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Daniel Sperling
Editor

Institute of Transportation Studies
University of California, Davis

James S. Cannon
Editor

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For more information contact its@ucdavis.edu

Chapter 13:

Improving the Energy Efficiency and Environmental Performance of Goods Movement

by James J. Winebrake and James J. Corbett

In the United States (U.S.), light duty vehicles (LDVs) have traditionally been the focus of regulatory action aimed at improving the fuel economy and environmental performance of transportation. The first LDV tailpipe emissions standards were promulgated in the mid-1960s, and corporate average fuel economy (CAFE) standards for LDVs were instituted a decade later and recently revised in May 2009. By contrast, heavy duty vehicles (HDVs), trains, and ships have only recently been affected by emissions standards, and currently do not face any restrictions affecting their fuel efficiency. Yet, it is clear that all opportunities for improving efficiency in all sectors of our economy must be exploited in order to avoid the calamitous consequences posed by climate change (Liu, J. *et al.* 2007a and 2007b). For the transportation sector, this includes improving the efficiency of our freight transportation systems through a variety of options.

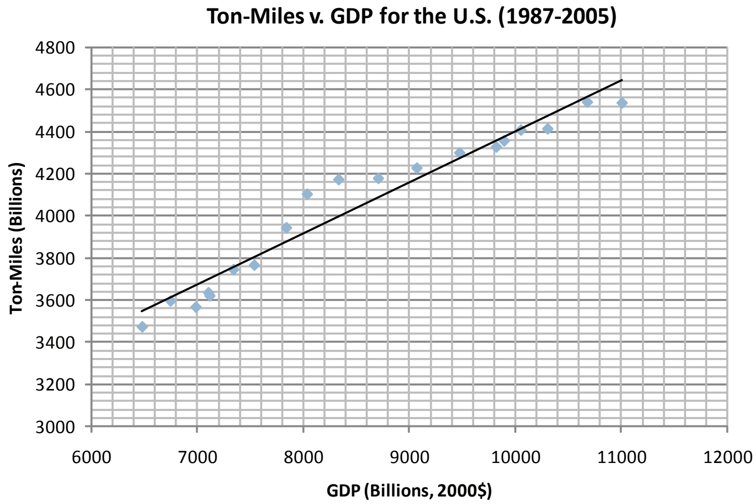
This chapter discusses the role of freight transportation as an important contributor to greenhouse gas (GHG) emissions. It presents a new context for discussing interrelated technology and policy options for reducing these emissions through an "IF-TOLD" analytical framework. In particular, the IF-TOLD framework is applied to evaluate opportunities for mode shifting, a credible method for reducing energy consumption and emissions in the freight sector. Based on this framework, a potential appears to exist for mode-shifting to help achieve energy and environmental goals, but expected benefits are likely overstated. Mode-shifting can have only limited impacts given the existing goods movement infrastructure in the United States. This argues for a more holistic approach to efficiency improvements in the freight sector. The chapter concludes with a discussion of the importance of technology policy mechanisms that encourage freight performance improvements across a range of long and near-term goals.

Overview of Goods Movement

The relationship between goods movement and economic activity in the United States is displayed in Figure 13-1, which depicts ton-miles of freight movement as a function of gross domestic product (GDP) over a 20-year period. In the consumer-based economy, the relationship is intuitive: the more economic activity there is, the greater the use of freight transportation services.

J. Winebrake is a professor in the Department of STS/Public Policy at the Rochester Institute of Technology. J. Corbett is a professor in the College of Earth Ocean and Environment at the University of Delaware.

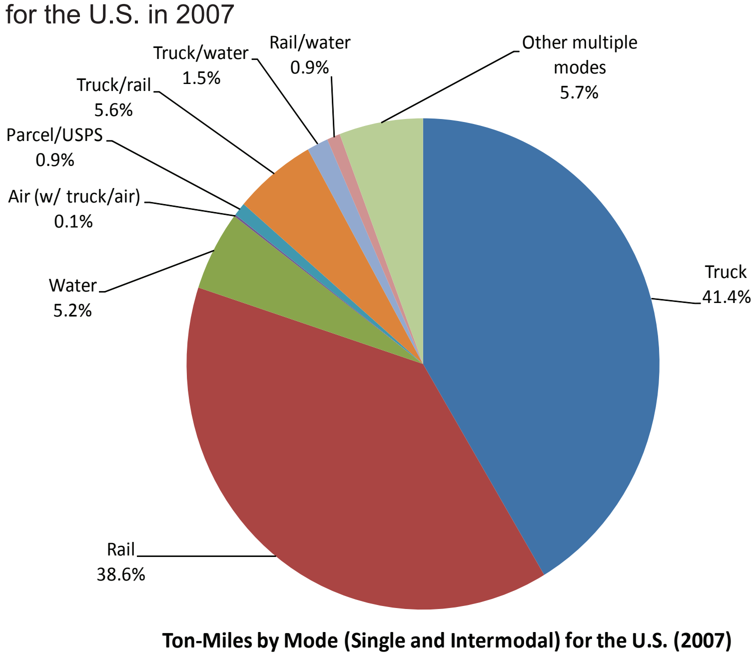
Figure 13-1: Relationship between freight transportation services and GDP for the U.S., 1987-2005



Source: Derived from BTS 2007a and BEA 2009

About 80 percent of this freight service is provided by truck and rail service, with other modes, including intermodal service, constituting the difference. The full breakdown of ton-miles by mode is shown in Figure 13-2.

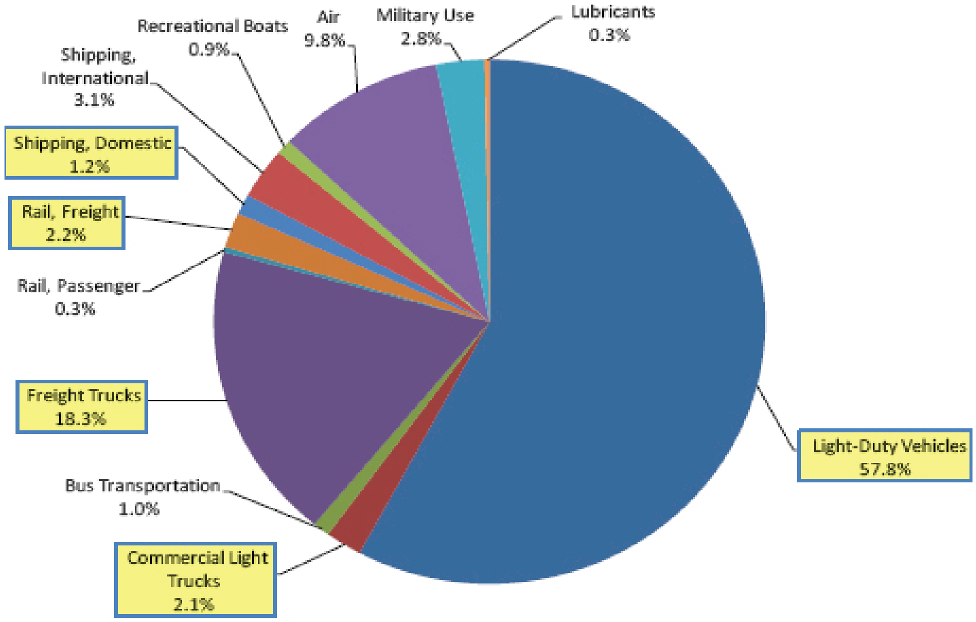
Figure 13-2: Ton-miles by mode (single and intermodal) for the U.S. in 2007



Source: Derived from BTS 2007b

Energy is required to move these goods, and most of this energy is derived from fossil fuels that power the fleets of trucks, trains, and ships employed in freight operations. This fuel consumption has had a large impact on GHG emissions in the United States. Driven almost entirely by petroleum, the freight sector represents about 25 percent of the GHG emissions from the transportation sector, as shown in Figure 13-3. Since the transportation sector represents about 30 percent of the total U.S. GHG inventory, freight transportation accounted for about 9 percent of total GHG emissions. This is significant, especially given its rate of growth has generally exceeded the overall growth in economic activity. The increasing importance of this sector makes it important to identify ways that allow this sector to serve economic needs most efficiently.

Figure 13-3: Transportation-related carbon dioxide emissions by mode for the U.S. in 2008



Source: Derived from EIA 2009

Modal Comparisons

Different modes of transportation are used for different types of freight services, and the energy-to-work relationships are asymmetric across modes. Domestic ships and trains are often used for long-distance travel greater than 300 miles and for bulk cargo transport services, often when cargo is not time sensitive. These modes are capable of moving the greatest volumes with the least energy per unit work. Trucks are used for shorter trips, time sensitive cargo, and delivery to locations where ship and rail infrastructure is not available. Independently routed trucks, higher speeds, and smaller package densities increase energy required by trucks per unit work relative to bulk transport. Rail can perform similarly to either water modes or trucking, depending on payload densities, distances, and backhaul usage. Airplanes are used typically for time-sensitive shipments where transportation costs are a small percentage of overall cargo value. The additional energy for flight compared to Archimedes principles of floatation or rolling friction make work done by this mode the most energy intensive.

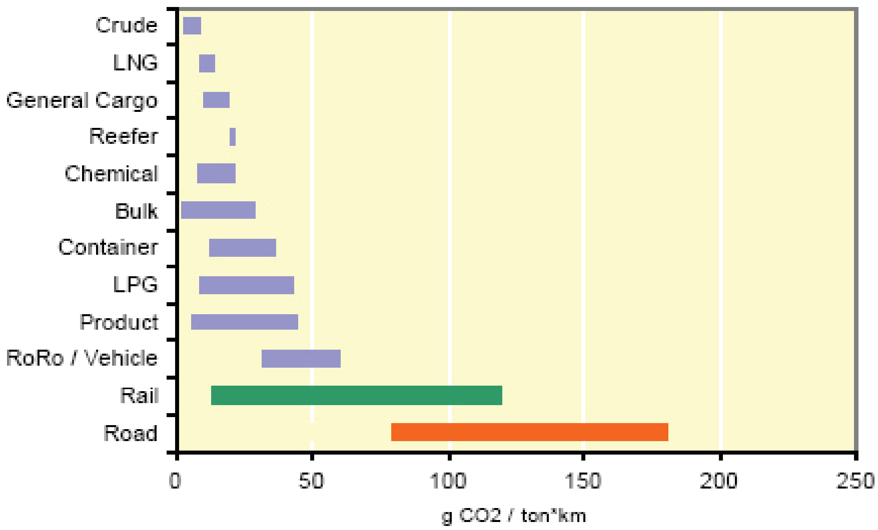
These freight modes have different characteristics dictated by a number of factors, including:

- Technology, for example, types of engines used and emissions control systems
- Fuel quality, including the sulfur, carbon, and energy content of fuel
- Transportation routes, such as gradients and distance
- Transport speed
- Operator behavior, including idling patterns and driving behavior
- Logistics, for example, dwell times and intermodal cargo transfer emissions

National statistics implicitly combine these characteristics, contributing to freight performance comparisons, often ranking trucks highest in surface transportation energy intensity. Using top-down calculations, which is the total annual energy use in a sector divided by total freight services performed, one can derive energy intensities on the order of 3,500 to 4,000 BTU/ton-mile for trucks, and only 350 to 500 BTU/ton-mile for trains and ships (EIA 2009). Air freight energy intensities are an order of magnitude greater than trucking statistics.

These composite comparisons allow for useful generalizations about different transport modes, but there are at least two dangers in using them for conducting modal comparisons for specific shipping events. First, top-down calculations include energy used in moving empty containers, repositioning equipment, and providing services that do not necessarily involve cargo movement. When comparing modes for a specific shipping service, an activity-based approach is recommended that accounts for cargo, logistics and technology characteristics. Figure 13-4 presents carbon dioxide intensities for ships, trains, and trucks derived using a range of activity-based parameters. The ranges show the variability that exists depending on modal, route, and operating characteristics. Figure 13-4 also implies an opportunity for reducing energy consumption and emissions by shifting from high energy intensity modes to lower energy intensity modes.

Figure 13-4: Range of carbon dioxide intensities for various cargo carriers



Source: Buhaug et al. 2008

Second, modal comparisons ignore the inherent complementarities among the modes, mistakenly posing them as simple substitutes. Where the origin/destination pairs do not offer multiple unimodal connectivity, the modes must be combined in an intermodal network. In other words, route-specific barriers and asymmetries may apply to any of the modal efficiencies in Figure 13-4 that result in re-ranking the best-to-least efficiencies by mode.

Route-specific modal comparisons have been explored and illustrated by a team of researchers at the University of Delaware (UD) and the Rochester Institute of Technology (RIT). The Geospatial Intermodal Freight Transportation (GIFT) model is a model jointly developed by the UD/RIT team with support from the U.S. Maritime Administration, the Great Lakes Maritime Research Institute, and the California Air Resources Board, among others. The model connects multiple road, rail, and waterway transportation networks at intermodal transfer facilities using a "hub-and-spoke" concept. Activity-based calculations are embedded in the model, adjustable by the user. Within this intermodal network, the model assigns various economic, time-of-delivery, energy, and environmental attributes to real-world goods movement routes. In this way, network optimization algorithms can be run to determine optimal routing for achieving different objectives, such as least cost, least carbon, and least time (Winebrake *et al.* 2008; Comer *et al.* 2009).

With such a model, the measures of performance improvement to one characteristic, for example, fuel economies, increased transit times, or payload densities, are presented along with coupled changes in emissions, delay, or energy intensity. The GIFT tool is currently being applied to study several dimensions of goods movement performance and is enabling a new context in which to explore freight technology/policy pathways to meet energy, environmental, and economic goals.

Opportunities for Mode-Shifting

There are three-dimensional interactions among fuels, technology, and vehicle miles traveled (VMT) and demand within the LDV sector. This has been a convenient framework for LDVs and has allowed for a simple, yet effective, way of communicating efficiency options to policy makers and the public.

Two key limitations are implicit in this three-dimensional context, however. First, individual driving patterns of citizens are treated as conditionally independent of the infrastructure, and second, routing choices are considered to be somewhat inelastic, for example, mostly ad hoc, discretionary, or commute-related. This has allowed economists and policy makers to identify technology providers as exercising greater influence on LDV fleet performance than drivers, except in regions where modal substitutes exist and where strong price signals are possible. This framework suggests that emissions can be addressed by a combination of fuel improvements, such as low carbon fuels; technology advancements, including more efficient technologies; or VTM reductions through demand management policies.

The freight sector is much different than the LDV sector, and a three-dimensional foundation fails to provide insights into the greater range of options that strong economic coupling makes available for freight sector emissions reductions. Moreover, informing good policy decisions requires that the long- and near-term planning activities by the public and private sectors be reconciled by considering dynamic response among decision drivers.

The IF-TOLD model is a better framework for considering freight options. The letters of this acronym represent the following:

- Intermodalism/infrastructure: employing different transportation modes and infrastructure to improve freight services
- Fuels: burning low carbon or clean fuels
- Technology: applying efficient technologies within each mode
- Operations: using of best practices in operator behavior
- Logistics: improving supply chain management
- Demand: reducing the amount of goods that are shipped, measured in ton-miles

Using the IF-TOLD model, a greater range of opportunities can be identified for improving the efficiency of goods movement. Intermodalism and mode-shifting are often looked upon as providing significant opportunities for emissions reduction in the freight transportation sector (Winebrake *et al.* 2008; NPWI 2004; Janic 2007; Komor, P. 1995; Kreutzberger *et al.* 2003; Patterson, Z. *et al.* 2008; Racunica and Wynter 2005).

Given the lower energy intensity of modes such as rail or ship, conventional wisdom holds that movement of goods from truck to these other modes will greatly enhance the environmental performance of the freight sector. However, although ships and trains tend to be less energy intensive than trucks when measured per unit payload basis, the actual opportunities for system-wide mode-shifting with today's intermodal infrastructure must be evaluated.

The following equation describes the overall energy impacts associated with shifting a set of commodities (k) from one mode (i) to another mode (j):

$$\Delta E_{ij} = \sum_k \left[W_k \cdot c_{ijk} \cdot f_{ijk} \cdot p_{ijk} \left(E_i - E_j \right) \right] \quad (1)$$

Where,

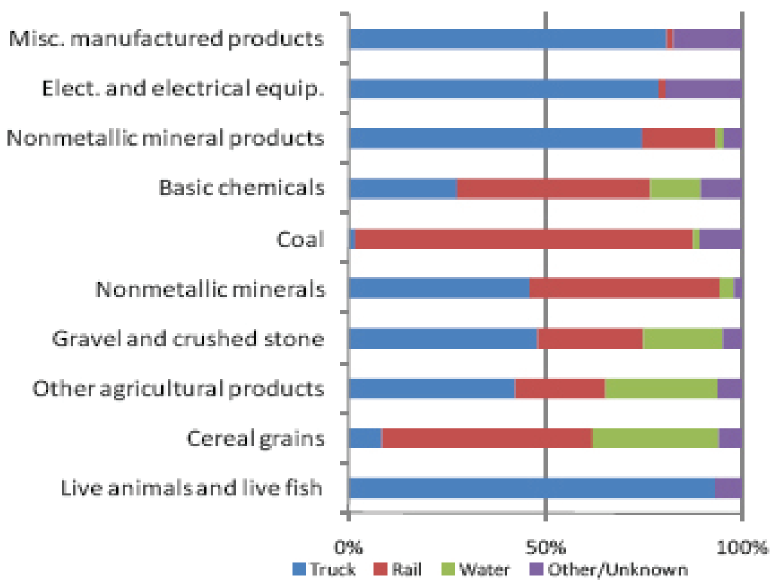
ΔE_{ij} = energy savings due to modal shift from mode i to mode j
W_{ik} = work done by mode i for commodity k (ton-miles)
c_{ijk} = shipment compatibility fraction of i to j for k (cargo)
f_{ijk} = shipment feasibility fraction of i to j for k (infrastructure)
p_{ijk} = shipment practicality fraction of i to j for k (economic)
E_i = energy intensity factor for mode i (Btu/ton-mile)
E_j = energy intensity factor for mode j (Btu/ton-mile)

The Compatibility, Feasibility, and Practicality Fractions

This equation introduces three new parameters that are important: compatibility fraction, feasibility fraction, and practicality fraction. Each represents the fraction of the total goods to be shipped that are affected by cargo compatibility, infrastructure feasibility, and economic practicality.

The cargo compatibility fraction is a reflection of how compatible a given cargo is with a different transportation mode, and whether there are options for consolidation, containerization, and facility location. For example, some commodities are shipped by truck for logistical considerations, such as time-of-delivery requirements associated with livestock transportation, while others must be shipped by train or ship due to the nature of the cargo, for example the shipment of chemicals. Figure 13-5 depicts a sample of commodities and the percentage of ton-miles of those commodities moved by different modes.

Figure 13-5: Percentage of goods movement in the U.S. by commodity and mode in 2002

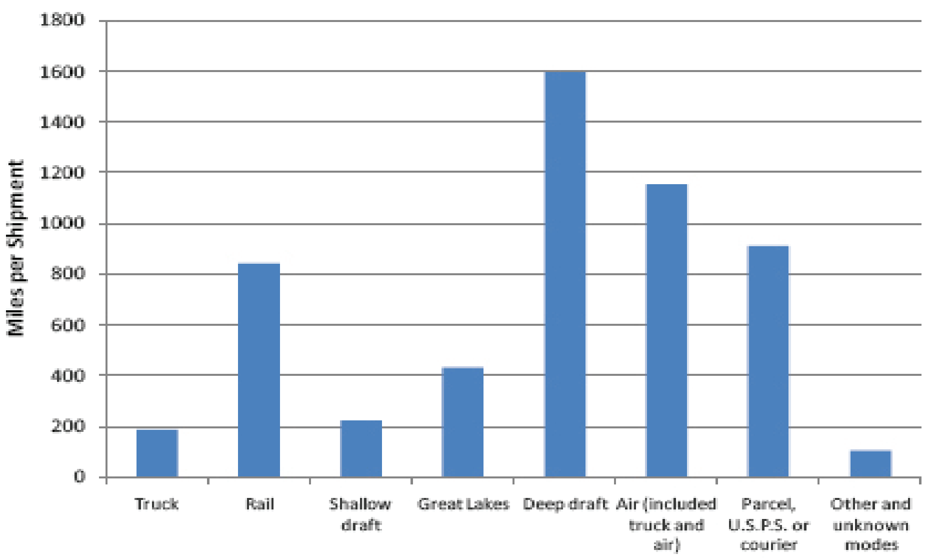


Source: Derived from BTS 2007b

In addition to whether a commodity is compatible with a given mode, the infrastructure must be available to support transport and delivery by one or more modes. Intermodal or multimodal routes are not always available, as some parts of the country do not have adequate rail infrastructure, waterways, or port or railyard transfer facilities that would allow effective mode-shifting. While mostly considered to be a long term and semi-public investment choice, reconfiguration and improvement of transportation nodes and segments can greatly affect the feasibility of intermodal transportation efficiencies.

Lastly, the economics of freight transportation play a significant role in determining whether mode-shifting opportunities exist. To understand the potential role for mode-shifting, consider Figure 13-6, which presents the average miles per shipment for U.S. freight transportation in 2007 by mode. This chart demonstrates that on average, truck transportation is used for shipments of less than 200 miles, while rail is used for shipments greater than 800 miles. These distances are a function of compatibility, infrastructure, and the economics of freight transportation. Of course, operational choices can involve more cost-minimization measures than mode choice. Freight transportation consists of both marginal costs, such as fuel costs associated with moving goods over network segments, and fixed costs, including transfer costs associated with moving cargo from one mode to another mode. Typically, ships and trains have much lower marginal costs than trucks, but vehicle fixed costs for ships and locomotives are higher because of fewer unit sales and larger size. Moreover, the freight-only network embedded fixed costs are much higher because rails and waterways rarely share infrastructure with passenger use. For long-distance transport, the marginal cost advantages of trains and ships offset higher fixed costs and lead to lower average costs compared to trucks. For shorter distances, however, the opposite is true.

Figure 13-6: Average miles per shipment by mode for the U.S. in 2007

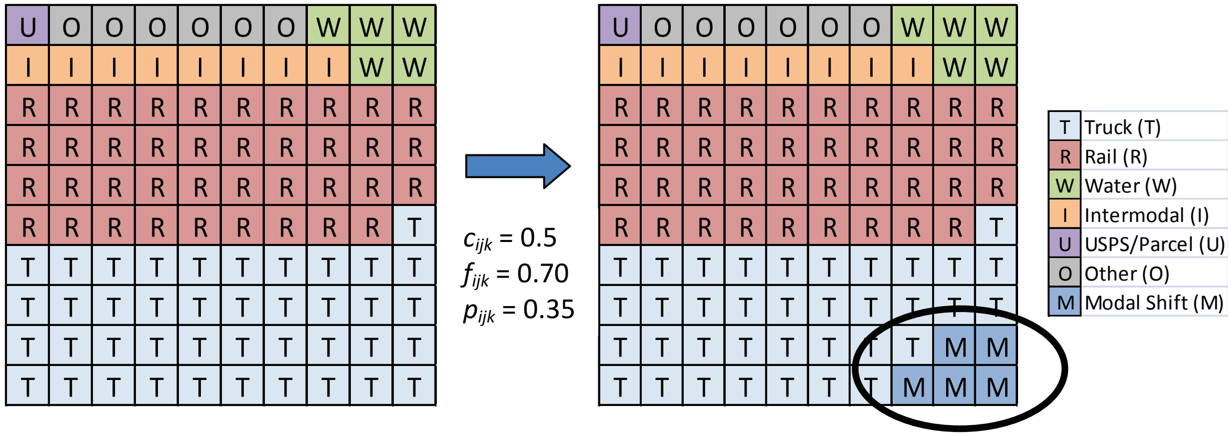


Source: Derived from BTS 2007b

The Potential of Mode-Shifting

Application of Equation 1 demonstrates conceptually the overall opportunity for mode-shifting in the United States. Figure 13-7 depicts a box of 100 cells, each representing 1 percent of ton-miles service in the U.S. freight sector and divided by mode from 2007 data. The lightest shade at the bottom in the figure represents the trucking mode and is the target of the analysis, which is to move freight from truck to some other mode, such as rail or ship. Assuming values for c_{ijk}, f_{ijk}, and p_{ijk} of 0.50, 0.70, and 0.35, respectively, the figure shows how the potential opportunity for truck beginning at 41 percent of the total ton-miles is reduced to a situation where only about 5 percent of the total ton-miles representing 12 percent of truck ton-miles can be moved from truck to rail or ship. If energy intensity of truck is five times greater than rail or ship, then this implies an 8 percent reduction in total energy consumption, certainly not negligible, but much less than would be expected without the compatibility, infrastructure and practicality constraints on the system.

Figure 13-7: Estimation of mode-shifting potential for the U.S.



Policies for Promoting Efficiency

The opportunities for mode shifting identified above cannot be achieved without creating different signals to industry. These can be "invisible hand" signals as fuel prices rise, the cost of inventory falls, and consumption changes result from recession or boom years. More relevant may be the policy choices to commit to energy and environmental goals not currently priced in the market, through policy instruments.

A wide variety of policy mechanisms are available to provide incentives or disincentives within the IF-TOLD context, as shown in Table 13-1. This table provides each element of IF-TOLD in columns, and a set of common policy instruments in rows. Cells are identified where a particular policy instrument may directly influence the behavior within an IF-TOLD element. For example, emissions or efficiency standards may improve modal performance of the most polluting or energy-intensive modes to achieve targets without mode-shift through the application of control devices; economic instruments, including taxes, may

Table 13.1: Cross matrix of policy instruments and IF-TOLD framework elements

Transportation Policies	*Intermodalism*	*Fuel*	*Technology*	*Operations*	*Logistics*	*Demand*
Policy Instruments	I	F	T	O	L	D
Performance standards	•	•	•			
Taxes	•	•	•	•	•	•
Subsidies	•	•	•			
Technology mandates			•			
Infrastructure Investment	•				•	
R&D investment		•	•			
Alternative/low-carbon fuels		•	•			
Size/weight restrictions	•			•	•	
Operator training/education				•		
Demand management					•	•

have greater potential to influence all decisions within the IF-TOLD context, offering choice in meeting performance goals through multi-attribute optimization. More research to evaluate the effectiveness of different policy instruments on the freight transport system could access the IF-TOLD rubric for how to structure those analyses.

Conclusion

The goods movement sector in the United States is highly correlated with economic activity. As such, it is expected that freight transportation will continue to grow with the economy. With this growth comes the responsibility for an increasing energy and environmental burden, mostly due to the high energy intensity of certain modes, especially trucks, and system characteristics. Options exist to reduce this energy consumption, and this chapter presented some ideas on the potential of mode-shifting as one possible approach. However, the freight system benefits of mode-shifting are limited by factors not considered previously and will vary depending on vessel, vehicle, locomotive, and route characteristics.

In addition to mode-shifting, there are other ways to improve the environmental performance of freight transport, captured in the IF-TOLD framework discussed above. Importantly, achieving energy and environmental goals will require policy makers to look at the freight sector as a system of different modes operating under asymmetric constraints even where there may be common objectives. The IF-TOLD framework is one useful way to explore policy options, enabling better application of research designs, such as wedge analyses, to describe the role new policy decisions might play.

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