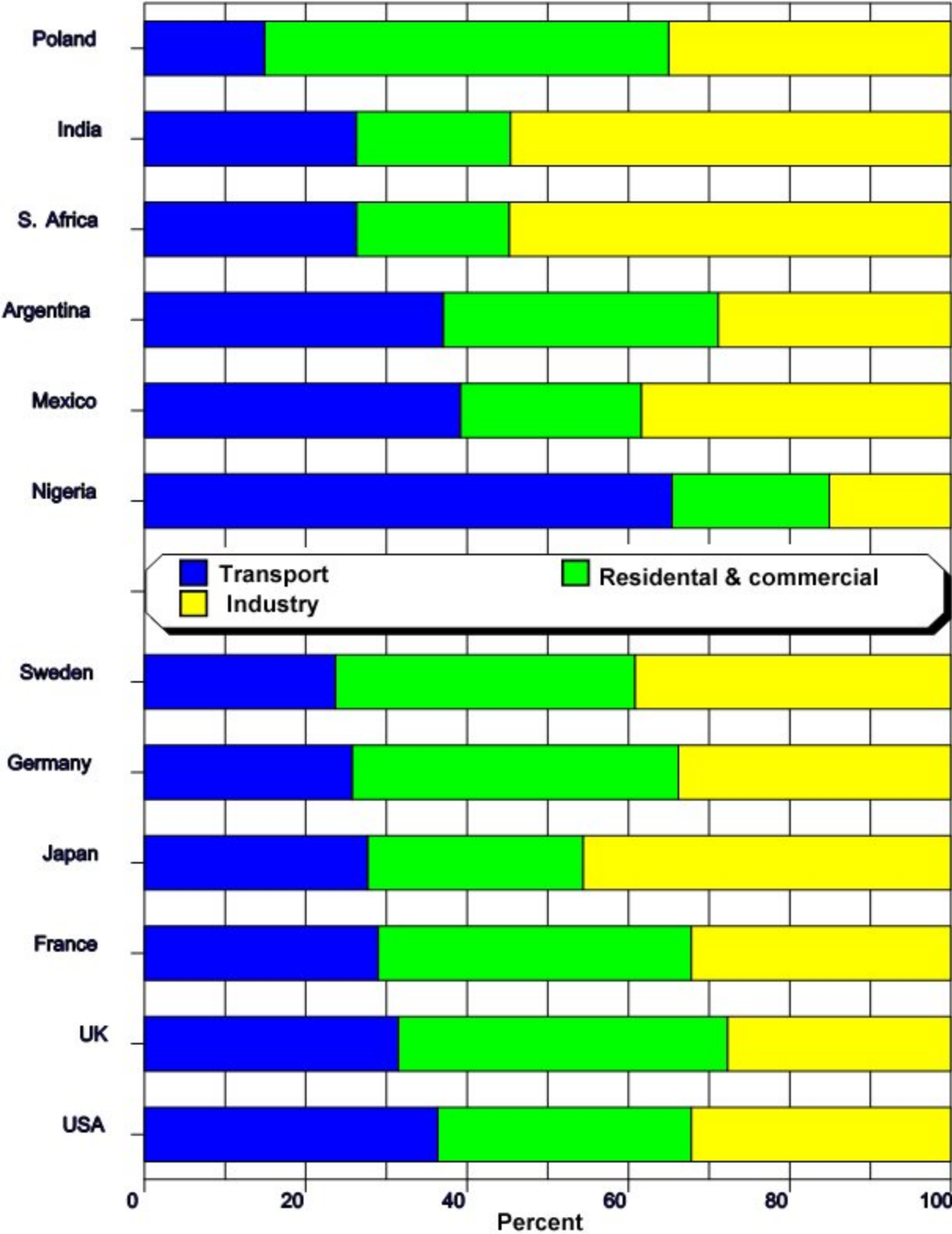
- di Prampero, P.E. 1986. "The Energy Cost of Human Locomotion on Land and Water." *International Journal of Sports Medicine* 7: 55-72.
- Drish, William F. and S. Singh. 1992. *Train Energy Model Validation using Revenue Service Mixed Intermodal Train Data*. Association of American Railroads, Research and Test Department, Chicago.
- Economos, Angelos C. 1982. "On the Origins of Biological Similarity." *J. theor. Biol.* 94:25-60.
- Elangovan, Tango. 1992. *Assessment of Transportation Growth in Asia and it's Effects on Energy Use, the Environment and Traffic Congestion: Case Study of Varanasi, India*. International Institute for Energy Conservation, Washington, D.C.
- Everall, P.F. 1968. *The Effect of Road and Traffic Conditions on Fuel Consumption*. Road Research Laboratory Report LR226. Berkshire.
- Fluck, Richard C., C.D. Baird. 1980. *Agricultural Energetics*. Westport, Conn.: AVI Pub. Co.
- Gunawan, Wibowo. 1992. *Assessment of Transportation Growth in Asia and it's Effects on Energy Use, the Environment and Traffic Congestion: Case Study of Surabaya, Indonesia*. International Institute for Energy Conservation, Washington, D.C.
- Gwilliam, K.M and Geerlings. 1992. *Research and Technology Strategy to Help the Environmental Problems in Relation to Transport: Overall Strategic Review*. Luxembourg: EEC.
- Harms L.S., ed. 1991. *Telecommunications and the Travel Industry: Impacts on National and Regional Development*. Honolulu: Pacific Telecommunication Council.
- Heierli, Urs. 1993. *Environmental Limits to Motorization Non-Motorized Transport in Developed and Developing Countries*. St. Gallen, Switzerland: SKAT, Swiss Centre for Development Cooperation in Technology and Management.
- Hussain, Khalifa Afzal. 1980. *Bus Logistics for Developing Countries: A Comprehensive Guide*. Dar-es-Salaam.
- Imran, Mudassar and P. Barnes. 1990. "Energy Demand in the Developing Countries: Prospects for the Future." World Bank Staff Commodity Working Paper No 23. World Bank, Washington D.C.
- India. Planning Commission. 1988. *Perspective Planning for Transport Development: Report of Steering Committee*. New Delhi: Planning Commission, Government of India.
- Ishiguro, Masayasu and T. Akiyama. 1995. *Energy Demand in Five Major Asian Developing Countries*. World Bank Discussion Paper 277. World Bank, Washington, D.C.
- Kipke, Barbara G., ed. 1991. *Bicycle Reference Manual for Developing Countries*. GATE, Deutsches Zentrum fur Entwicklungstechnologien.

- Leach, Gerald. 1976. *Energy and Food Production*. Guildford: IPC Science and Technology Press for International Institute for Environment and Development.
- Levine, Mark D. et al. 1991. *Energy Efficiency, Developing Nations, and Eastern Europe*. A Report to the U.S. Working Group on Global Energy Efficiency.
- Lockertz, William. 1977. *Agriculture and Energy*.
- Madhavan, Shobhana. 1989. "Use of Energy in Non-Motorized Transport in Developing Countries: An Indian Case Study." In *Fifth World Conference on Transport Research* held in Yokohama, Japan, 10-14 July 1989. London: The Polytechnic of Central London.
- Martin, D.J. and Michaelis. 1992. *Research and Technology Strategy to Help Overcome the Environmental Problems in Relation to Transport: Global Pollution Study*. Luxembourg: EEC.
- Masud, Jamil. 1992. *Assessment of Transportation Growth in Asia and its Effects on Energy Use, the Environment and Traffic Congestion: Case Study of Islamabad, Pakistan*. International Institute for Energy Conservation, Washington, D.C.
- Mauritius. 1987. *Digest of Road Transport Statistics*. Ministry of Economic Planning and Development, Central Statistical Office, Mauritius.
- Meyer, John R. and J. Gomez-Ibanez. 1981. *Auto Transit and Cities*. Cambridge: Harvard University Press.
- National Council of Applied Economic Research. 1981. "Transport Technology for Rural Areas: India." World Employment Programme Research Working Paper. International Labour Office, Geneva.
- Noll, Scott A. 1982. *Transportation and Energy Conservation in Developing Countries*. Washington, D.C.: Resources for the Future.
- Ocampo, Romeo B. 1982. *Low Cost Transport in Asia: A Comparative Report on Five Countries*. Ottawa: International Development Research Centre.
- Organization for Economic Cooperation and Development. 1985. *Energy Savings and Road Traffic Management*. Paris: OECD.
- Owen, Wilfred. 1976. *Transportation for Cities: The Role of Federal Policy*. Washington, D.C.: Brookings Institution.
- Paul, A.A. and D. Southgate. *The Composition of Food*. London: Elsevier/North-Holland Biomedical Press.
- Pimentel, David, ed. *Handbook of Energy Utilization in Agriculture*. Boca Raton: CRC Press.

- Ramaswamy, N.S. "Planning and Development of Animal Energy Resources in India." *No. 5 Appropriate Industrial Technology for Energy for Rural Requirement*. United Nations Industrial Development Organization.
- Reddy, B. Sudhakara. 1995. "Transportation, Energy and Environment: A Case Study of Bangalore." *Economic and Political Weekly*. January 21, 1995: 161-170.
- Redsell, M., G. Lucas, and N. Ashford. 1988. *Comparison of on-road Fuel Consumption for Diesel and Petrol Cars*. Transport and Road Research Laboratory. Berkshire.
- Replege, Michael. 1992. *Non-Motorized Vehicles in Asian Cities*. Technical Paper 162. World Bank, Asia Technical Department, Washington, D.C.
- Rose, A.B. 1979. *Energy Intensity and Related Parameters of Selected Transportation Modes: Passenger Movement*. U.S Department of Energy. Oak Ridge, Tenn: Oak Ridge National Laboratory.
- Sayeg, Philip, M. Birk and C. Zegras. 1992. *Assessment of Transportation Growth in Asia and it's Effects on Energy Use, the Environment and Traffic Congestion: Case Study of Bangkok, Thailand*. International Institute for Energy Conservation, Washington, D.C.
- Schipper, Lee and S. Meyers. 1992. *Energy Efficiency and Human Activity: Past Trends, Future Prospects*. Cambridge University Press.
- Transportation Research Board. 1983. *Energy Impacts of Geometrics: A Symposium*. National Academy of Sciences, Washington, D.C.
- United Nations. Economic Commission for Europe. 1983. *An Efficient Energy Future: Prospect for Europe & North America*. Boston: United Nations Economic Commission for Europe: Butterworths.
- U.S. Agency for International Development. 1984. *Energy Initiative for Africa - Energy Conservation Workbook Series: Transportation*. Washington, D.C.
- U.S. Congress, Office of Technology Assessment. 1991. *Improving Automobile Fuel Economy: New Standards and Approaches*. OTA-E-504. Washington, D.C: U.S. Government Printing Office.
- U.S. Department of Transportation. 1990. *Compendium of National Urban Mass Transportation Statistics from the 1987 Section 15 Report*. Urban Mass Transportation Administration, Washington, D.C.
- . 1973. *The Effect of Speed on Automobile Gasoline Consumption Rates*. Federal Highway Administration, Office of Highway Planning, Highway Statistics Department, Washington, D.C.
- Wagner, Frederick A. and Institute of Transportation Engineers. 1980. *Energy Impacts of Urban Transportation Improvements*. Washington, D.C.: The Institute.

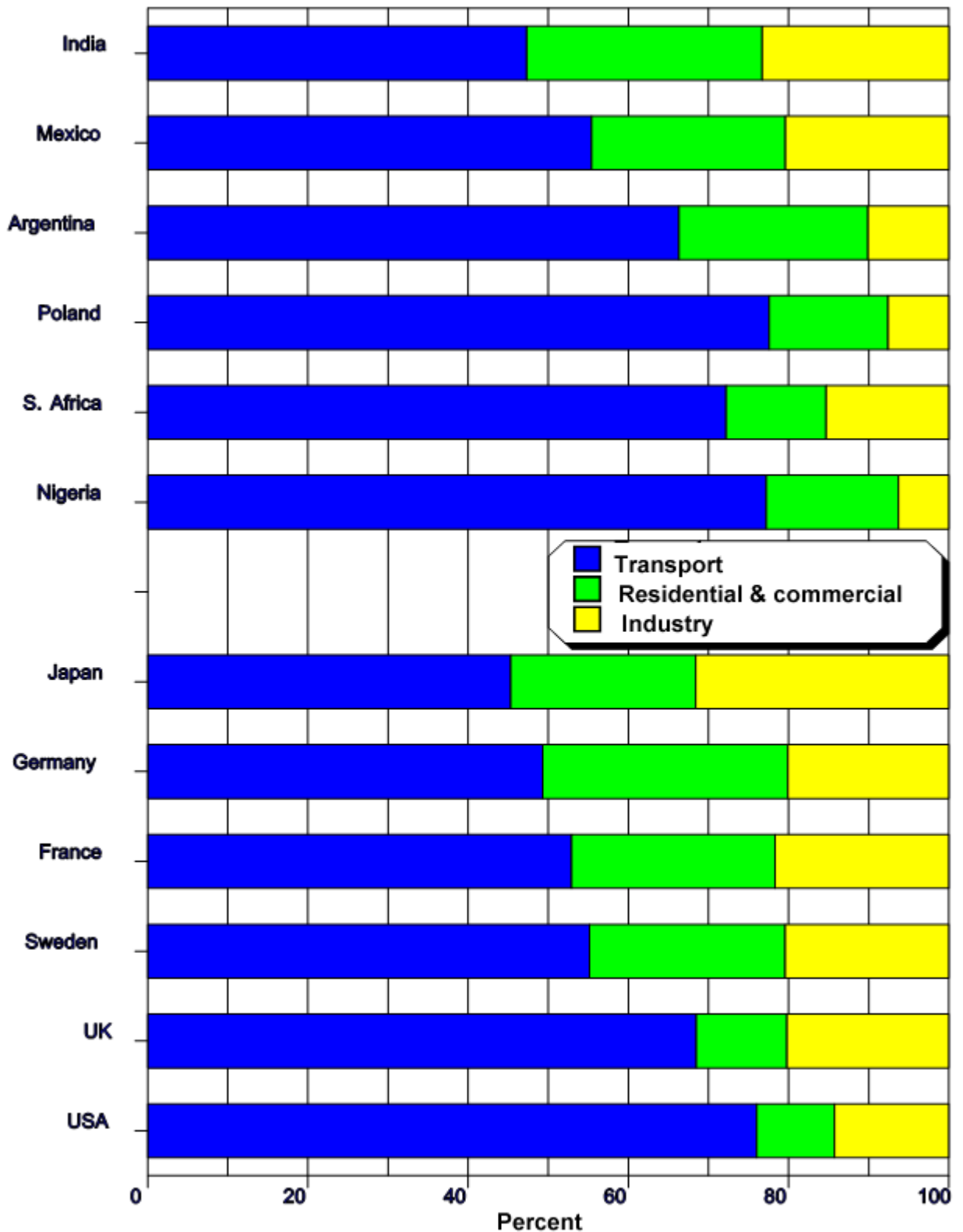
- Walters, A.A. 1978. *The Economics of Road User Charges*. World Bank Staff Occasional Papers No 5, World Bank, Washington, D.C.
- Watson, R.L. 1989. *Car Fuel Consumption: Its Relationships to Official List Consumptions*. Crowthorne, Berkshire: Vehicles and Environment Division, Vehicles Group, Transport and Road Research Laboratory.
- World Bank. 1993a. *Energy Efficiency and Conservation in the Developing World*. World Bank Policy Paper. Washington, D.C.
- 1993b. *Road Maintenance Project: Pilot Labour Based Road Rehabilitation Sub- Project (PLRP), Final Report*. Washington, D.C.
- 1992. *Indonesia: Bukit Asam Coal Mining Development and Transportation Project*. Project Performance Audit Report. Washington, D.C.
- 1991a. *Urban Transport in Asia: An Operational Strategy for the 1990s*. Asia Technical Department, Infrastructure Division, Washington, D.C.
- 1991b. *Peoples Republic of Congo: River Transport Project*. Project Completion Report. Washington, D.C.
- 1989. *Dominican Republic: Itabo Coal Terminal and Power Engineering Project*. Project Completion Report. Washington, D.C.
- 1988. *Road Deterioration in Developing Countries: Causes and Remedies*. World Bank Policy Study. Washington, D.C.
- 1984. *India: Railway Electrification and Workshop Modernization Project*. Staff Appraisal Report. Washington, D.C.
- Wright, Charles L. 1990. "A Characteristic Analysis of Non-Motorized Transport." Presented at the *Transportation Research Board Conference* held in Washington, D.C., 7-11 January 1990.

Figure 1-1: Percent Total Energy Consumption by End-Use Sector



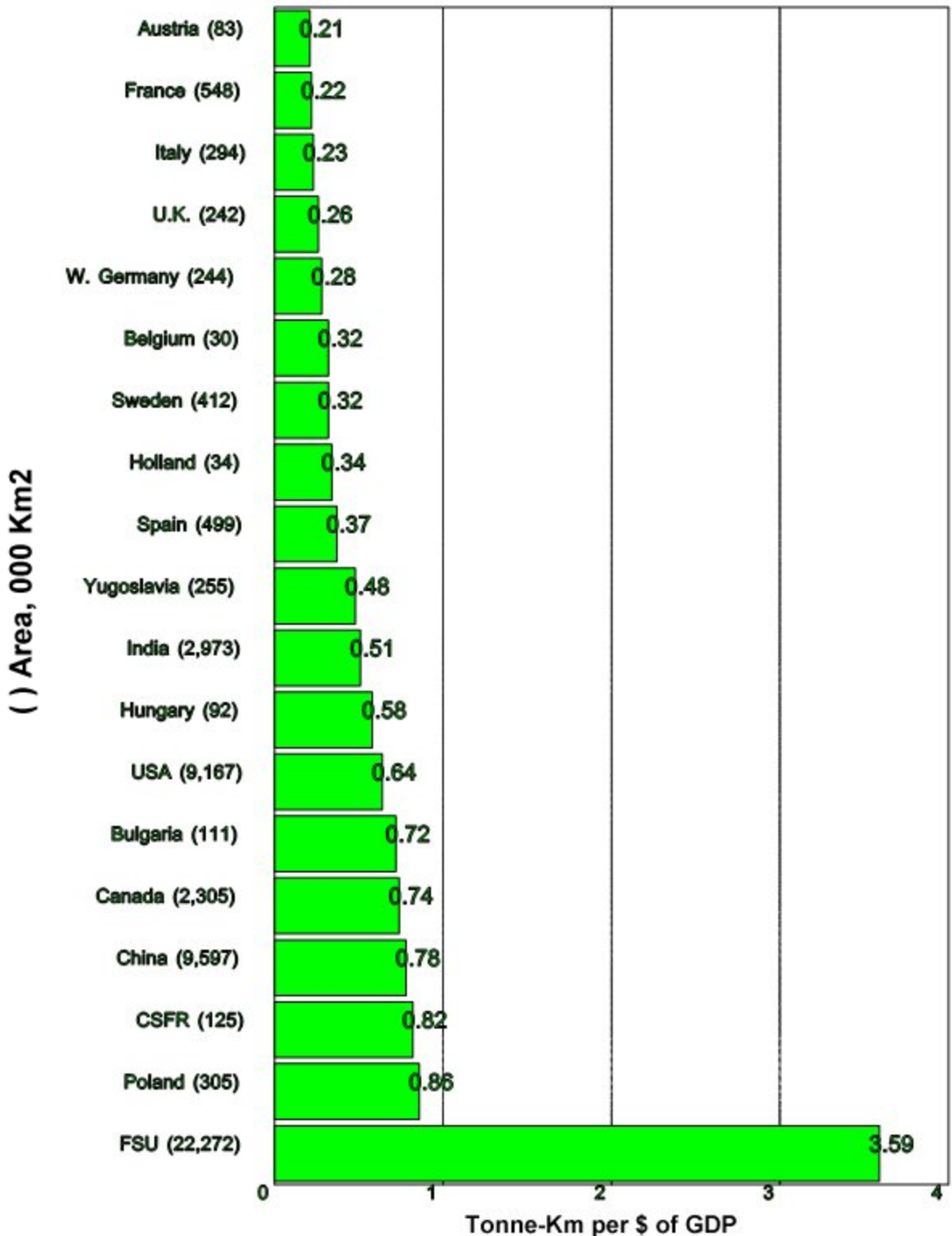
Source: International Energy Agency, 1991-92

Figure 1-2. Percent Petroleum Consumption by End-Use Sector



Source: International Energy Agency, 1991-92

Figure 1-3. Transport Tonne-Km per \$ of GDP
(Road, Rail & Water)



GDP is purchasing power adjusted

Figure 1-4. Rail Share of Rail+Truck Tonne-km (1988) vs Length of Haul for Developing, Developed and Socialist Countries

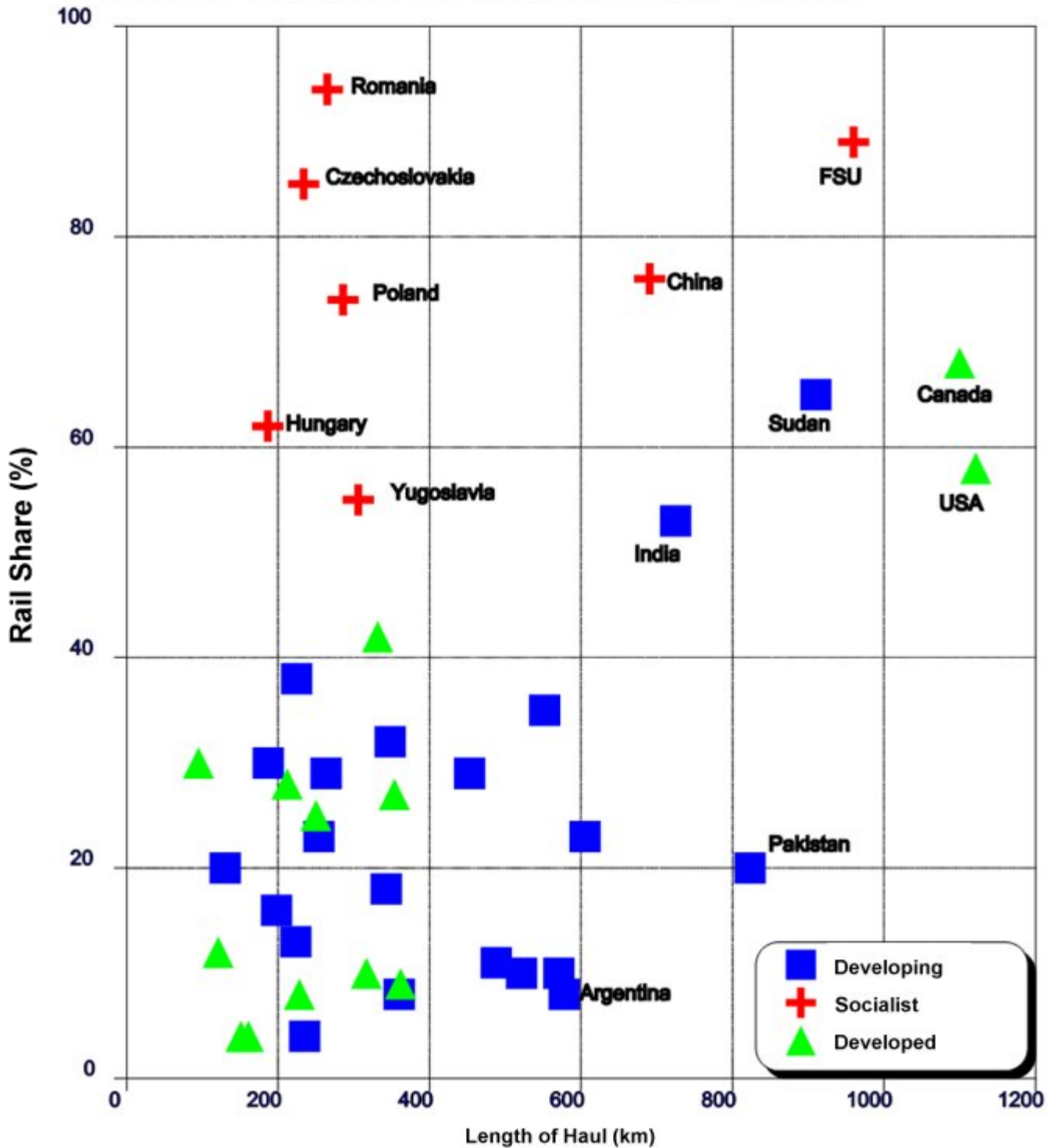
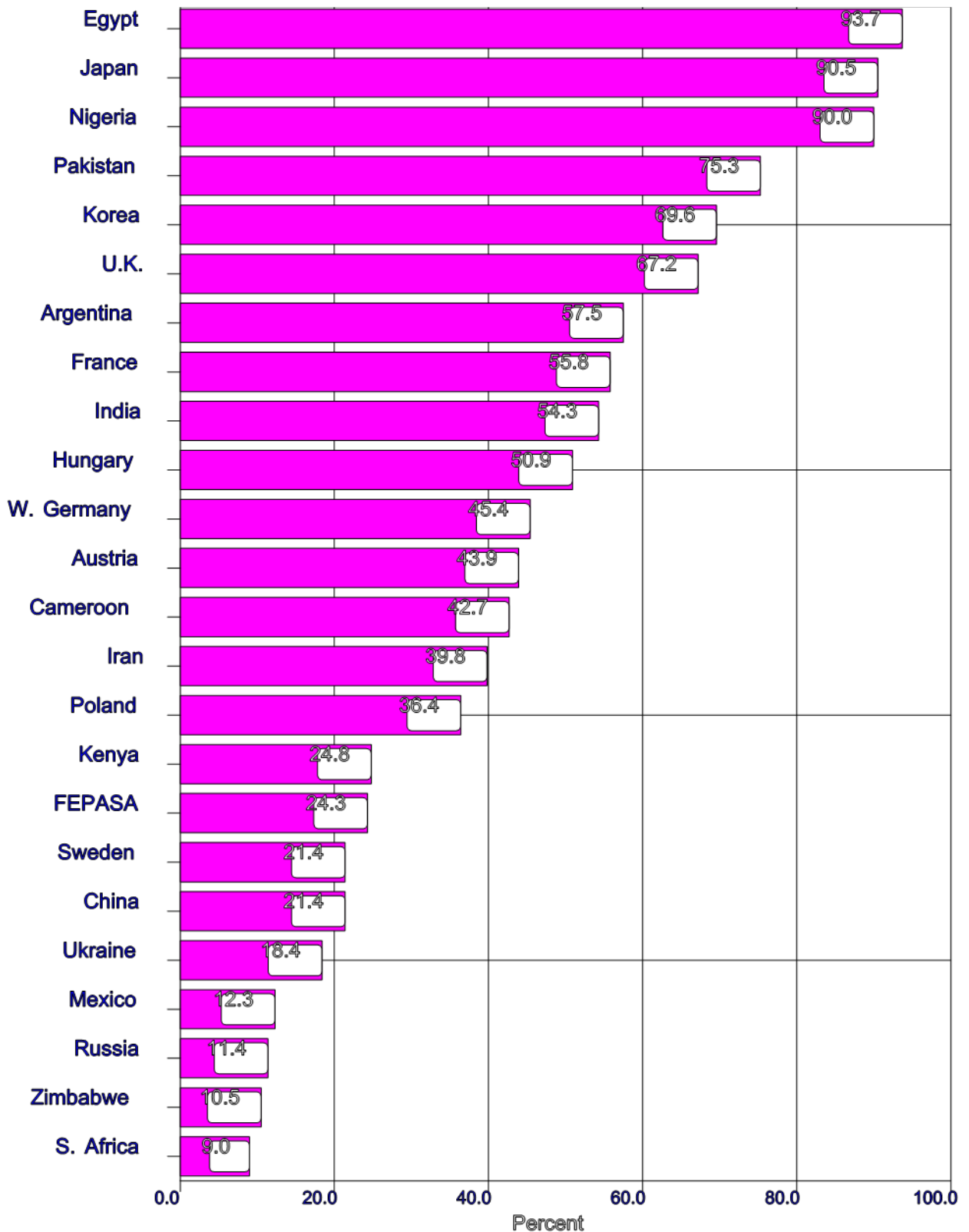
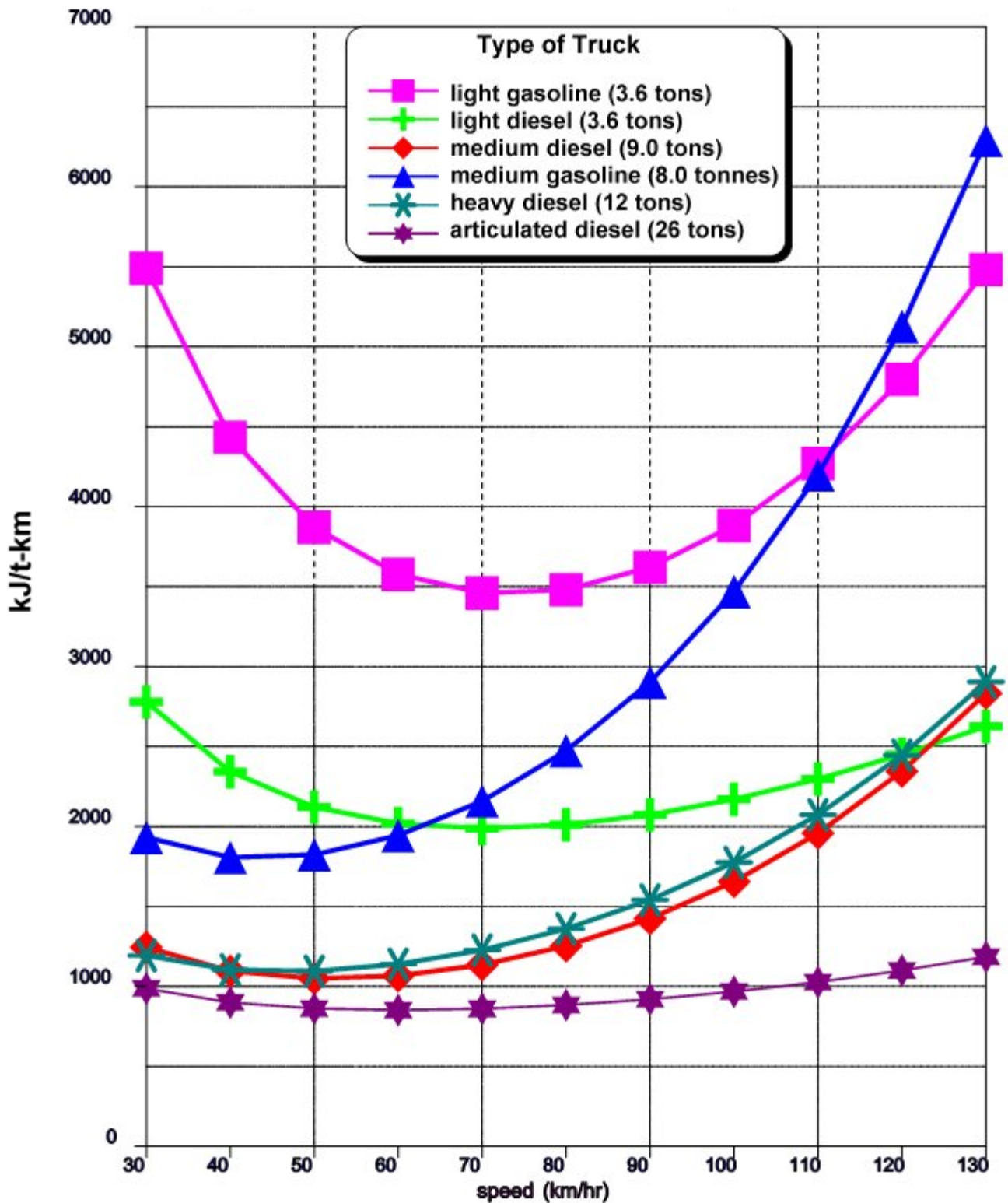


Figure 1-5. Rail Passenger-Km as Percent of Total Rail Traffic for Selected Countries



Source: World Bank Railway Database

Figure 2-1. Truck Fuel Efficiency at Various Speeds (fully loaded on paved roads, flat terrain)



Source: HDM

Figure 2-2. Truck Fuel Efficiency at Various Load Factors (paved roads, flat terrain, 60 km/hr speed)

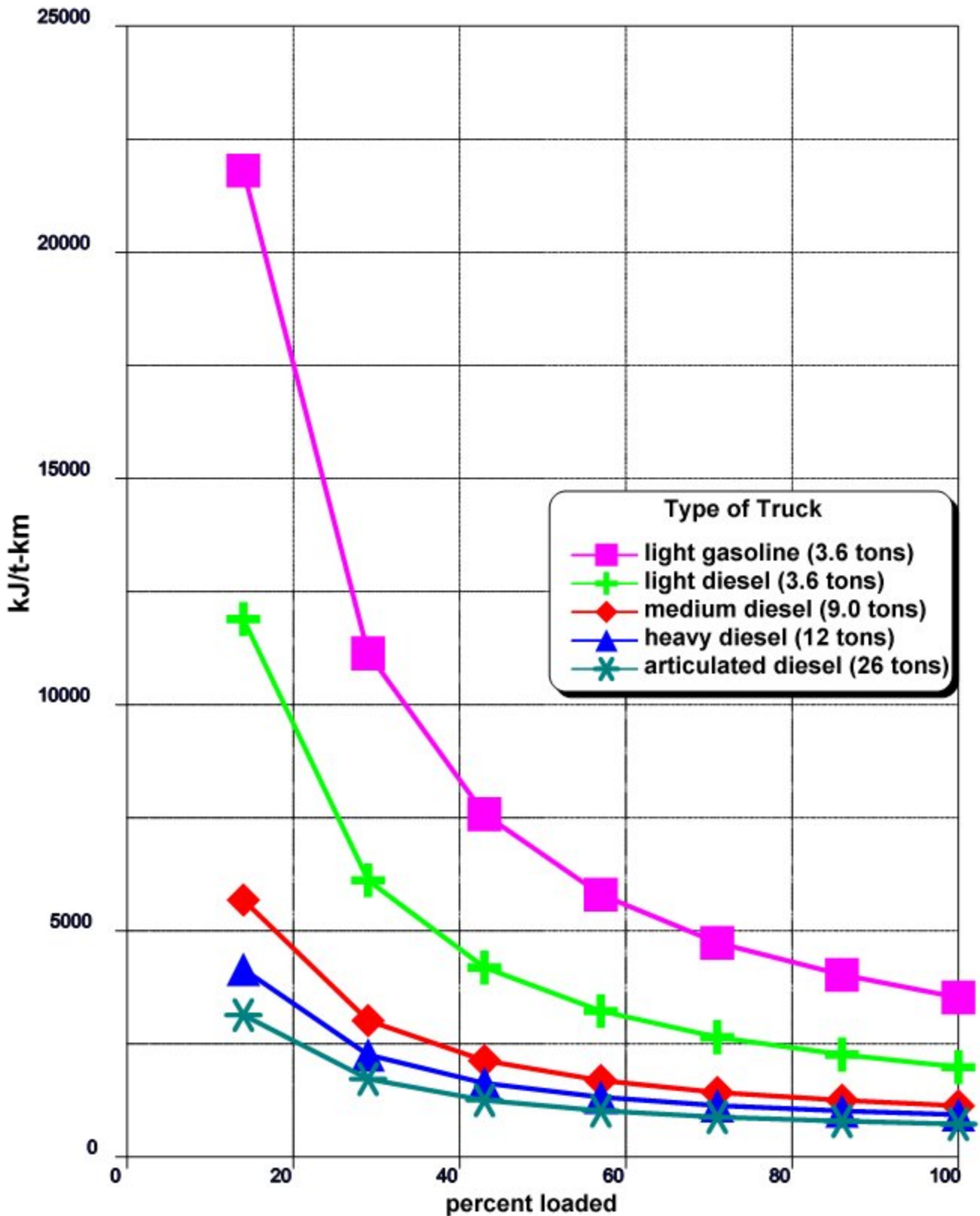
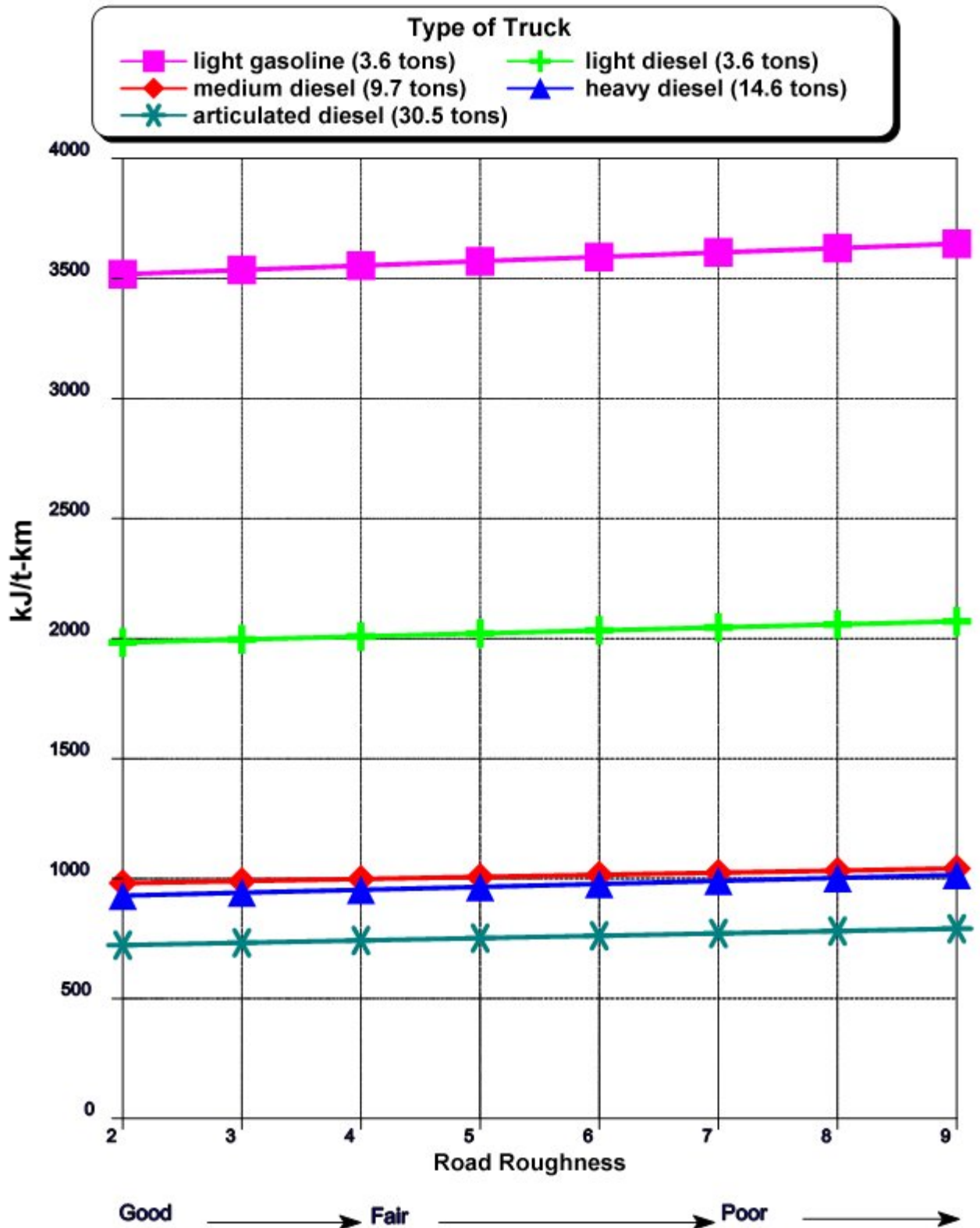
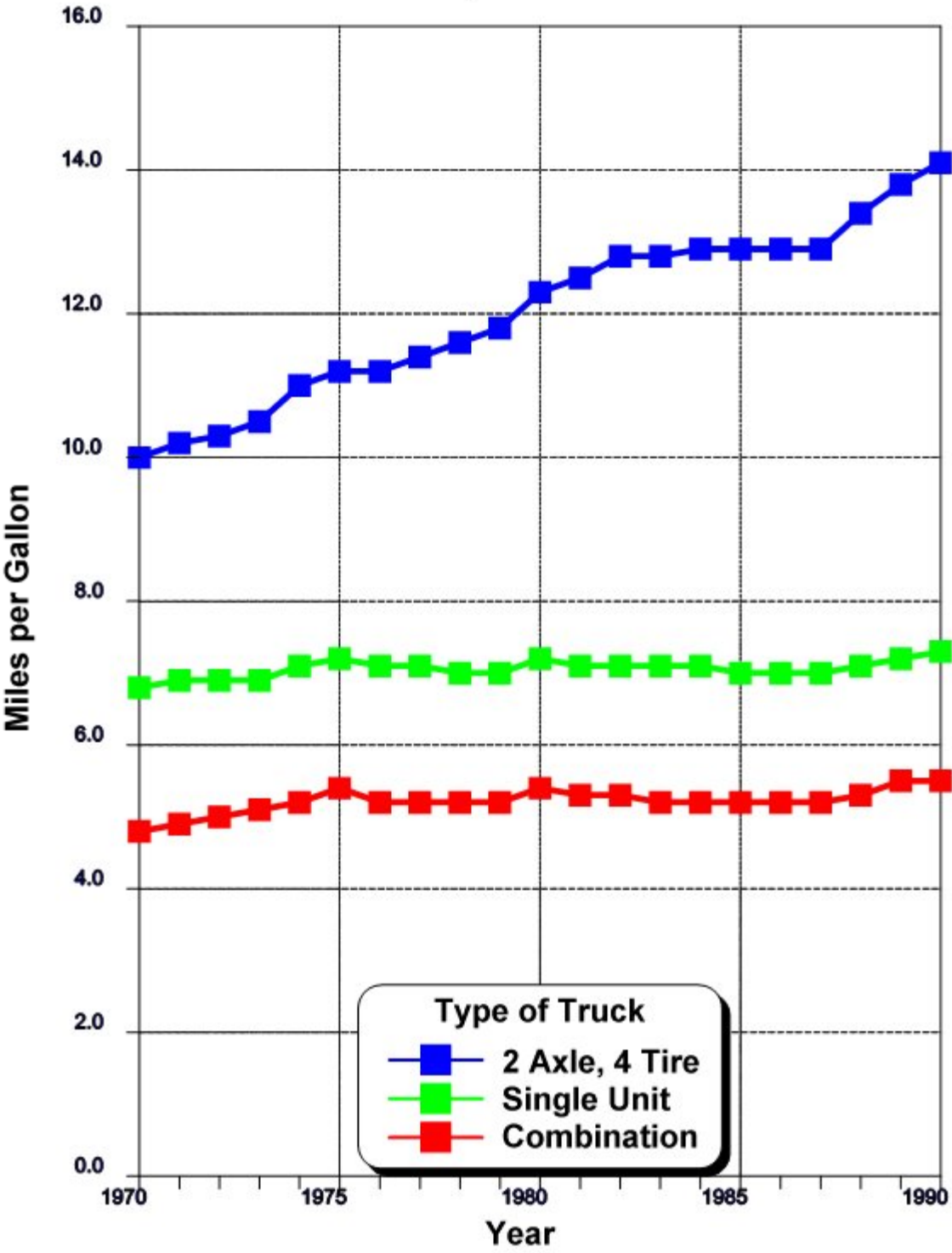


Figure 2-3. Truck Fuel Efficiency at Various Road Conditions (fully loaded, 60 km/hr speed)



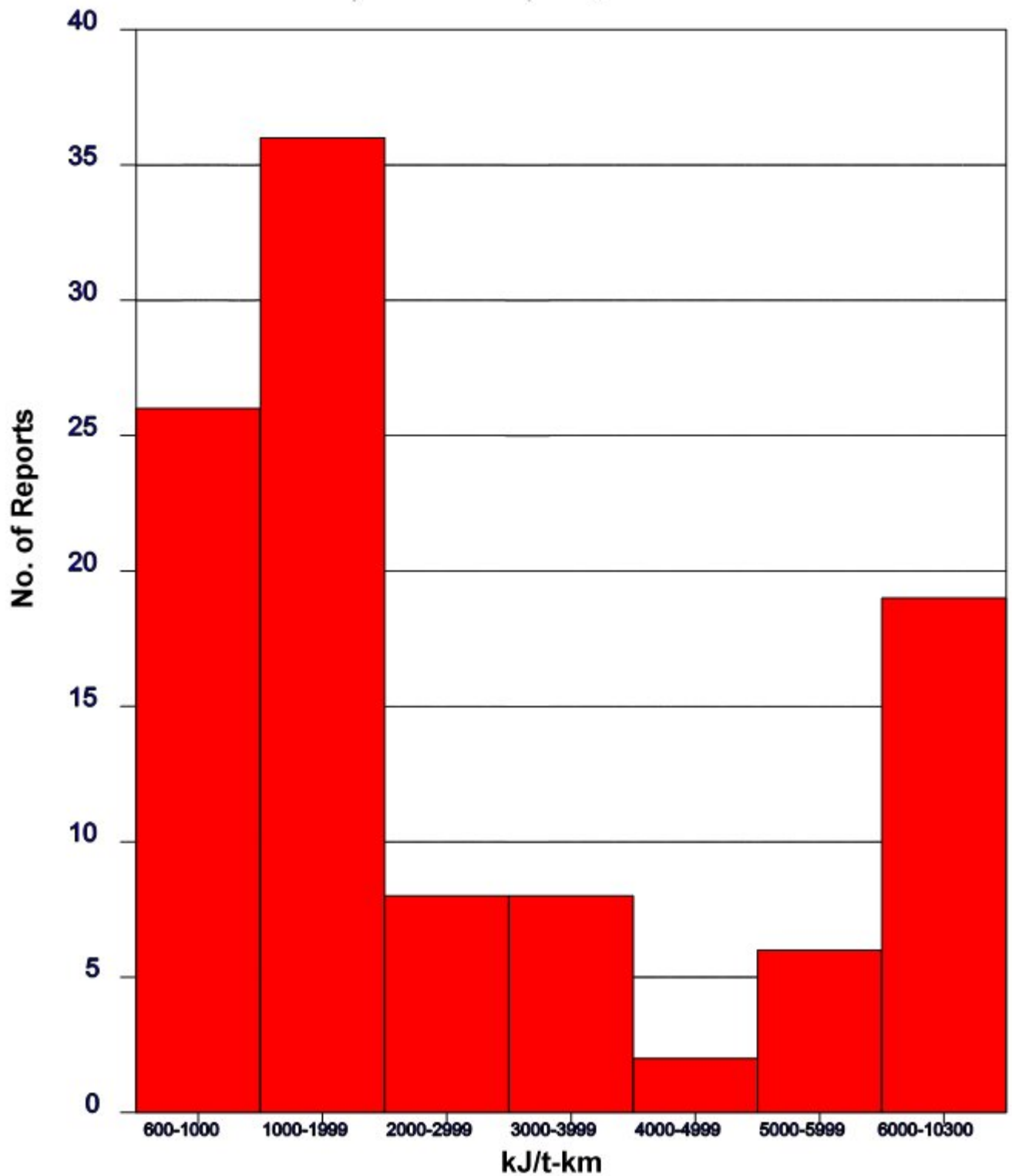
Source: HDM

Figure 2-4. Truck Fuel Economy in the US.
1970-90



Source: ORNL 13, pp. 3-38, 3-40, 3-42

Figure 2-5. Frequency Distribution of Truck Fuel Economy for Actually Reported Data



Source: Annex A4

Figure 2-6. Rail Energy Consumption for Various Cases Based on the Train Energy Model of AAR

Case one: varying tons per carload.

Uses 50 cars/train and speed of 40 mph. (36 mph avg.)

	Tons/car			
	40	60	80	100
Fuel Consumed (gallons):	1437	1580	2104	2280
energy in kJ/t-km	134	98	98	85

Case two: varying speed.

Use 50s cars/train and 100 tons/car

	Speed (miles/hr)			
	18	44	56	72
Fuel Consumed (gallons):	2270	2190	2150	3124
energy in kJ/t-km	85	82	80	116
	1 hp/ton 2 locos	1 hp/ton 2 locos	1 hp/ton 2 locos	2.3 hp/ton 5 locos

Case three: varying length of train.

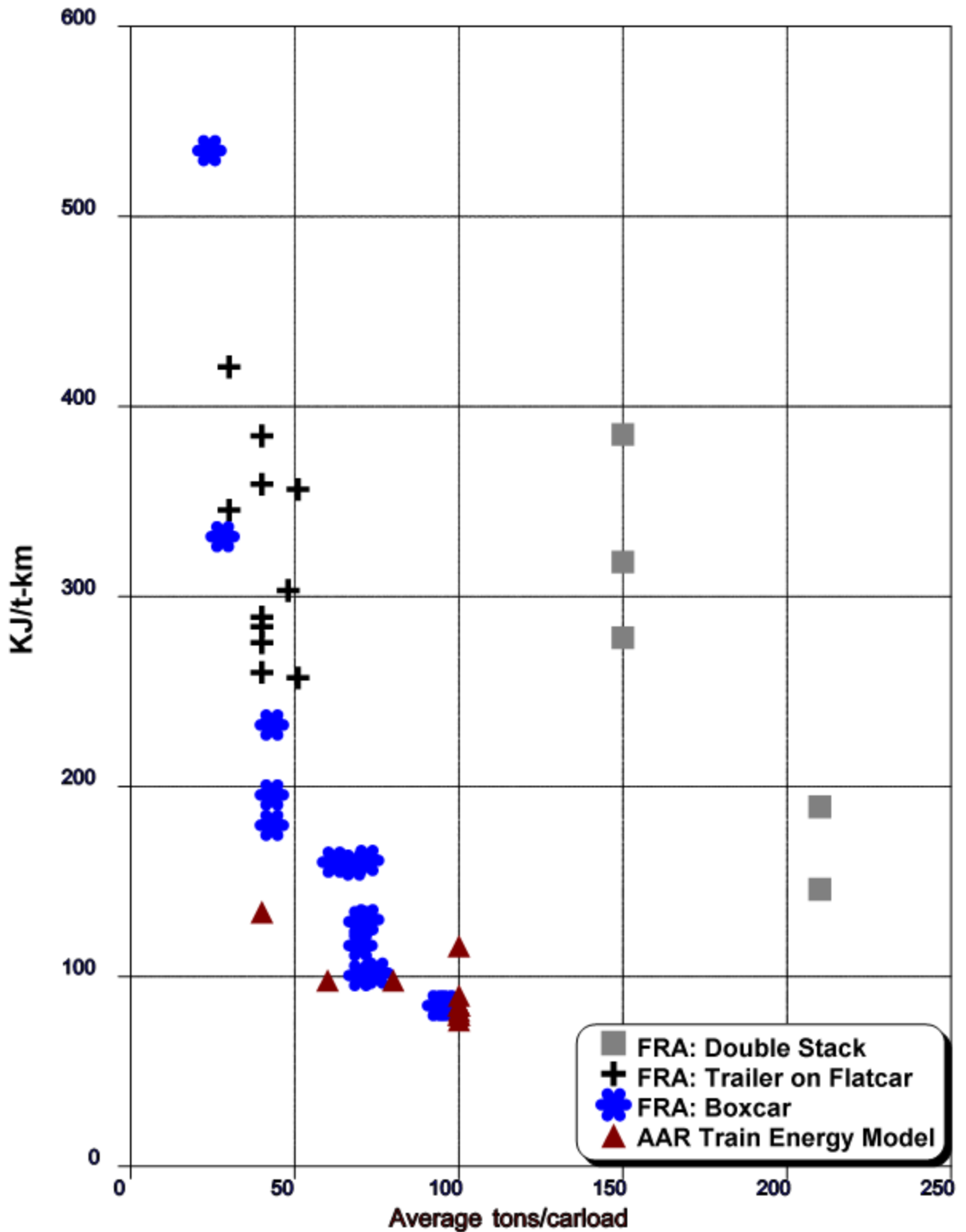
Use 20 mph and 100 tons/car.

	Length of train (cars)			
	25	50	75	100
Fuel Consumed (gallons):	1210	2270	3234	4112
energy in kJ/t-km	90	85	80	77
	1 loco	2 locos	3 locos	4 locos

For All Cases: length of trip is 500 miles, train has only 100 ton, covered hoppers. Power dispatch is consistent with 1% maximum ruling grade (1 hp/ton except for the 72 mph case). No fuel restrictions, no stops or congestion, flat track with no curves.

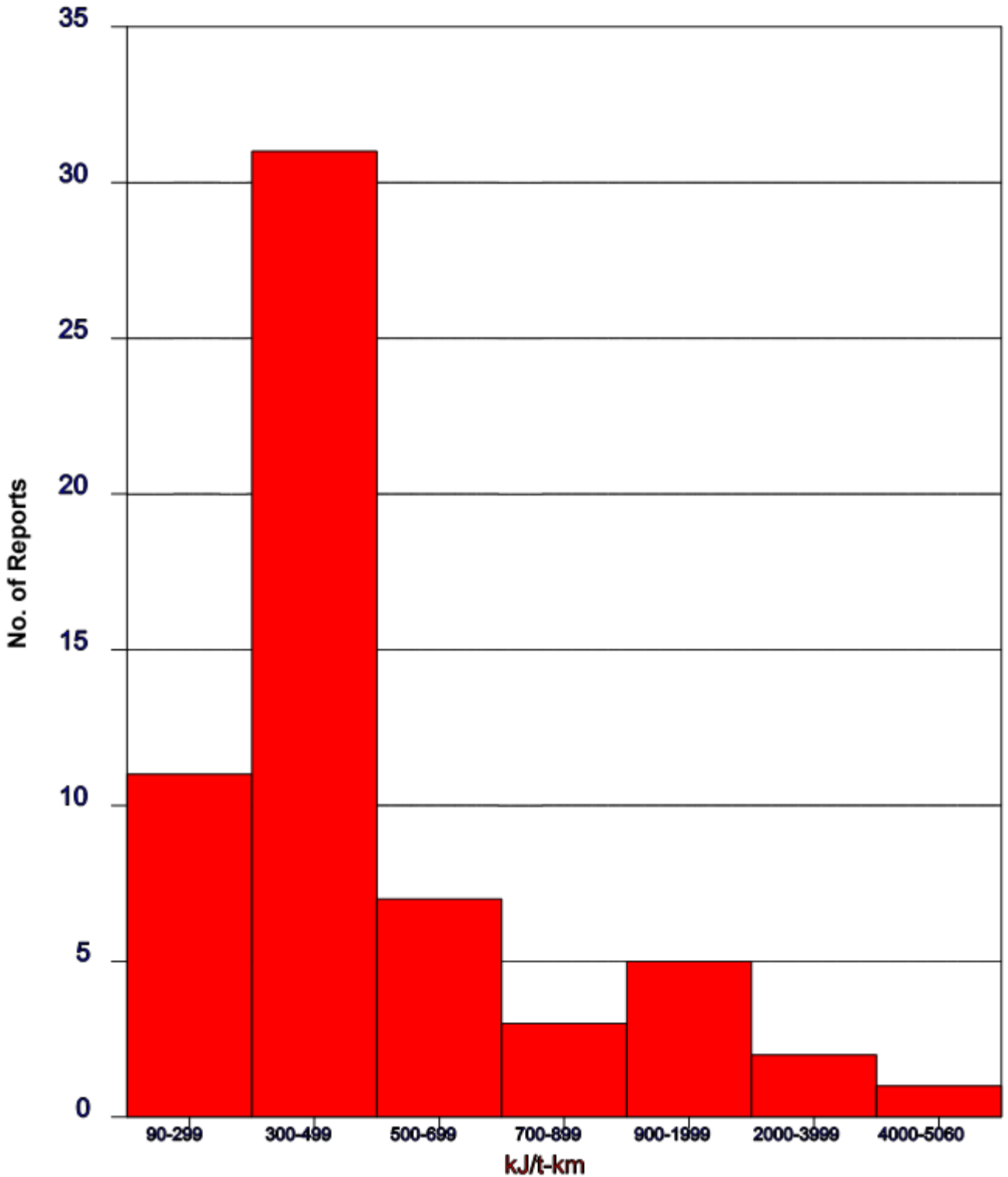
Source: AAR Train Energy Model (TEM)

Figure 2-7. Energy Consumption in Rail Freight Model Estimates



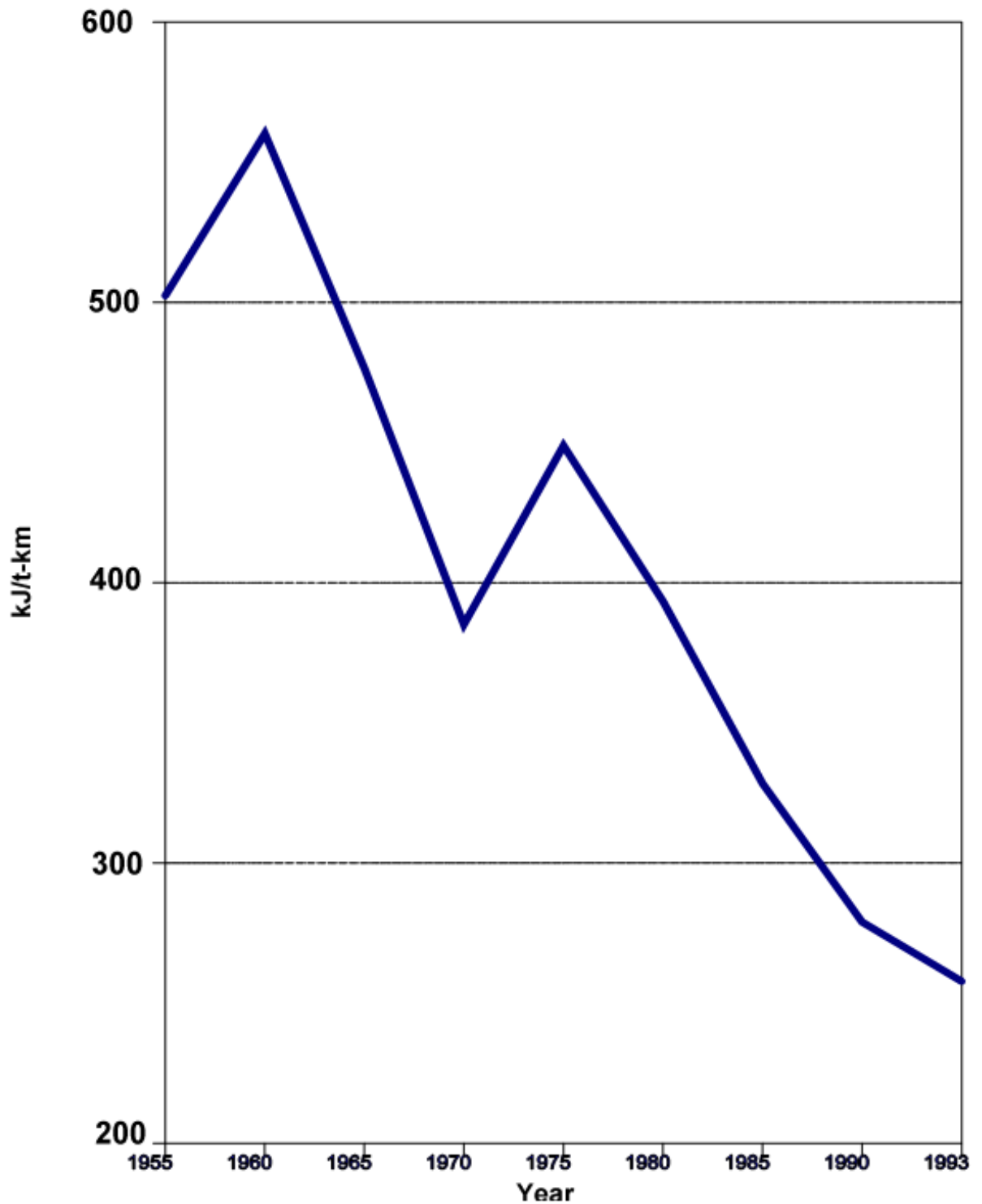
Source: Figure 2-6 and FRA

Figure 2-8. Frequency Distribution of Freight Rail Fuel Economy for Actually Reported Data



Source: Annex A3

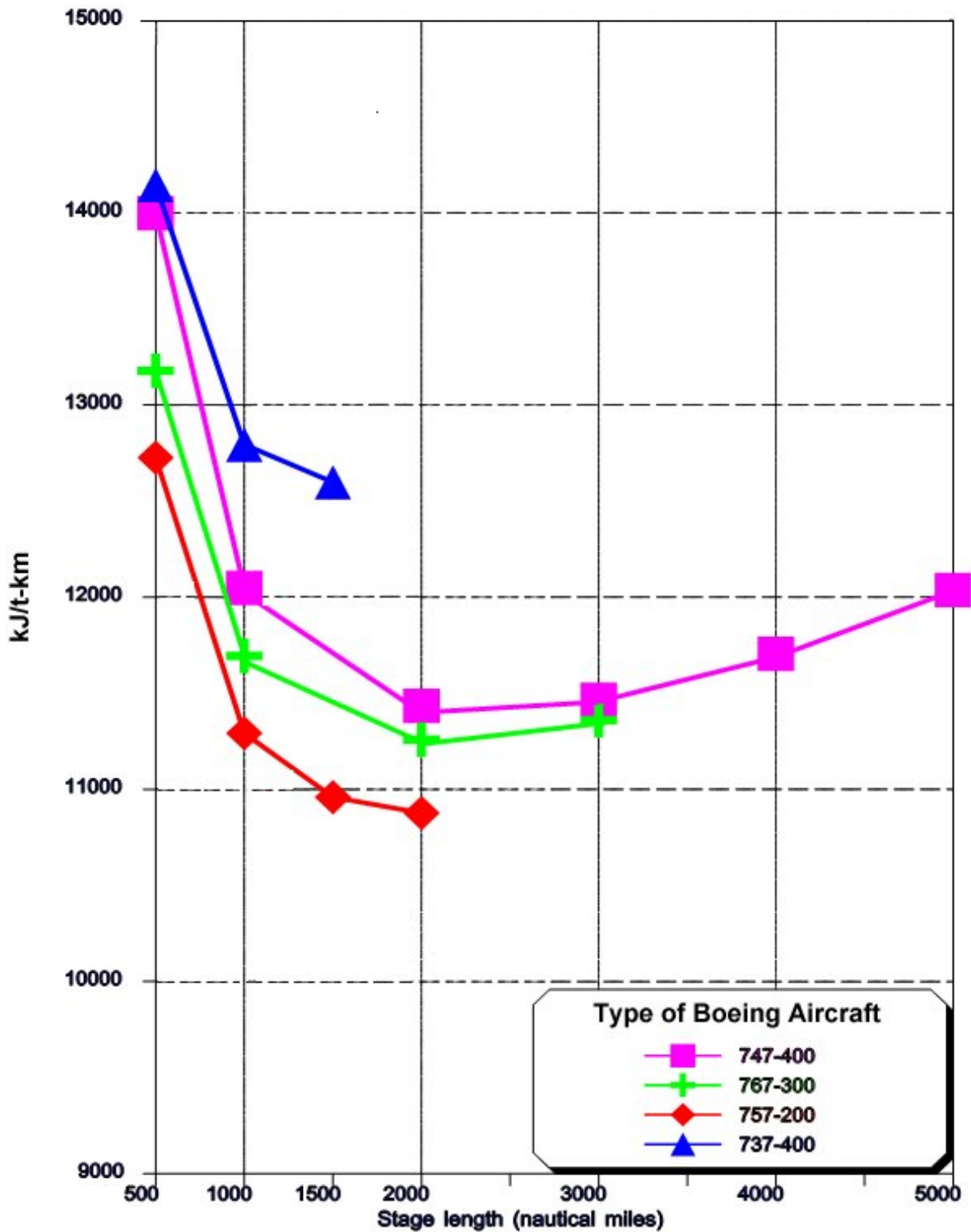
Figure 2-9. Rail Fuel Efficiency in the U.S.
1955-1993



Source: Railroad Facts 1994, AAR, page 40

Note: Between 1960 and 1990, specific fuel consumption in locomotives (kJ/hp-hr) fell by 35%. (Source: General Motors and General Electric)

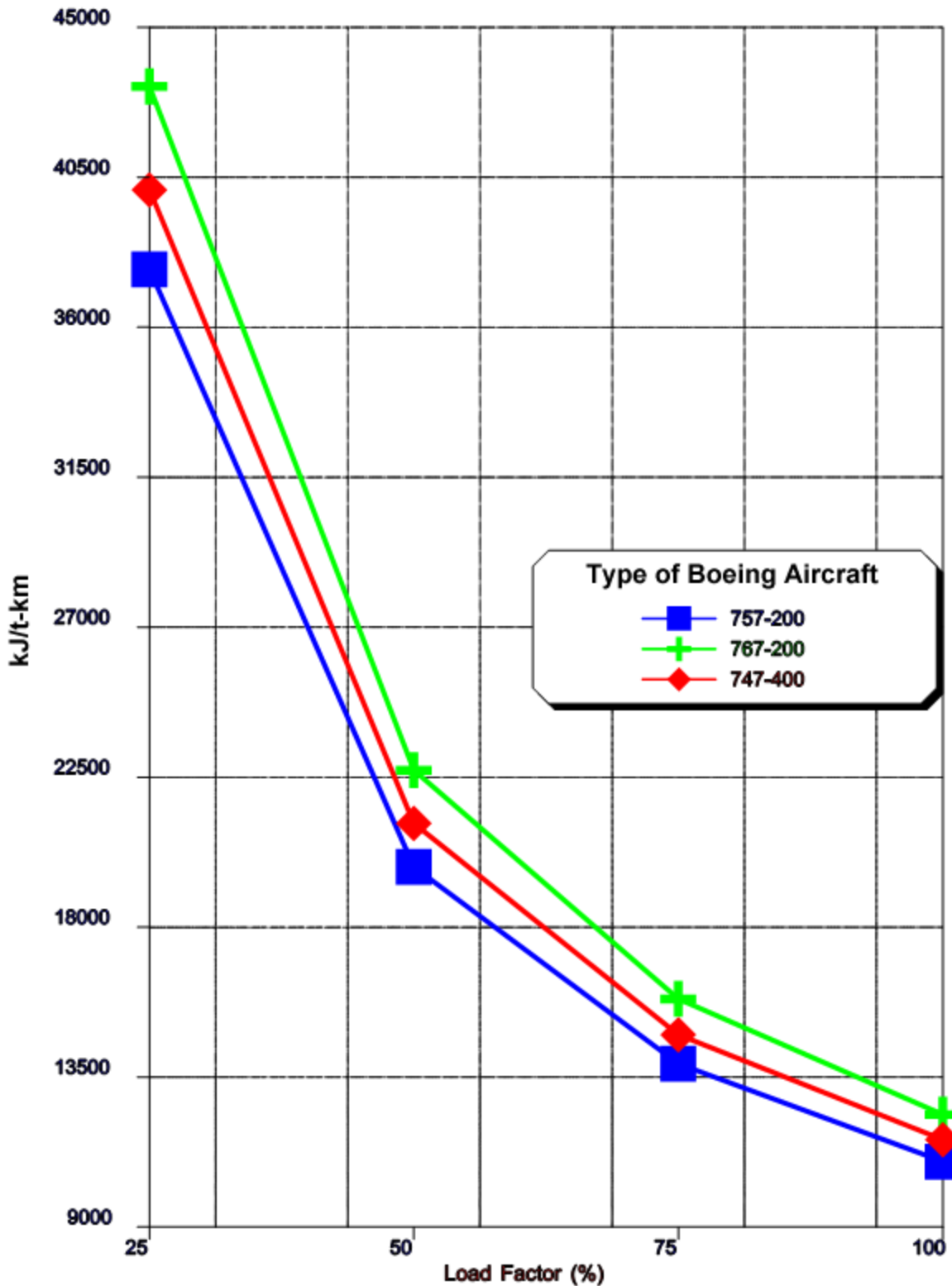
Figure 2-10. Fuel Consumption for Freight Aircraft at Various Stage Lengths



Source: Boeing, Airplane Economic Group

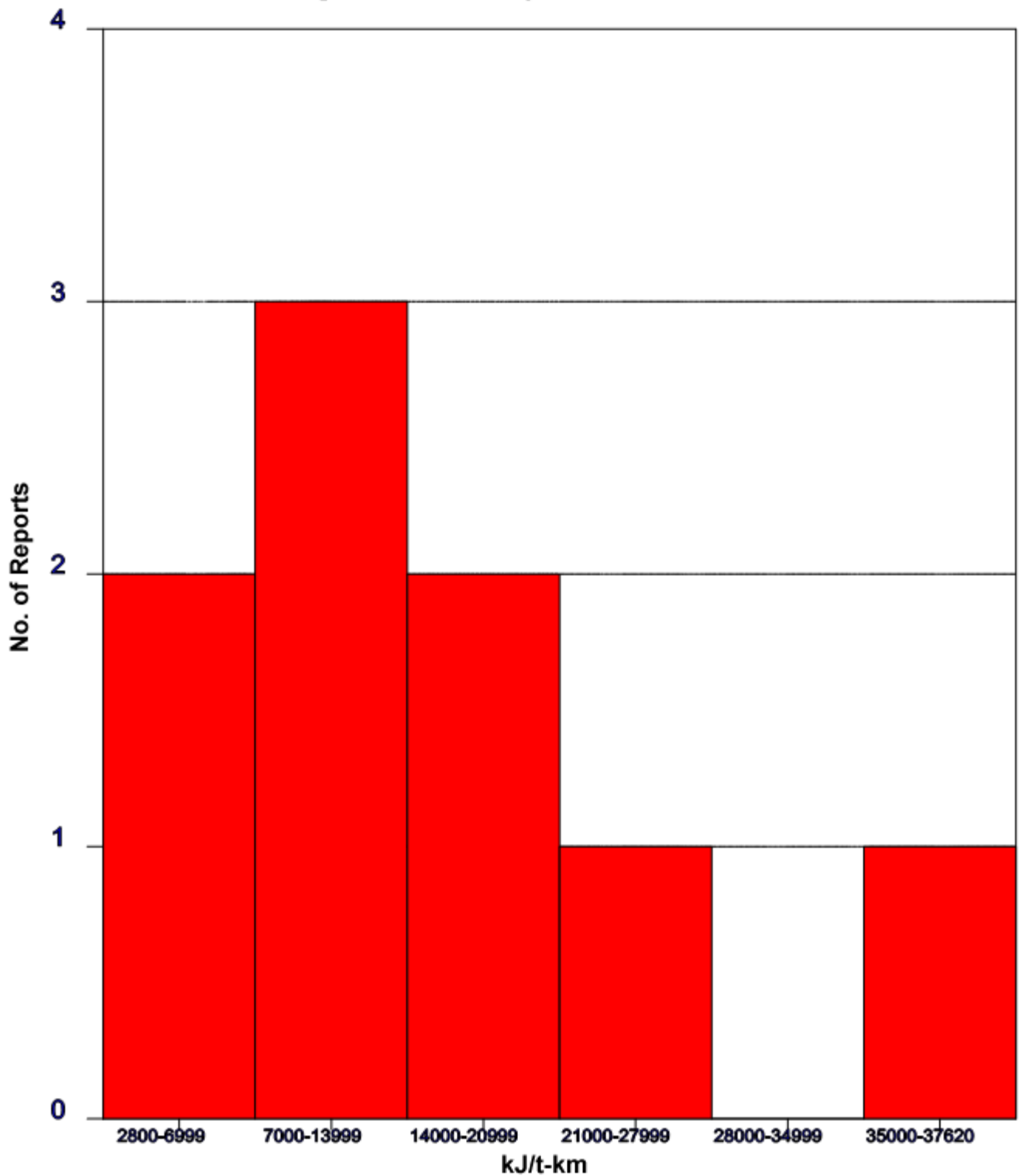
(Based on 200 lbs per passenger including luggage as equivalent to freight.)

Figure 2-11. Fuel Consumption for Freight Aircraft at Various Load Factors



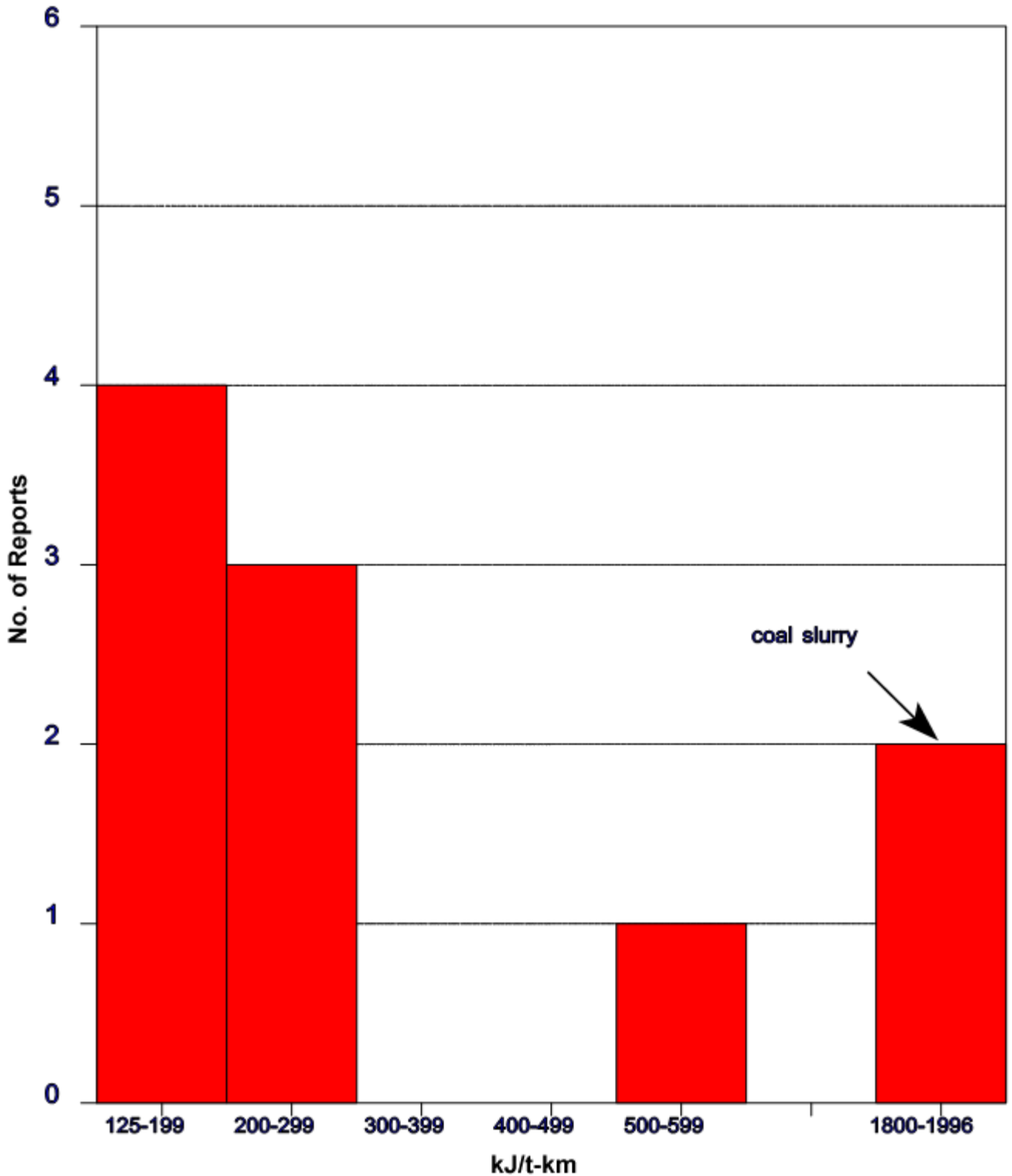
Source: Boeing, Airplane Economic Group

Figure 2-12. Frequency Distribution of Energy Efficiency for Air Freight for Actually Reported Data



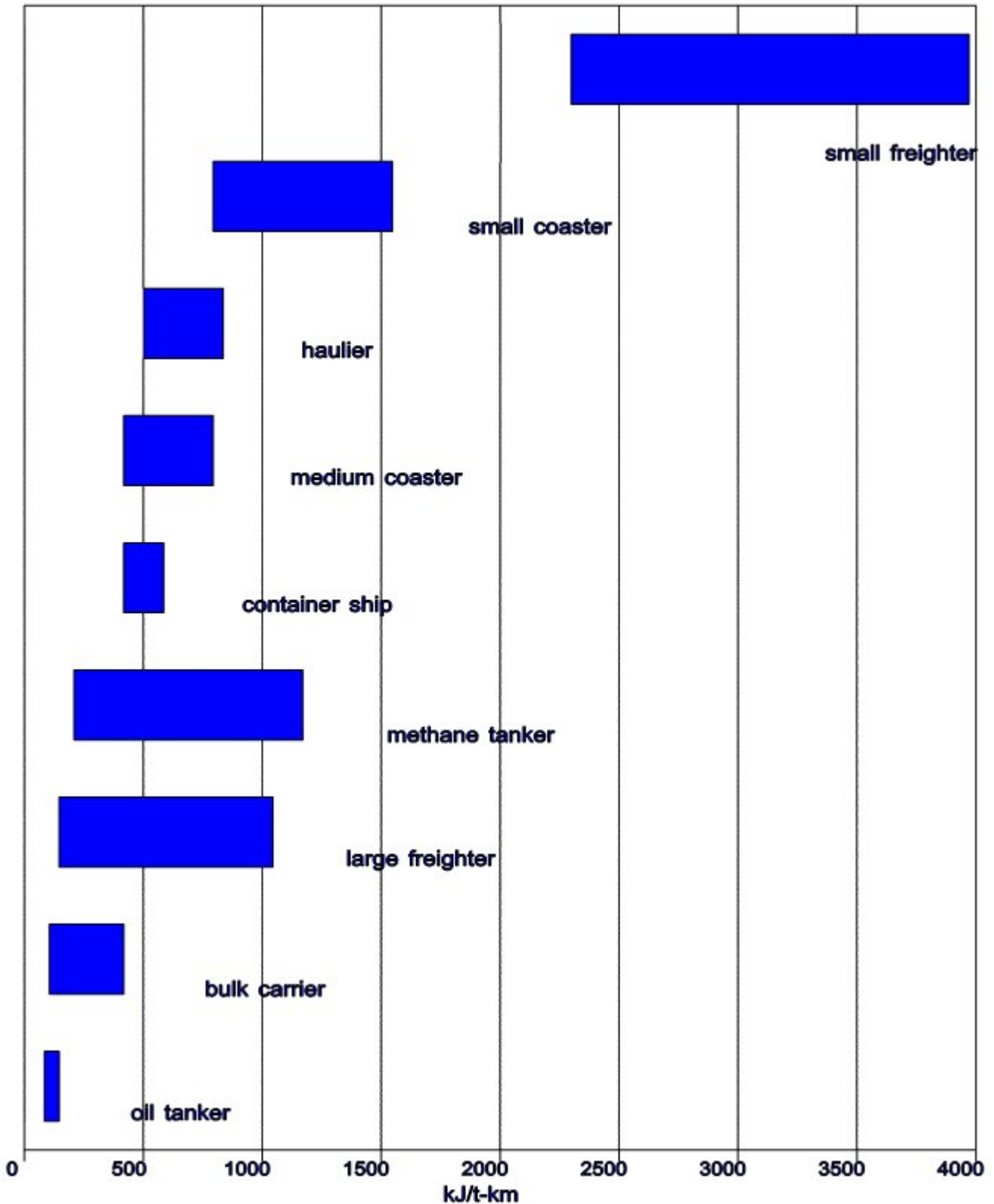
Source: Annex A1

Figure 2-13. Frequency Distribution of Energy Efficiency for Pipelines for Actually Reported Data



Source: Annex A2

Figure 2-14. Energy Consumption Ranges for Sea Shipping



Source: Igazato B., "Energy and Road Transport in Hungary."

Figure 2-15. Energy Efficiency in Freight
Non-motorized Transport

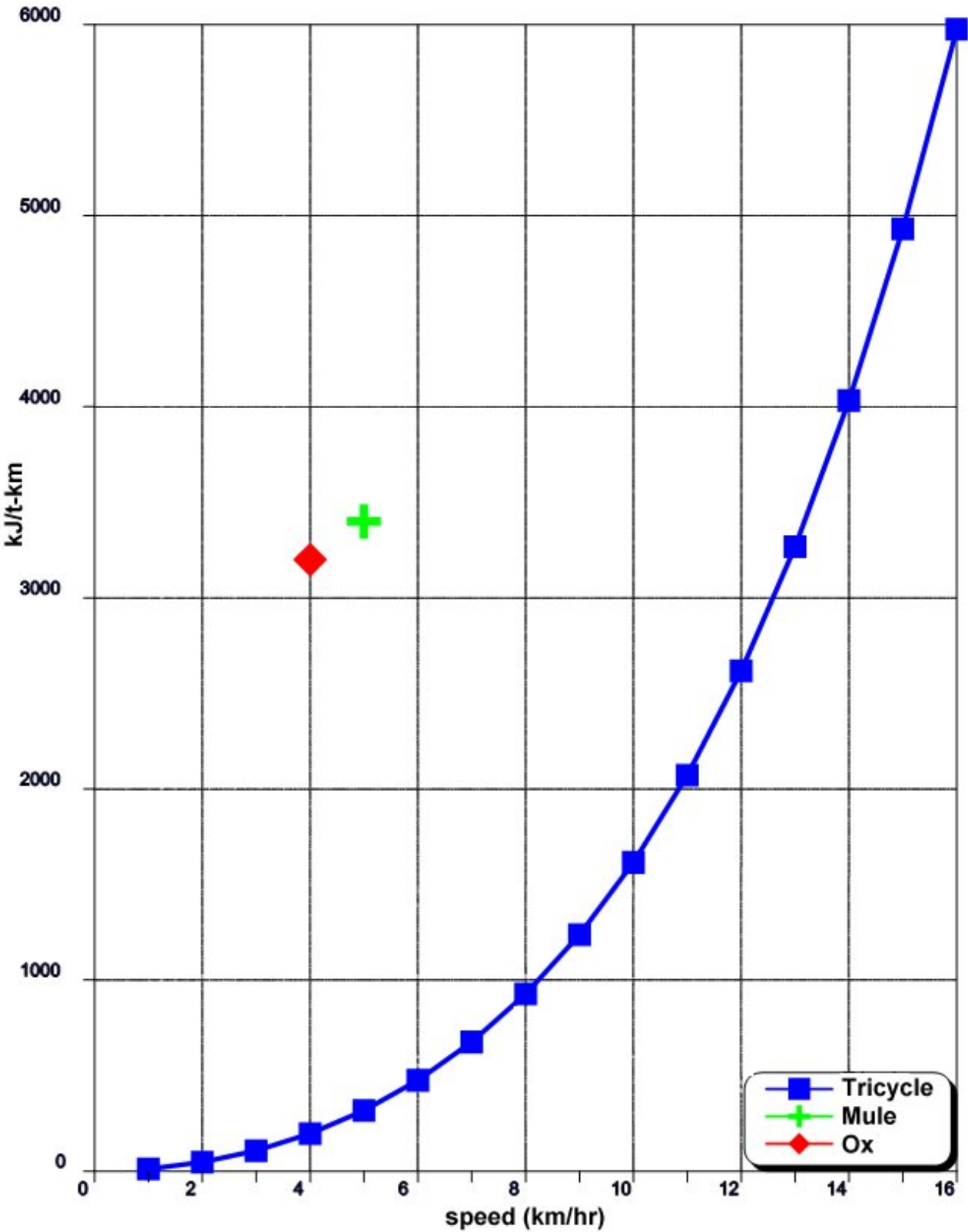


Figure 2-16. Energy Consumption Ranges in Freight Transport

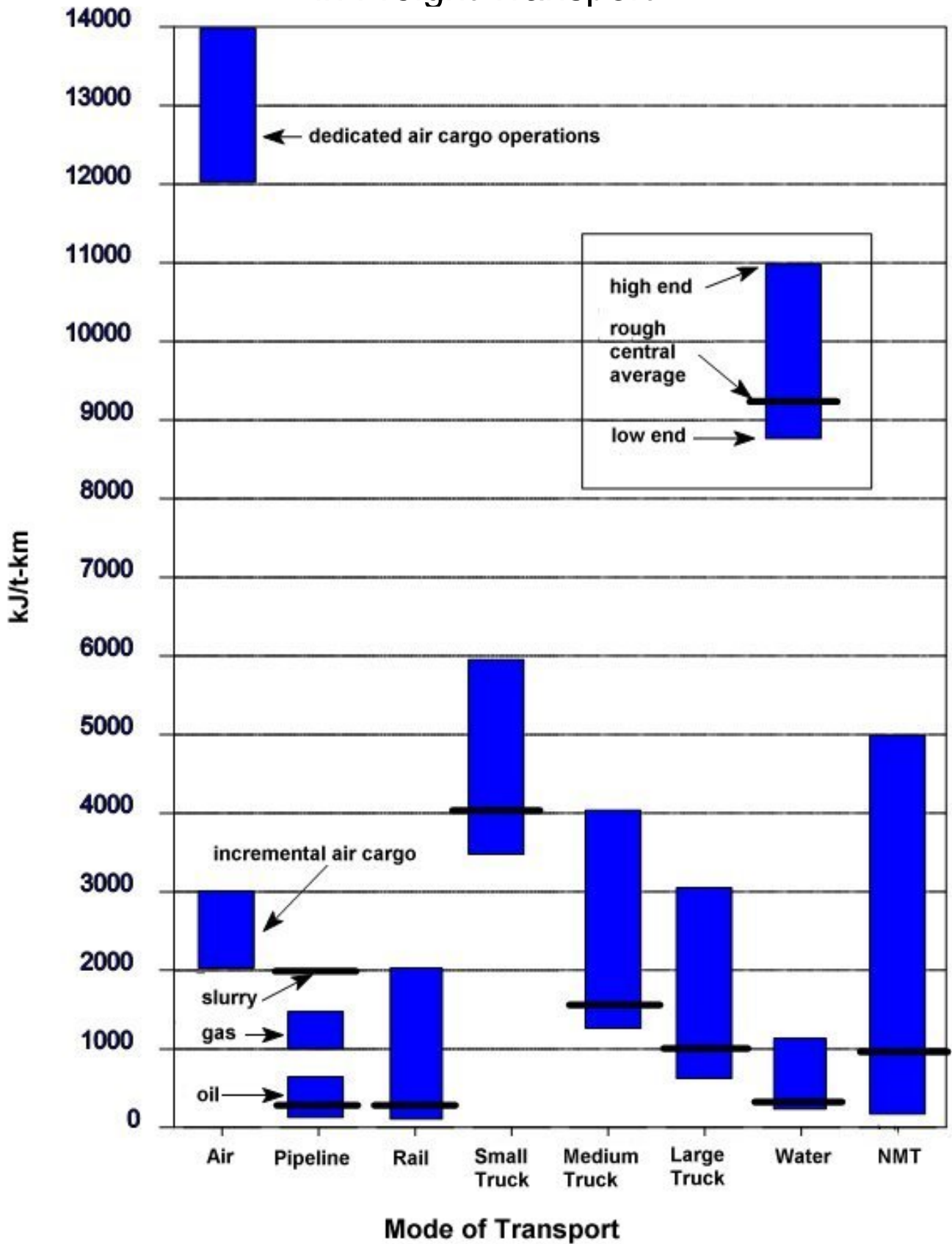
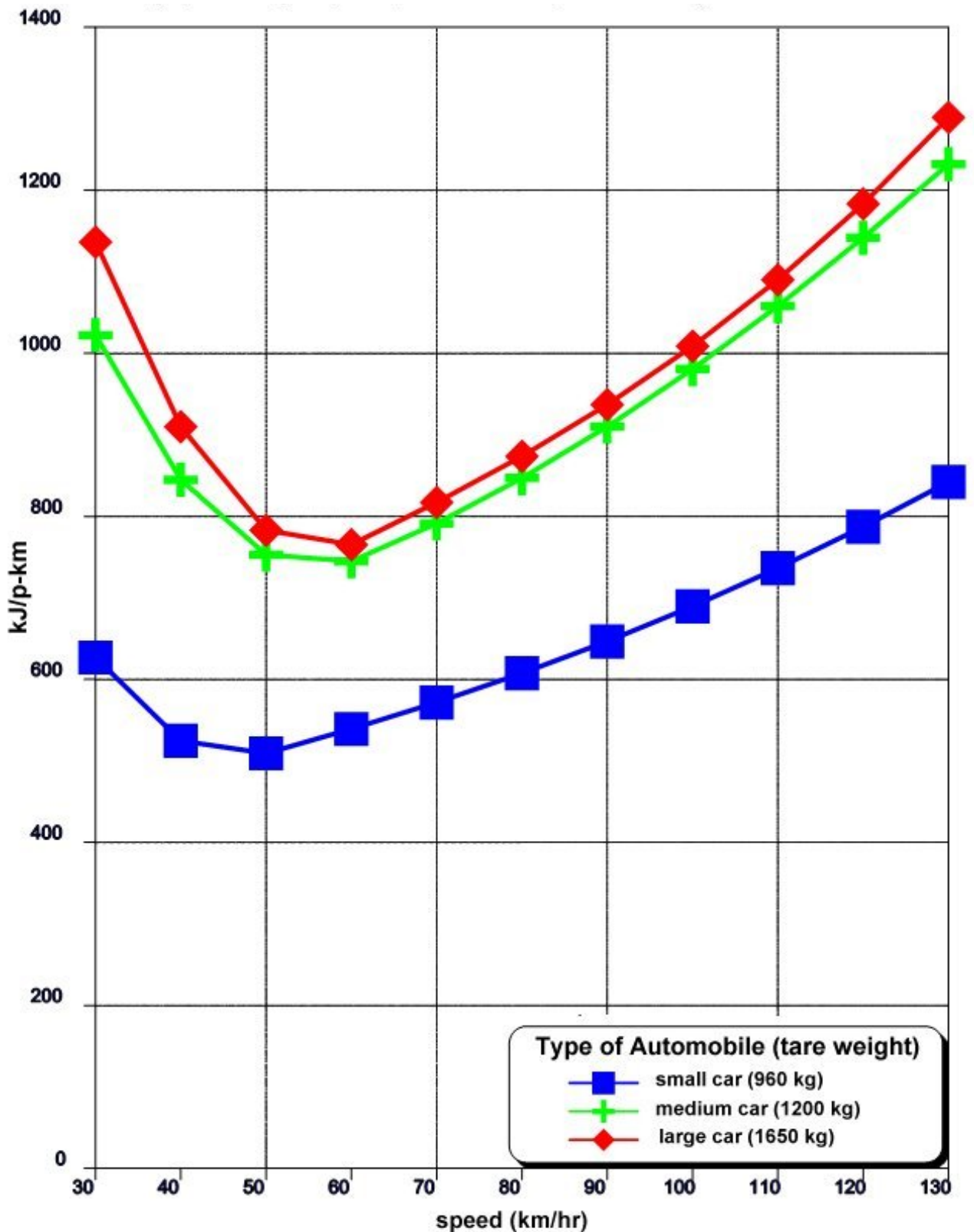
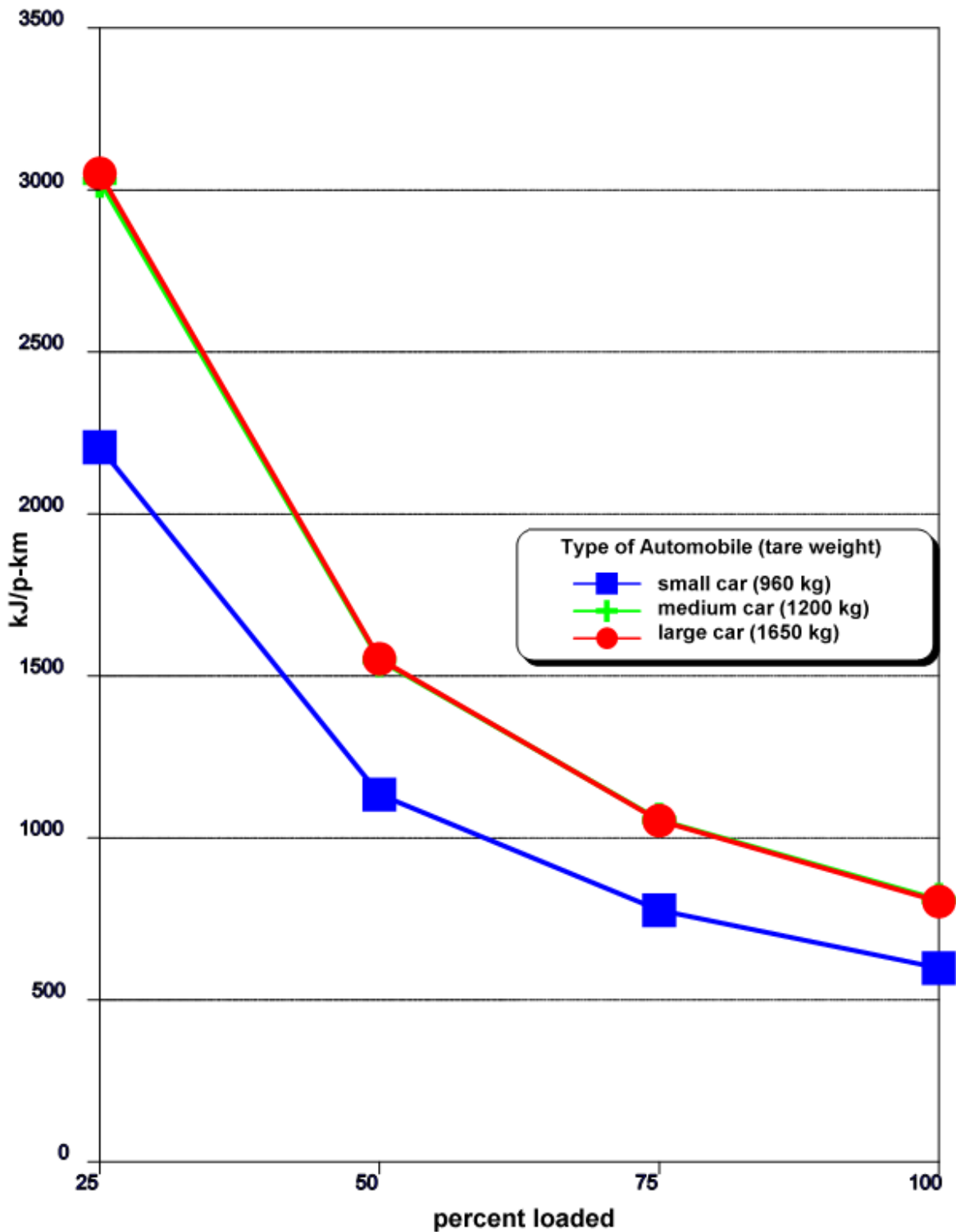


Figure 2-17. Automobile Fuel Efficiency at Various Speeds (4 passengers on paved roads, flat terrain)



Source: HDM

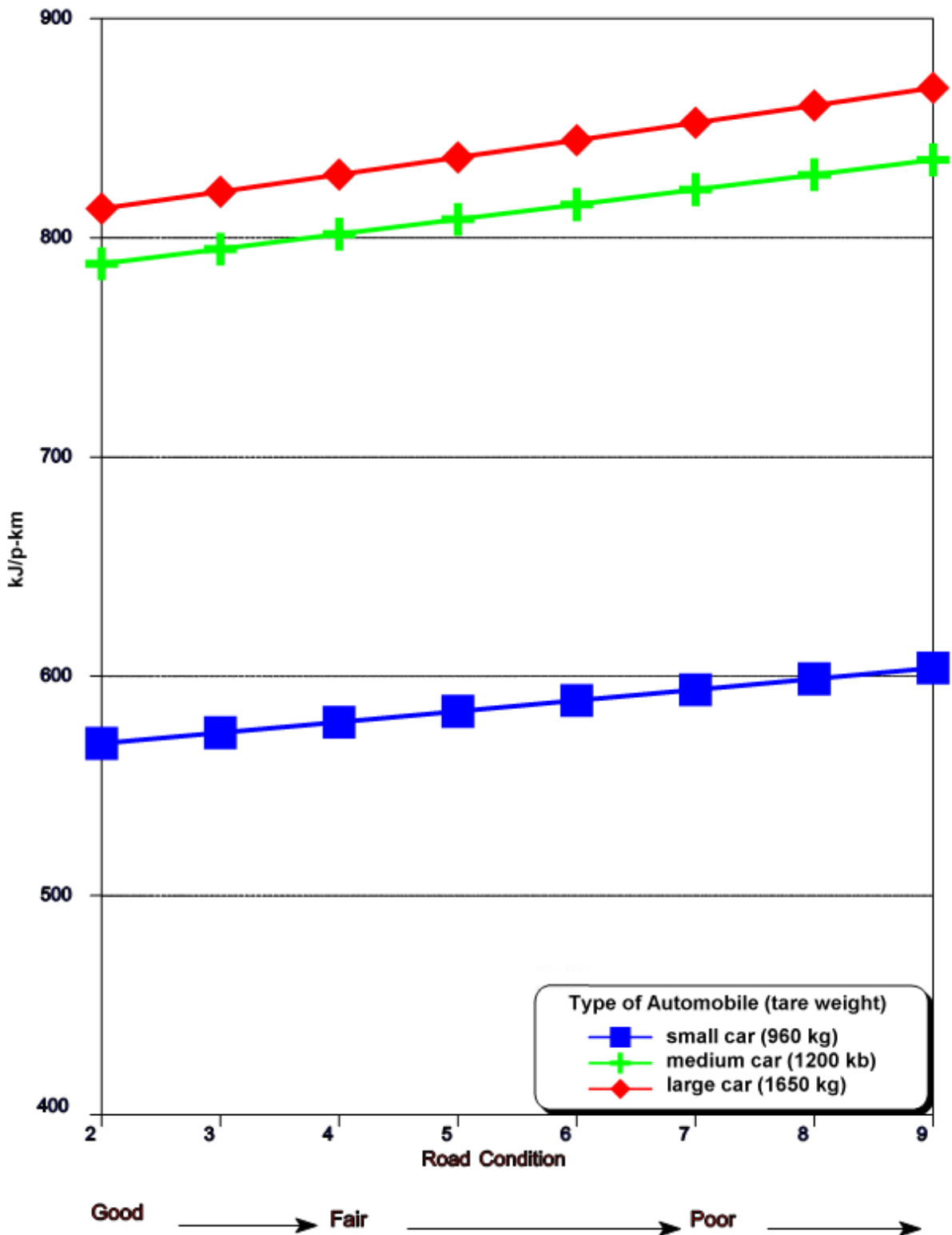
Figure 2-18. Automobile Fuel Efficiency at Varying Load Factors
(paved roads, flat terrain, 70 km/hr speed)



(100% loaded = 4 passengers)

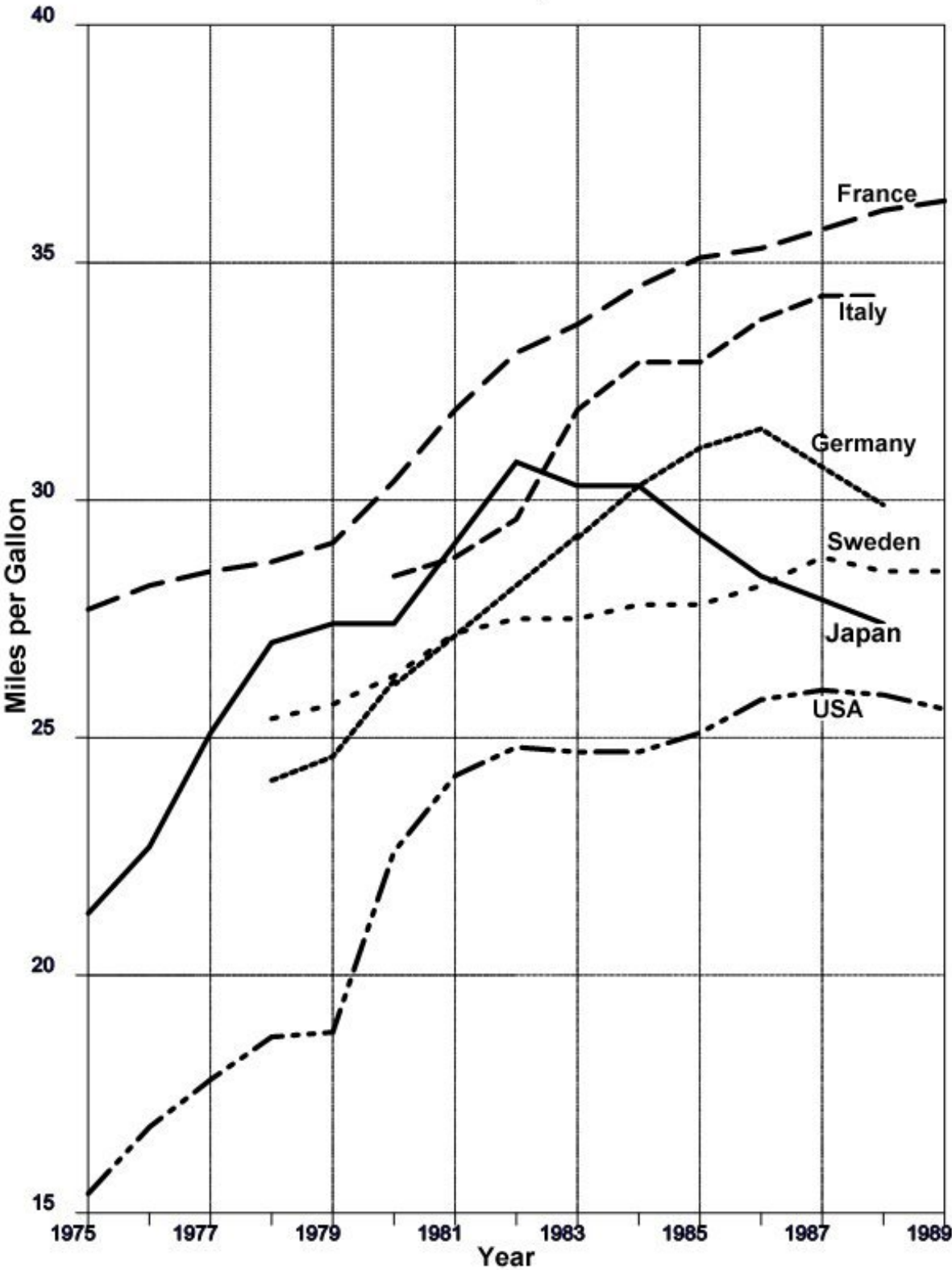
Source: HDM

Figure 2-19. Automobile Fuel Efficiency at Varying Road Conditions (4 passengers, 70 km/hr speed)



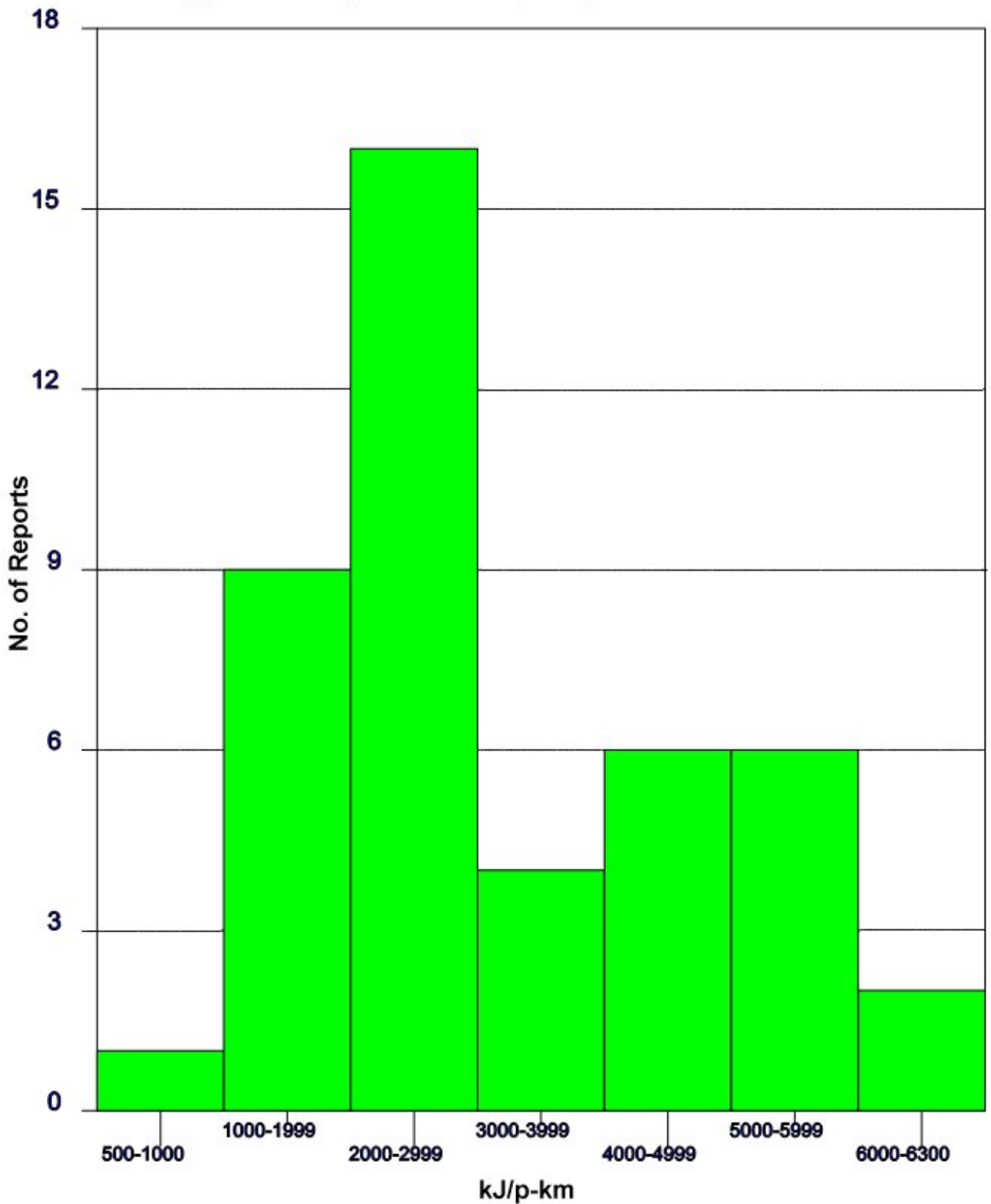
Source: HDM

Figure 2-20. New Gasoline Car Fuel Economy for Selected Countries, 1975-89



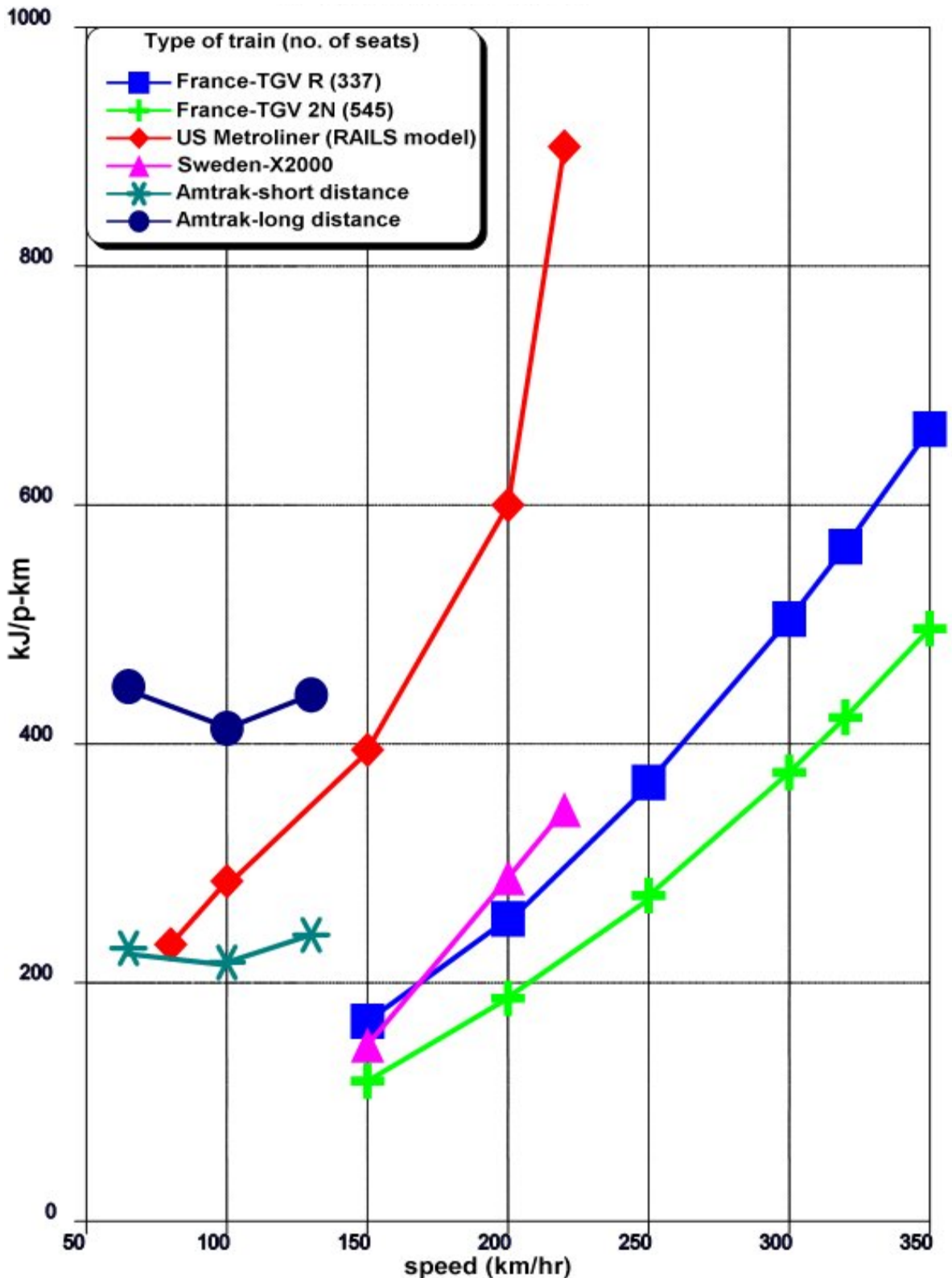
Source: ORNL 13, p. 1-13

Figure 2-21. Frequency Distribution of Automobile Energy Efficiency for Actually Reported Data



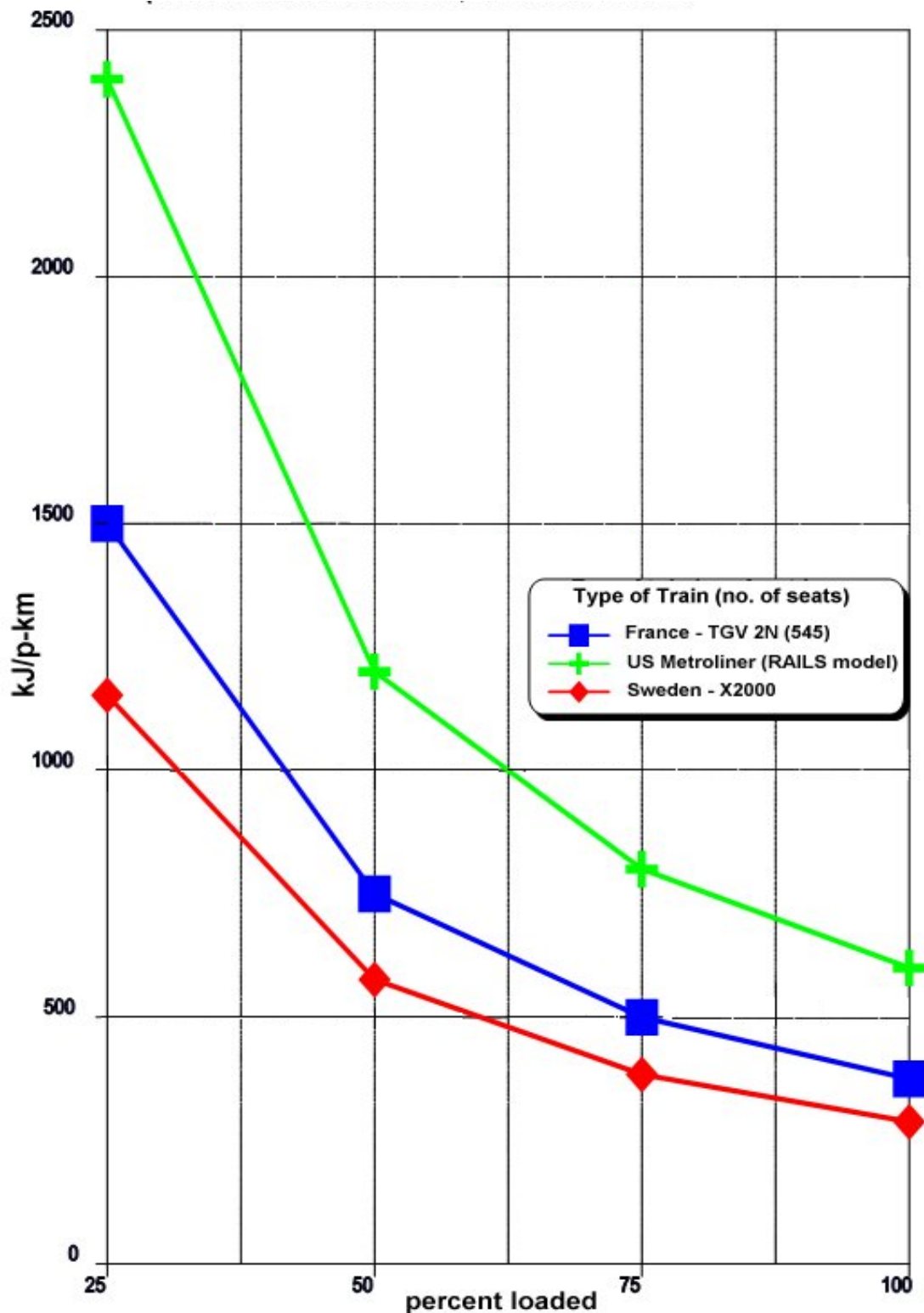
Source: Annex B2

Figure 2-22: Passenger Train Fuel Efficiency as a Function of Speed



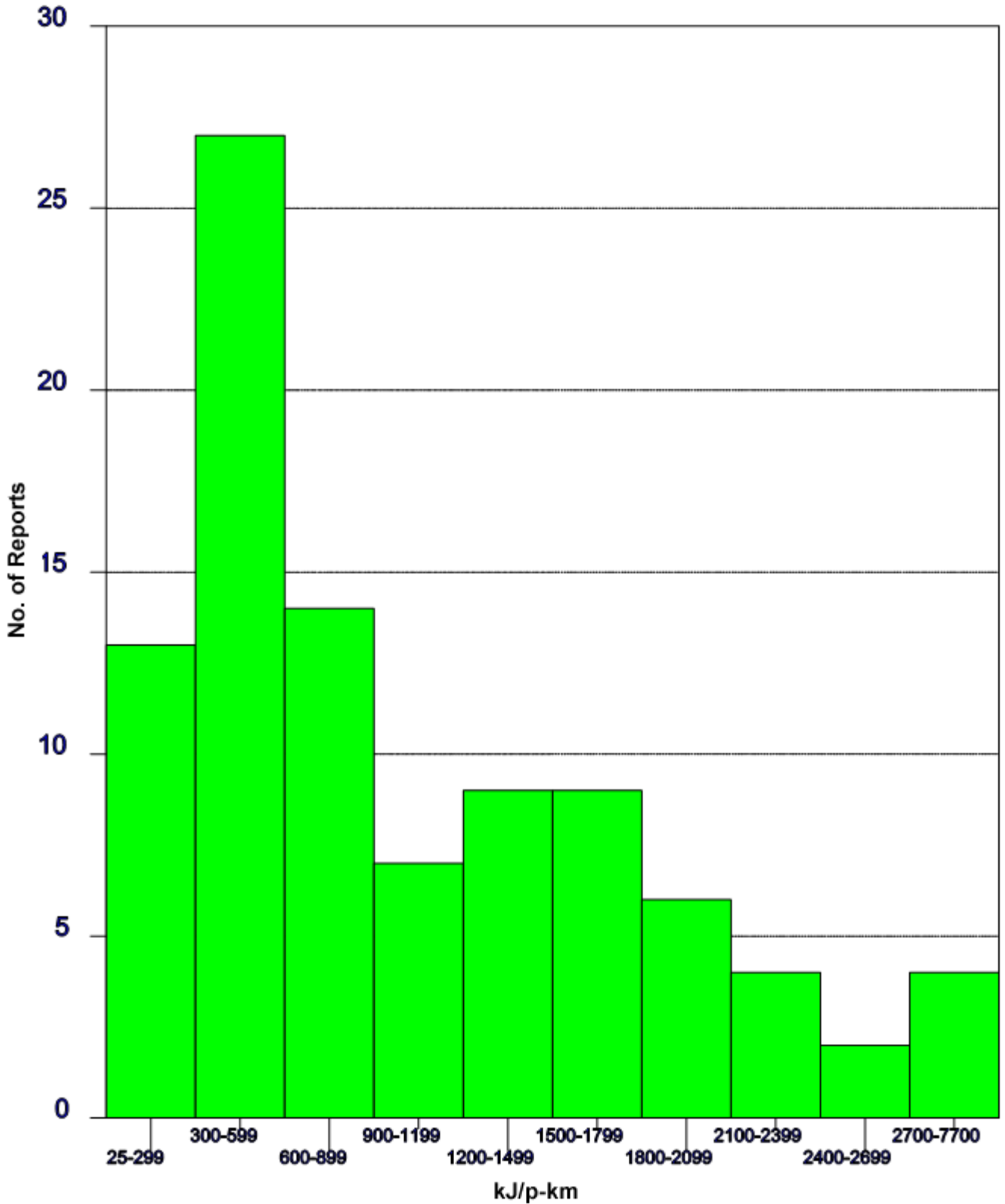
NOTE: This is an estimate of gross energy consumed at the power plant, and not reported electrical energy consumed by the train.

Figure 2-23. Passenger Train Energy Efficiency at Varying Load Factors (200 km/hr for Metroliner/X-2000; 300 km/hr for TGV 2N)



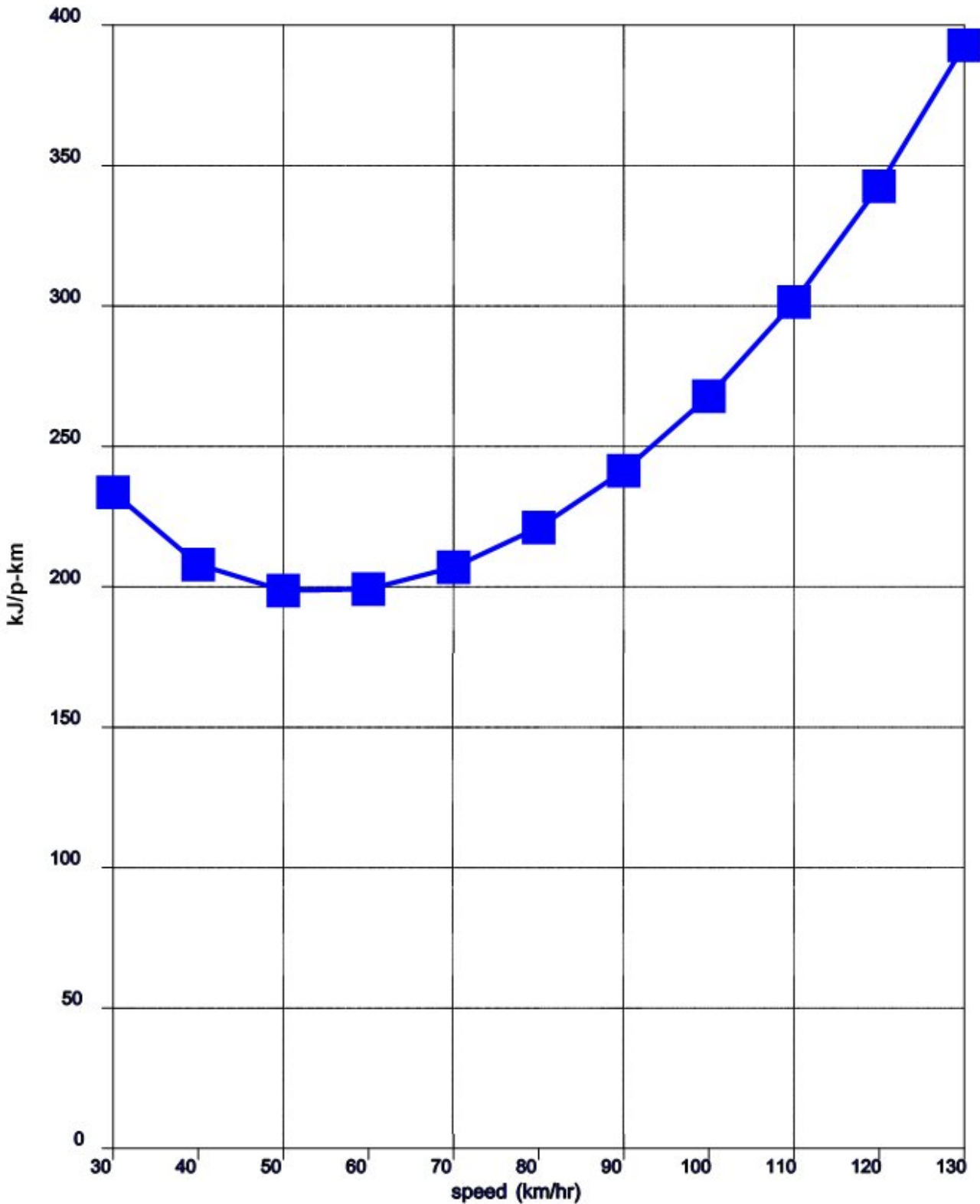
Source: Figure 2-22. Note the difference in speed between Metroliner (200 km/hr), X-2000 (200 km/hr) and TGV 2N (300 km/hr)

Figure 2-24. Frequency Distribution of Passenger Rail Energy Efficiency for Actually Reported Data



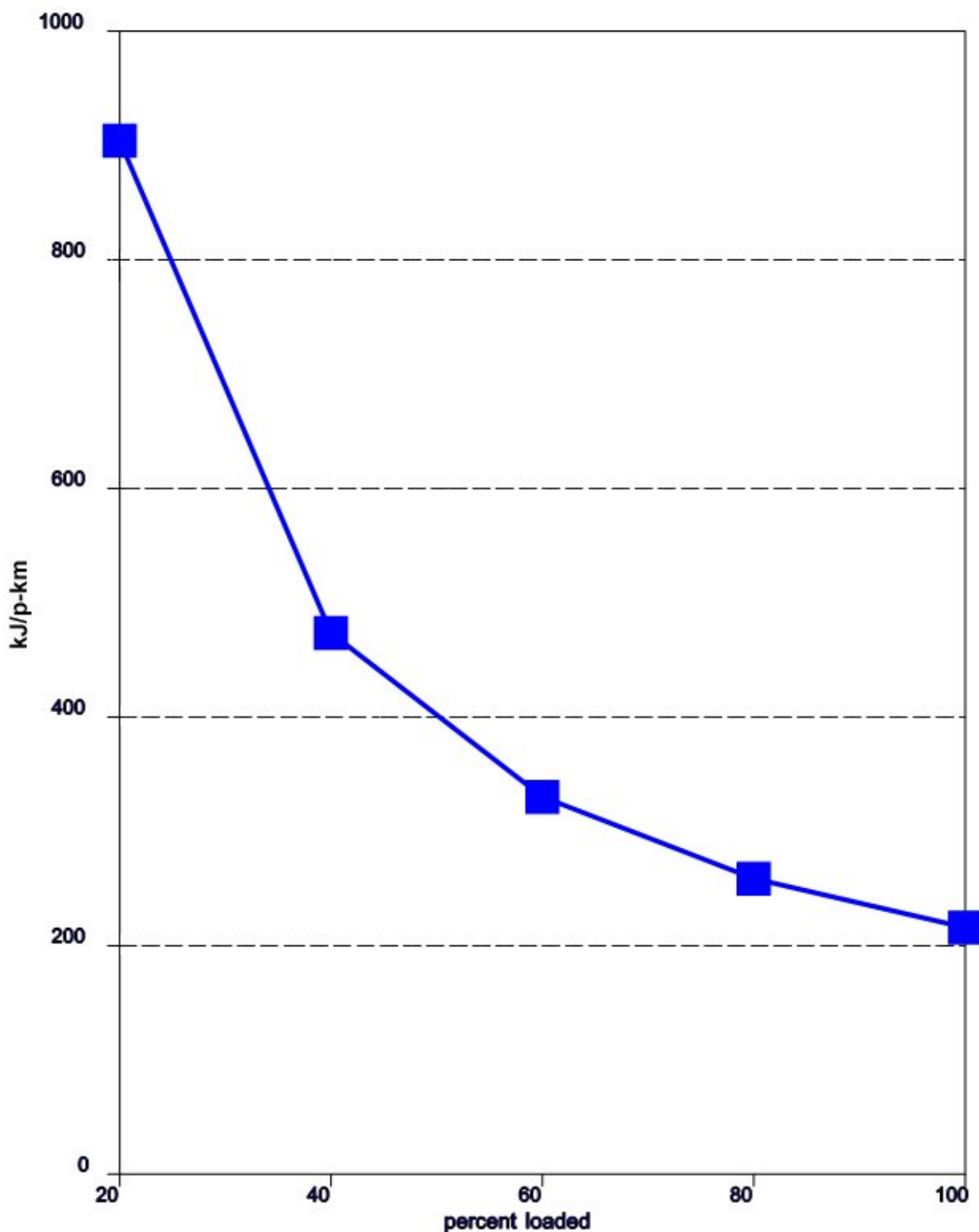
Source: Annex B6

Figure 2-25. Bus Fuel Efficiency at Various Speeds
(50 passengers, on paved roads, flat terrain)



Source: HDM

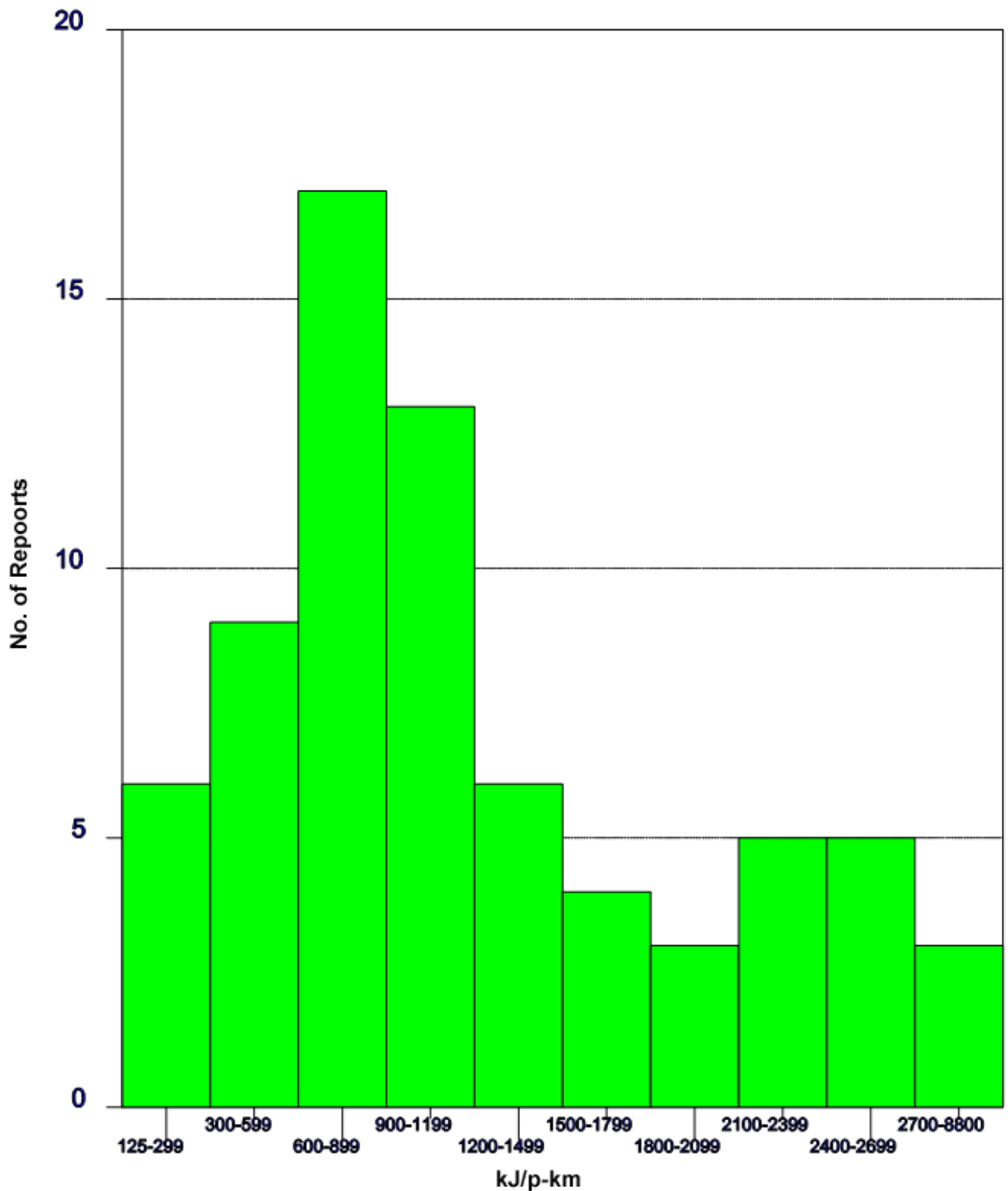
Figure 2-26. Bus Fuel Efficiency at Varying Load Factors
(paved roads, flat terrain, 70 km/hr speed)



(100% loaded = 50 passengers)

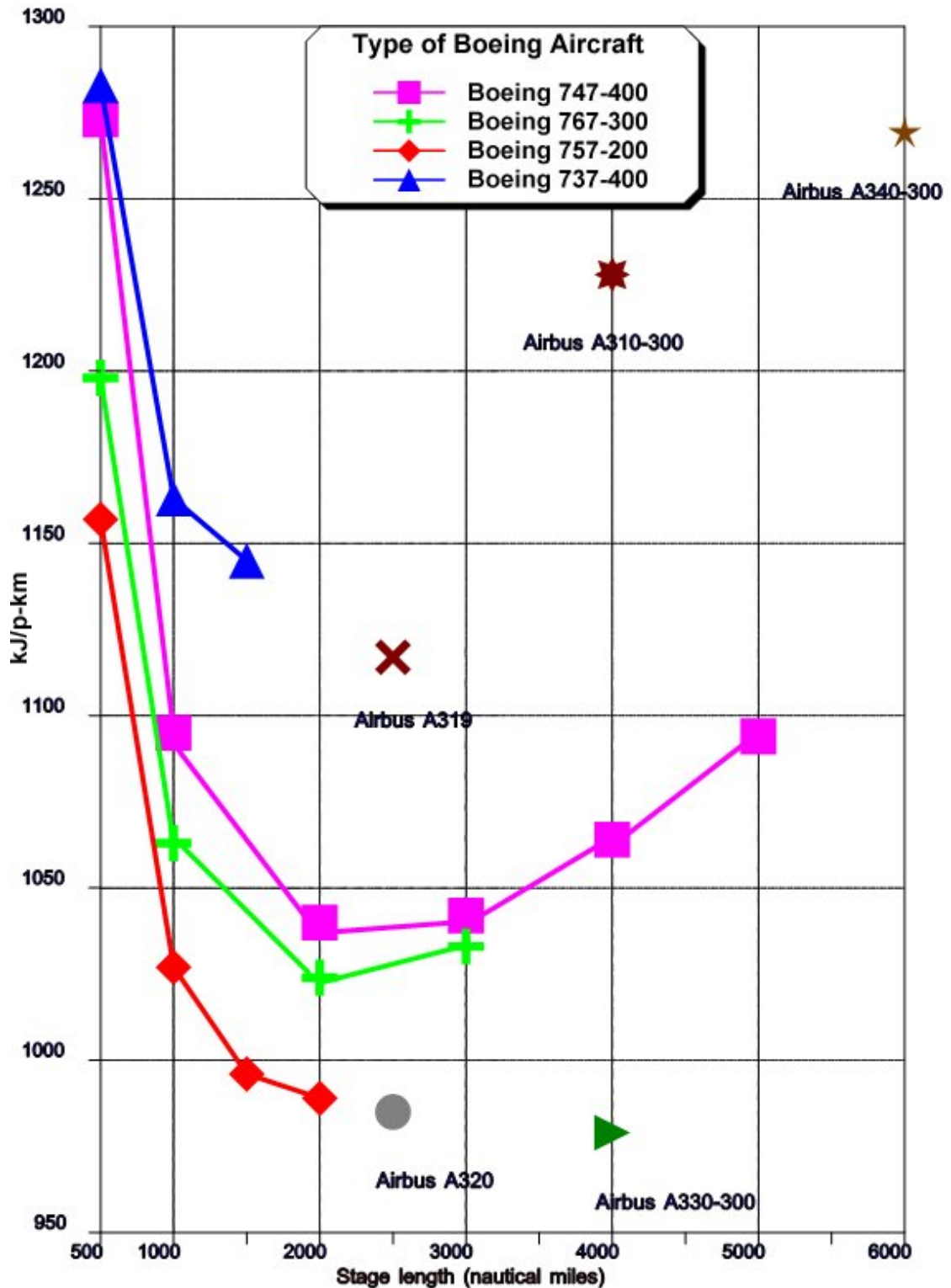
Source: HDM

Figure 2-27. Frequency Distribution of Passenger Bus Energy Efficiency for Actually Reported Data



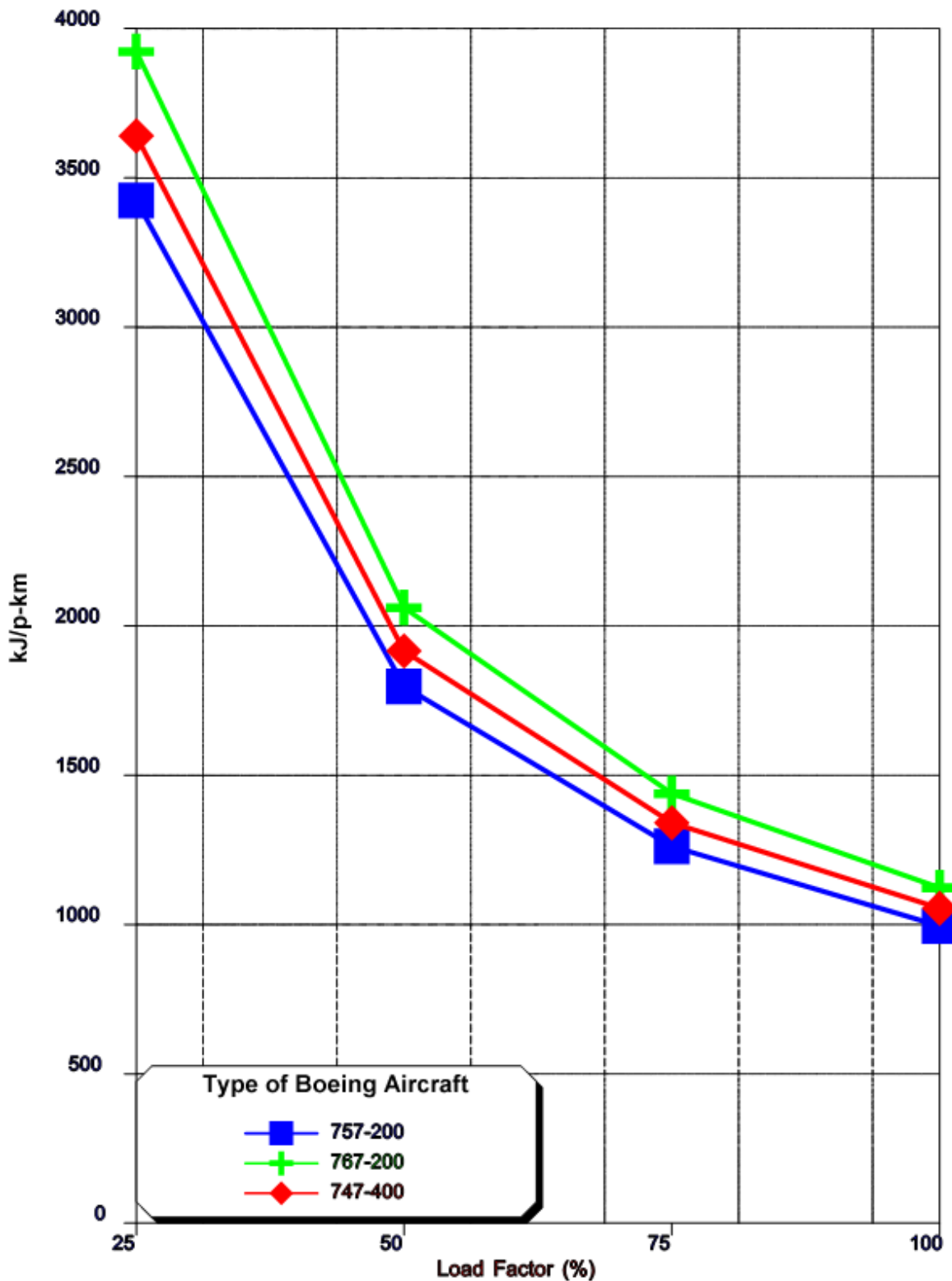
Source: Annex B3

Figure 2-28. Reported Fuel Consumption for Passenger Aircraft at Various Stage Lengths



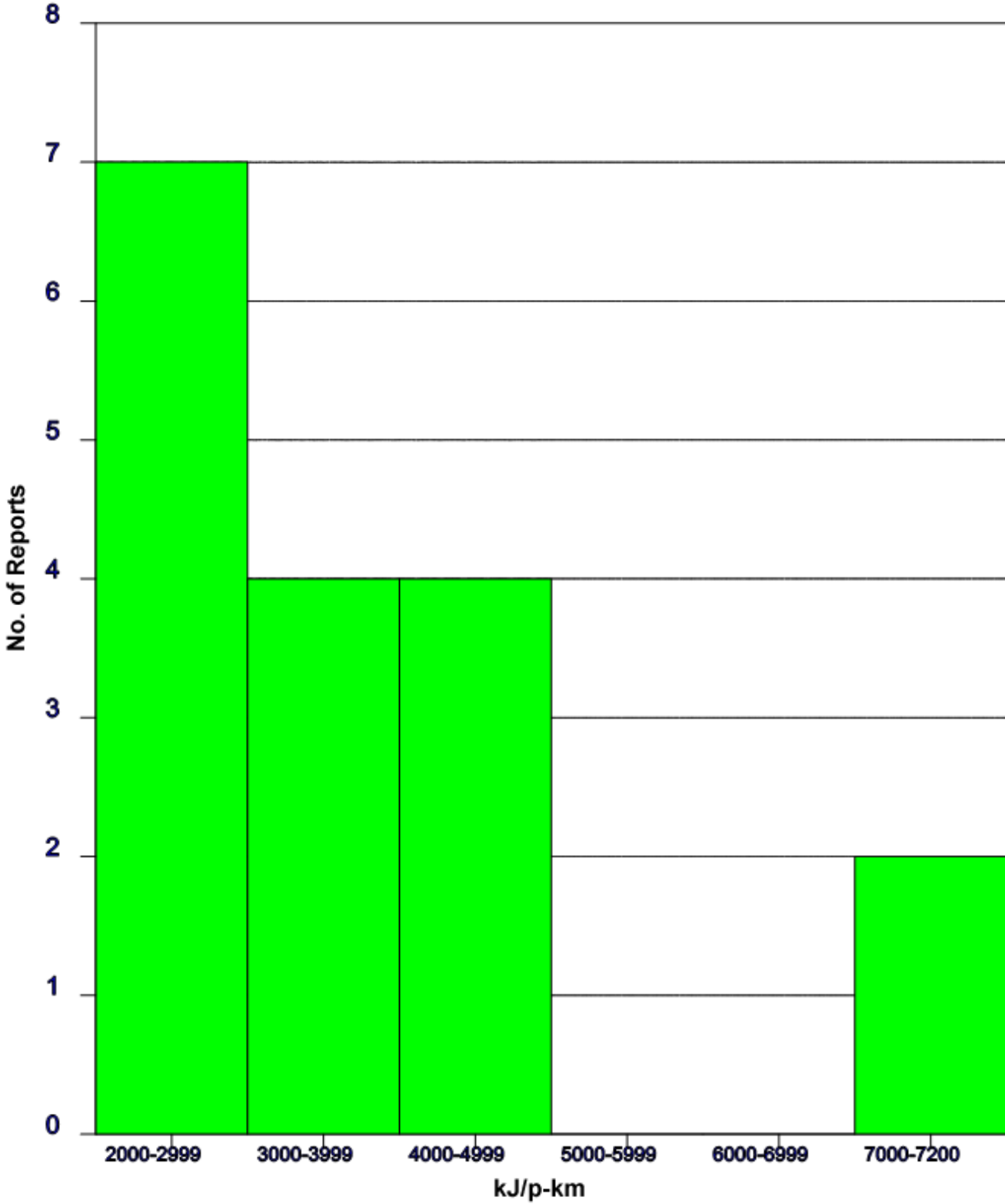
Note: the Concorde consumes 6260 kJ/p-km for a 4,150 nautical mile trip.
 The Cessna Citation VII consumes 7594 kJ/p-km for a 2,100 nautical mile trip.

Figure 2-29. Fuel Consumption for Passenger Aircraft at Various Load Factors



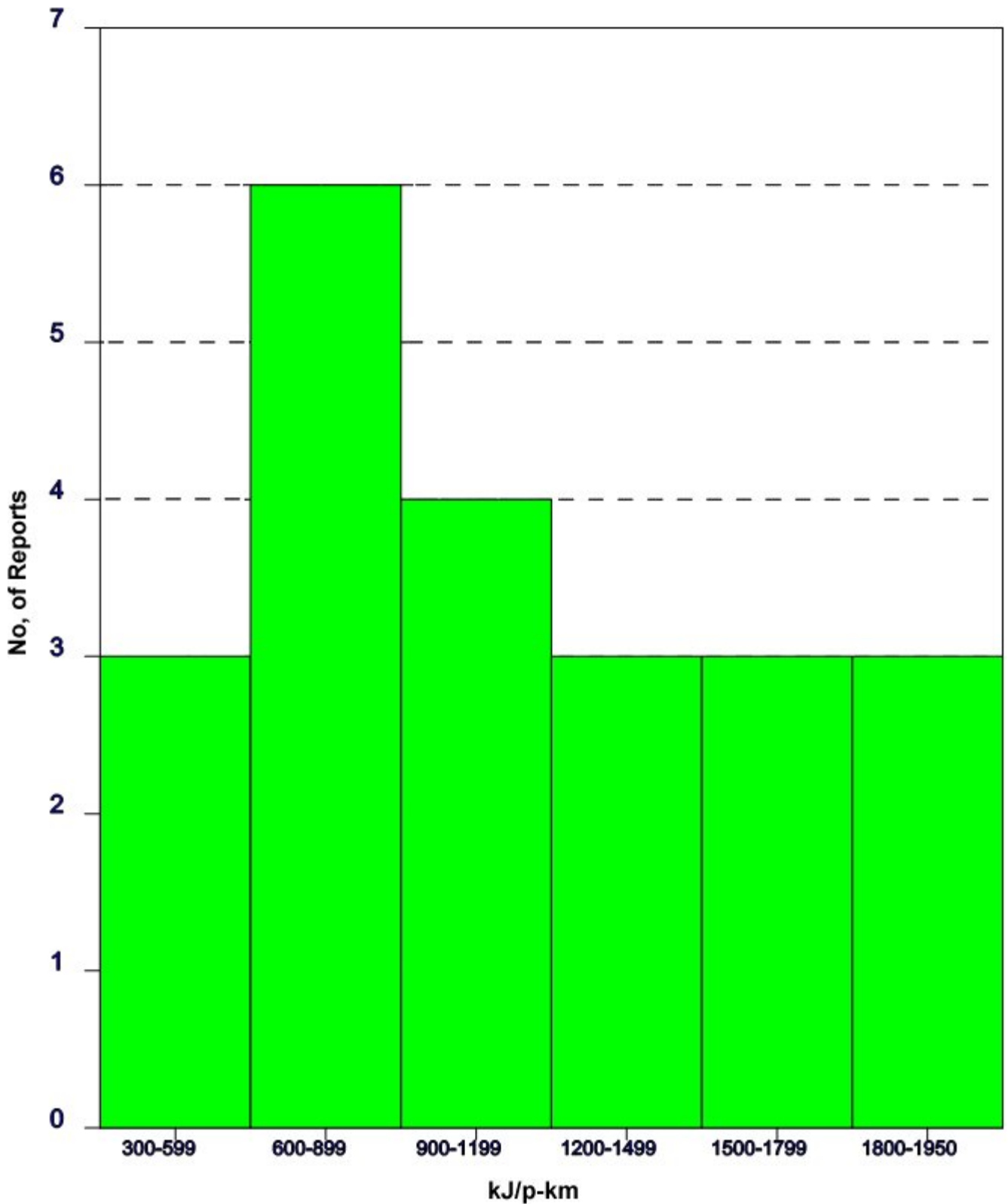
Source: Boeing, Airplane Economic Group

Figure 2-30. Frequency Distribution of Passenger Aircraft Energy Efficiency for Actually Reported Data



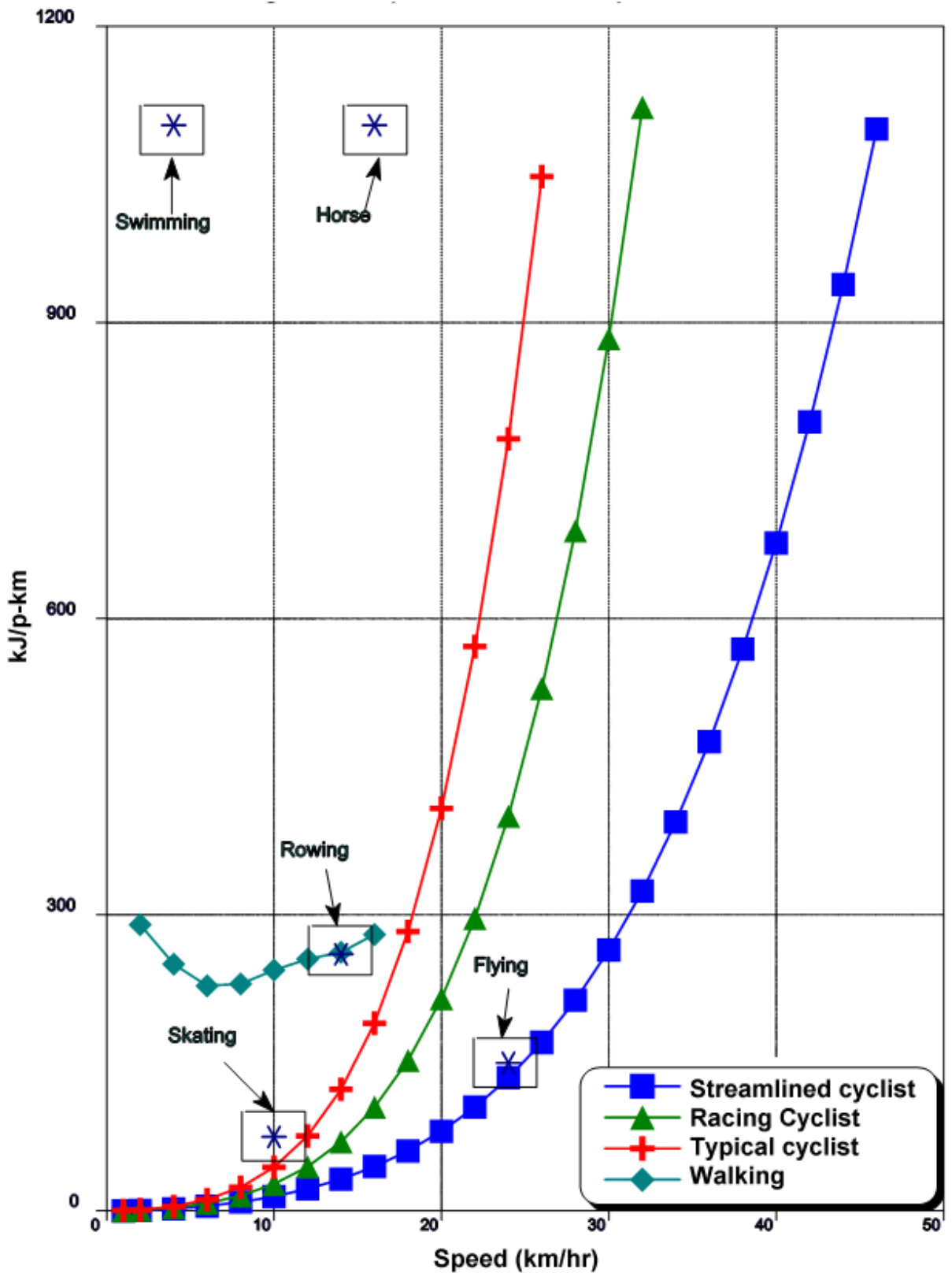
Source: Annex B1

Figure 2-31. Frequency Distribution of Motorcycle Energy Efficiency for Actually Reported Data



Source: Annex B5

Figure 2-32. Energy Consumption for Non-motorized Passenger Transport at Various Speeds



Source Annex B4

Figure 2-33. Energy Consumption Ranges in Passenger Transport

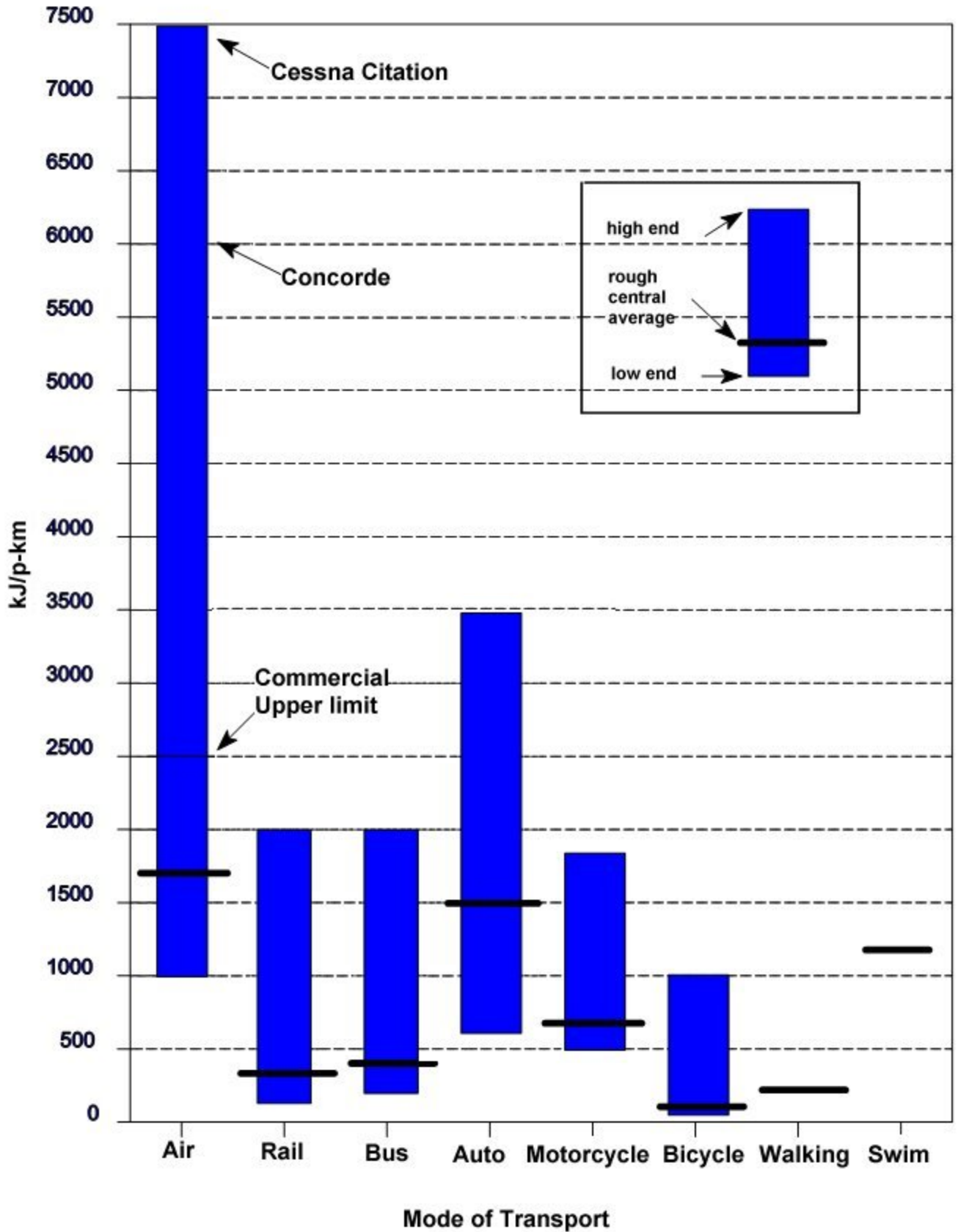


Figure 3-1. Transport Domains in the Production-Consumption Chain

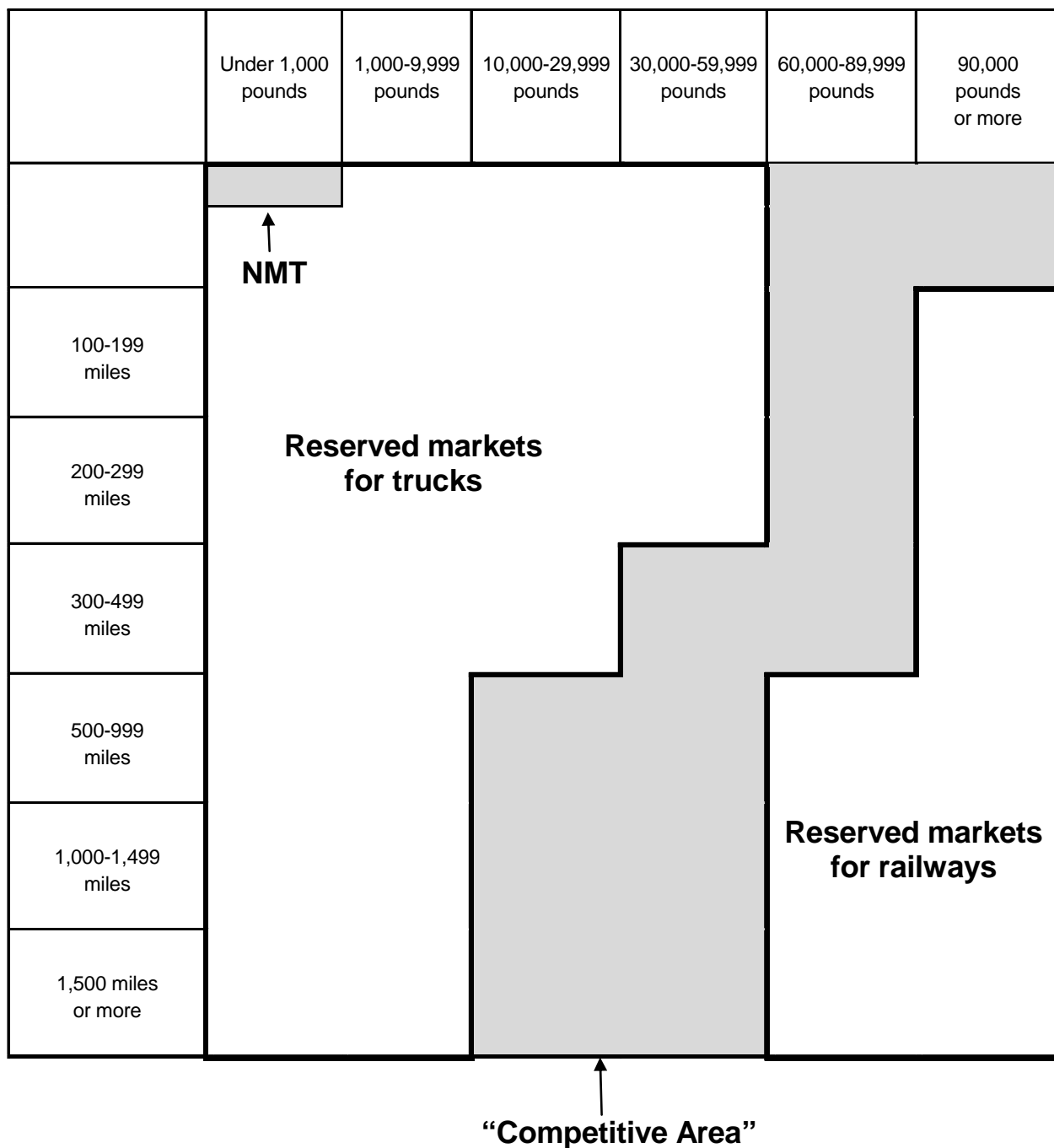
RAIL DOMAIN	IN-BETWEEN DOMAIN	ROAD DOMAIN
<i>Position in Production—Consumption Chain</i>		
Raw Materials	Processing, Construction or Production Lines	Assembling Industries or Dealers/Shops/Consumer
<i>Characteristics of Flows</i>		
High Volumes Large Shipments Regular Destinations Larger Inventories <i>Higher Volume JIT*</i>	Smaller Volumes Smaller Shipments More Irregular Destinations Just-in-time Production Small Inventories	Smallest Volumes Smaller Shipments More Irregular Destinations Just-in-time Production Small Inventories
<i>Characteristics of Materials</i>		
Few Articles per Production Unit Bulk Cheaper Per Tonne Large Transport Share of Price <i>Readily Containerizable*</i>	Hundreds of Articles Big and Small Objects	Thousands of Articles Small and Refined Object Expensive Per Tonne Small Transport Share of Price
<i>Typical Modal Choice Variable</i>		
Price	Reliability of Arrival	Speed

Note: 1 tonne=2,205 pounds.

Source: Road Transport Research, "Technico-Economic Analysis of the Role of Road Freight Transport." OECD:1986. p.79.

* *Added to original chart by the authors.*

Figure 3-2. Reserved Markets* and Competition Areas as Function of Hauling Distance and Size of Shipments



Source: Road Transport Research, "Technico-Economic Analysis of the Role of Road Freight Transport." OECD:1986. p.78.

* This is the term used in the source document. It means "markets in which a specific mode has an overwhelming cost advantage." It does not imply that there is, or should be, any regulatory reservation of traffic.

Figure 3-3. The Urban Modal Choice Diagram
Small Towns and Medium-size Cities

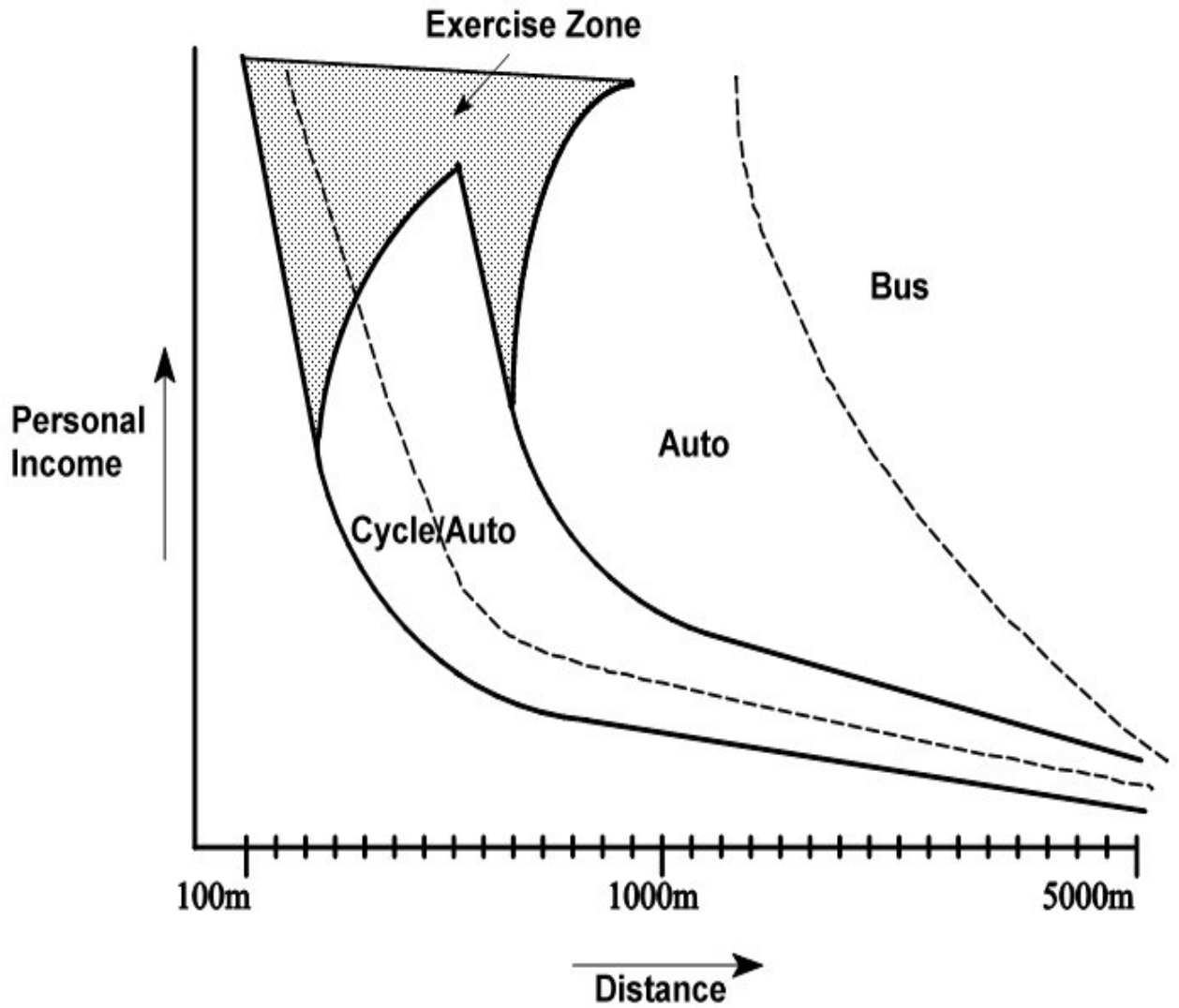


Figure 3-4. Non-Leisure Intercity Trips:
The Modal “Domains”

