Estimating the CO₂ Intensity of Intermodal Freight Transportation

Anthony J. Craig*
Engineering Systems Division
Massachusetts Institute of Technology
77 Massachusetts Ave, E40-261
Cambridge, MA, 02139, USA
E-Mail: tcraig@mit.edu

Yossi Sheffi
Engineering Systems Division
Massachusetts Institute of Technology
77 Massachusetts Ave, E40-261
Cambridge, MA, 02139, USA

Edgar E. Blanco
Center for Transportation & Logistics
Massachusetts Institute of Technology
77 Massachusetts Ave, E40-276
Cambridge, MA, 02139, USA

*Corresponding author
Estimating the CO$_2$ Intensity of Intermodal Freight Transportation

Anthony J. Craig$^{a,*}$, Edgar E. Blanco$^b$, Yossi Sheffi$^a$

$^a$Engineering Systems Division, Massachusetts Institute of Technology, 77 Massachusetts Ave, E40-261, Cambridge, MA, 02139, USA

$^b$Center for Transportation & Logistics, Massachusetts Institute of Technology, 77 Massachusetts Ave, E40-276, Cambridge, MA, 02139, USA

Abstract

Greenhouse gas emissions from transportation represent a significant and growing amount of total global emissions, with road freight among the fastest growing areas. Modal shift from road to rail is one of a number of proposed strategies for reducing emissions, and intermodal transport offers shippers an attractive alternative to truckload service. Unfortunately little data is available to shippers to calculate the potential savings of a modal shift. In this paper we analyze a data set of more than 400,000 intermodal shipments to calculate the CO$_2$ intensity of intermodal transportation as a distinct mode. We compare our results to a publicly available intermodal emissions calculator and apply the market area concept to explain the variance between individual shipments. The results provide useful guidance for shippers to estimate the potential reductions through modal shift and identify areas for intermodal operators to improve service.

Keywords: Intermodal freight transport, Carbon intensity, Greenhouse gas emissions, Market area

1. Introduction

The transportation sector is a significant contributor to global greenhouse gas emissions and energy usage. Transportation as a whole accounts for 19%...
of global energy use (IEA, 2009). In the US, with the largest transportation footprint, the sector represents 28% of total greenhouse gas emissions. The IEA predicts emissions from transportation to grow by 50% by 2030 and by 100% by 2050 from 2007 levels (IEA, 2009). The EIA predicts similar high growth, with energy consumption rising by 39% by 2030 and 92% by 2050 from 2006 levels (EIA, 2011).

Within the transportation sector freight is expected to experience the fastest growth. Freight accounted for 27% of transportation energy use globally in 2006 (IEA, 2009). In the United States it represented 28% of transportation energy use, or 8% of overall energy use. Freight is expected to grow by 30% by 2050, compared with 20% for the sector as a whole. This growth is not a new development, as emissions from transportation have been increasing for the past 30 years. From 1973 to 1992 emissions and energy use from freight grew faster than any other sector in an analysis of 10 industrialized countries (Schipper et al., 1997). This growth has continued despite pledges by many nations to reduce emissions under the Kyoto Protocol. Canada committed to a 6% reduction of emissions below 1990 levels by 2012, but total emissions rose by 17% by 2009. This includes a 35% increase in the transportation sector, and a 91% increase in emissions from Heavy Duty Diesel road vehicles (Environment Canada, 2011) The struggle to meet this target led Canada to announce it’s withdrawal from Kyoto, citing an estimated $14 billion in penalty costs (Austen, 2011). Emissions from transportation have risen even for countries on track to meet their Kyoto targets. Sweden committed to a reduction of emissions to 8% below 1990 levels, and planned to stabilize transportation emissions at the 1990 level by 2010 (Foden, 2007). Despite achieving an 11% reduction in total emissions from 1990 levels Sweden did not meet the transportation goal, as emissions rose by 9% from 1990 levels by 2010 (EEA, 2011).

The high rate of growth in freight emissions is caused primarily by road transport. Truck transportation is responsible for 90% of freight energy use globally (IEA, 2009) It accounts for more than 60% of the total freight transportation emissions in the United States, moving 40% of all goods by weight, and more than 80% by value (Greene and Plotkin, 2011). Since 1991 road transportation has grown at an annual rate of 3.3% in the EU-15, outpacing all other modes of transport (Blauwens et al., 2006). As countries grow and become more industrialized the increasing shipment of intermediate and final goods results in more use of trucks due to the increased flexibility they offer (Schipper et al., 1997). The growth of freight and share of trucking are cou-
pled with GDP growth, with practices such as increased international trade, “just in time” practices, e-commerce, and handling of intermediate goods contributing (Kamakate and Schipper, 2009). This coupling of economic growth with increased road transportation has significant implications for emissions growth in developing markets, with the vast majority of emissions increases by 2050 coming from non-OECD countries (IEA, 2009).

Given the projected growth in demand for freight transportation a number of strategies for reducing emissions must be considered. Possible approaches can be grouped into three categories: improved technological efficiency, improved operational efficiency, and shifting to more efficient modes (Vanek and Morlok, 2000). Much of the work in the technological and operational efficiency has been devoted to the trucking industry, as trucking represents the largest share of emissions as well as having a relatively high intensity (Vanek and Morlok, 2000). However, the increase in demand for trucking has overshadowed any improvements in transport intensity. Over a 20 year period from 1973-1992 road transport energy intensity remained relatively level, increasing by only 2% in the U.S. and EU-8, while the intensity of rail declined by 41% in the U.S. and 23% in the EU-8 during that timespan (Schipper et al., 1997). Given the high levels of emissions associated with trucking even small improvement in efficiency are likely to have a significant impact compared with modal shift due to the difficulty in shifting significant amounts of freight from road to rail (McKinnon, 1999). Other projections are more optimistic regarding the role of modal shift in emissions reductions. The Pew Center on Global Climate Change identified modal shift as having the greatest potential for reducing emissions in the United States, with 5% of the possible 7-10% reduction in emissions achievable by 2030 being the result of improved logistics. This is in comparison to a reduction of only 2% possible through improvements in vehicle technology (Greene and Plotkin, 2011). The IEA’s Blue Shift scenario projects a reduction of 15% in GHG emissions from the baseline scenario by 2050 due to modal shift from road to rail. When combined with the Blue Map scenario’s improvements in efficiency (25% reduction) and the use of advanced fuels (15% reduction) this achieves a 50% reduction in emissions from the baseline scenario (IEA, 2009).

Reducing emissions through modal shift are achieved mainly through the shift from road transportation to rail. The relative energy efficiency of rail is estimated at two to five times that of trucking, with even the largest trucks being only half as efficient as rail (Schipper et al., 1997). GHG emissions intensities have a similar relationship; with trucking producing twice the
amount of emissions that rail does over the full life cycle (Horvath, 2006). Despite the efficiency benefits of rail a number of factors prevent a significant shift from road to rail, including the high level of service required by modern supply chain practices (Kamakate and Schipper, 2009), access to rail terminals (McKinnon, 1999), and capacity constraints on the railroads (Vanek and Morlok, 2000).

Road-rail intermodal is one popular method for shifting transportation from road to rail, offering shippers the convenience of point-to-point service like trucking combined with the efficiency gains from rail. Despite worries about capacity constraints intermodal rail units increased by 63% between 1993 and 2005 (Association of American Railroads, 2006). Bitzan and Keeler (2011) estimate that a shift of only 1% of current intercity truck freight to intermodal could generate savings of 0.92-2.18 Tg of CO\textsubscript{2} per year, an amount equal to 24-56% of the total possible savings available by urban public transit. Thus, while a modal shift to intermodal freight may replace only a small amount of current truckload freight traffic it is increasingly popular with shippers and can provide benefits on par with other popular policy measures.

Despite the popularity of intermodal as an alternative to trucking there is relatively little information regarding the actual efficiency of intermodal in comparison to other modes (Bitzan and Keeler, 2011). In this paper we attempt to fill this gap in the literature with an analysis of a large data set of intermodal shipments in North America. We compare the results of this analysis with estimates obtained using a publicly available carbon calculator targeted towards shippers and assess the relative efficiency of intermodal in comparison to truckload. In the second part we apply the market area concept to the carbon efficiency of intermodal shipping to explain the difficulty in assessing an overall efficiency for it as a mode. From these results we identify opportunities for intermodal operators to work with shippers to reduce emissions.

2. Literature Review

2.1. Intermodal

In addition to increased popularity with shippers, intermodal transportation has increased as a topic of research (Bontekoning et al., 2004). In a review of the literature on intermodal research Bontekoning et al. (2004) identified eight areas of research. Five of the eight categories focus on issues related to the characteristics of an intermodal shipment, including work on
drayage, rail hauls, transshipment, standardization, and multi-actor chain and control. Two other areas of research identified by Bontekoning et al. (2004), mode choice and pricing strategies and intermodal transportation planning and policy, have generated interest in the role of intermodal transportation in reducing greenhouse gas emissions.

At the policy level much of the analysis for the potential of modal shift have been focused on a macro approach suitable for estimating the potential in a given region, but not at a specific company level (Tsamboulas et al., 2007). In order to provide useful information for shippers and operators at the micro level it would be useful if more relevant data were provided by the actors involved (Bergqvist, 2008). Bitzan and Keeler (2011) noted this lack of available information on the overall efficiency of intermodal when attempting to estimate the potential for a modal shift in US. When attempts have been made to model emissions from intermodal transportation they have generally considered the rail and road segments separately, rather than as a single intermodal movement. Bauer et al. (2009) formulate a service network design problem with a goal of minimizing total greenhouse gas emissions and allowing the use of truck or rail in the network. Janic (2007) considers a simplified intermodal network in comparison to a road network in a model that includes both internal costs and external costs related to air pollution, noise, congestion, and traffic accidents. Patterson et al. (2008) estimated emissions savings from premium intermodal service in the Quebec City-Windsor corridor by calculating truck and rail distances using geocoded locations and then applying emissions factors specific to each mode to estimate emissions. Winebrake et al. (2008) use a Geographic Information System (GIS) approach to model a network using road, rail and water based on geographic data. Their model introduces “artificial” intermodal nodes that connect different network segments, with each network segment having attributes for time, distance, cost, energy, and emissions. Kim et al. (2009) use a multi-modal hub and spoke network that incorporates CO$_2$ emissions for different modes and at transshipment points. They solve a multi objective optimization under different constraints on CO$_2$ emissions to find the pareto optimal solution to the tradeoff between cost and CO$_2$ under a variety of scenarios in a simplified network.

In each of these cases the emissions from the intermodal shipment were calculated by breaking the shipment to its individual road and rail components. This approach is in contrast to the general perception by shippers that intermodal is its own distinct mode. A number of survey approaches
have been used to identify characteristics of intermodal transportation as a mode choice for shippers. Harper and Evers (1993) surveyed manufacturers in the state of Minnesota regarding their use and perception of intermodal service, while Evers et al. (1996) focused on the factors that influenced the perceptions of intermodal compared to truck and rail service. Ludvigsen (1999) surveyed retailers, manufacturers, and forwarders in several Nordic countries. Tsamboulas and Kapros (2000) surveyed large shippers in Europe that make use of intermodal transportation to create a simulation model of mode selection. These survey results have generally shown that shippers view intermodal as providing better service than rail, but worse than truckload (Bontekoning et al., 2004).

Considering the road and rail segments of intermodal separately has the advantage of more accurately accounting for the rail network during evaluation, but comes at an increased level of complexity required to account for all the possible nodes and links in the network (Macharis et al., 2011). In some cases the two approaches may be combined, by first using a detailed network representation to create a set of virtual links that connect the origin and destination, each by a different combination of modes, routes, and equipment (Beuthe et al., 2001). Such a network could have direct links between origin and destination nodes that represent an intermodal shipment (Macharis et al., 2011). Blauwens et al. (2006) use a total logistics cost model that includes transportation costs and inventory costs to explore potential shifts between modes under different policy options. They compare road transport with rail/road and barge/road intermodal. Each option is considered a distinct mode with an associated cost and lead time. While this approach may more closely resemble the decision made by the shipper it first required a case study to determine the cost and lead times of the different modes. Given the lack of publicly available information regarding the carbon efficiency of intermodal as a distinct mode such approaches may be difficult to implement.

2.2. Carbon Measurement Programs

A number of programs exist that provide standards for estimating the greenhouse gas emission from freight transportation (Hoen et al., 2010). Two of the most popular are the GHG Protocol standard and the NTM calculator. The GHG Protocol is the result of a partnership between the World Resources Institute (WRI) and the World Business Council of Sustainable Development (WBCSD). According to their website the GHG Protocol is the
most widely use accounting tool for greenhouse gas emissions, and the basis for nearly every GHG standard and program in the world. The Network for Transport and Environment (NTM) is a non-profit organization located in Sweden with a goal of establishing a base of values for calculating the environmental performance of transportation, and offers a calculation method among its services.

The GHG Protocol (WRI, 2011) provides two sources for the emissions factors, one from the Department for Environment, Food, and Rural Affairs (Defra) for the U.K. and one from the Environmental Protection Agency (EPA) for use in the United States. The EPA factors were created for the EPA’s ClimateLeaders program, and employ a top down methodology to calculate emissions factors by mode (EPA, 2008). Total emissions by mode are estimated from data provided by the EPA’s national greenhouse gas inventory (EPA, 2007). The total emissions are then divided by the estimated ton-miles carried by the mode using data from the Federal Highway Administration (FHWA, 2005). This produces an emissions factor in terms of kg of CO$_2$ per ton-mile for each of the major freight modes: road, rail, water, and air.

The emissions factors provided by Defra (2010) are similar, but more comprehensive than those supplied by the EPA. Emissions factors for road are supplied for a number of different equipment types within the mode. The methodology makes use of survey data to estimate fuel efficiency and average loading factors by equipment type. These two pieces of data are then combined to calculate an emissions factor in kg of CO$_2$ per tonne-km for each equipment type. For rail service Defra relies on statistics collected by the Office of Rail Regulation on total consumption of diesel and electricity by freight trains and the total freight moved for trains operating in the UK. The total CO$_2$ is calculated from the diesel and electricity consumption, and this is divided by the total tonne-km of freight to produce the final emissions factor.

The NTM methodology takes a different approach than those used by the EPA and Defra, relying instead on a bottom up simulation approach. For road NTM makes use of the ARTEMIS emissions modeling software to estimate the fuel consumption of a variety of vehicle types under different load factors and scenarios (NTM, 2010). For rail transport NTM uses data based off the EcoTransit model that estimates electricity and fuel consumption for trains under different weight and terrain types (NTM, 2008). The model accounts for transmission and conversion losses in electricity, generation tech-
Table 1: Carbon Intensity by Mode (g CO\textsubscript{2}/ton-mile)

<table>
<thead>
<tr>
<th>Mode</th>
<th>GHG Protocol (Defra)</th>
<th>GHG Protocol (EPA)</th>
<th>NTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road (light truck)</td>
<td>863</td>
<td>269</td>
<td>368</td>
</tr>
<tr>
<td>Road (medium truck)</td>
<td>490</td>
<td>269</td>
<td>258</td>
</tr>
<tr>
<td>Road (tractor + trailer)</td>
<td>126</td>
<td>269</td>
<td>92</td>
</tr>
<tr>
<td>Rail</td>
<td>31</td>
<td>23</td>
<td>29</td>
</tr>
</tbody>
</table>

Despite the difference in methodology the end result available for use in calculating emissions is similar across all methods. Users may enter the weight and distance of shipments, and a standard emissions factor per ton-mile is used to estimate total emissions. Some of the relevant emissions factors from the different methodologies are shown in Table 1. While each of the methods provides emissions factors for use with either road or rail transport none of the programs provide factors for intermodal. The distance methods available in both the GHG Protocol and NTM require knowledge of the specific routing of the shipment that the shipper may not possess.

The lack of methods available for calculating emissions from intermodal transportation represents a challenge to shippers when deciding whether to shift from truckload to intermodal. The standard multi-modal models used for most mode choice problems require knowledge of the routing, cost, and emissions within the intermodal network that may not be available to shippers. In their survey Harper and Evers (1993) reported that a high percentage of intermodal shipments were arranged through a third party. Macharis and Bontekoning (2004) identify four types of operators that may be involved in an intermodal shipment: drayage, terminal, network, and intermodal. Bontekoning et al. (2004) noted that the majority of mode choice models used in intermodal research have been focused at the level of these operators. Even models identified by as being targeted towards decision support for shippers, such as those of Barnhart and Ratliff (1993), Bookbinder and Fox (1998), and Min (1991), make use of models based on single mode routing along a
The intermodal operator is responsible for buying services from the drayage, terminal, and rail network operators (Macharis and Bontekoning, 2004). They coordinate the shipment and have visibility to each leg of the journey. Thus, current carbon calculation methods are sufficient for intermodal operators to include emissions in the mode choice decision. This is not the case for the shipper, where intermodal offers a distinct mode of shipment, different from either road or rail. The details and routing of the shipment are often handled by a third party, and the shipper often has only limited information regarding the actual routing. To include greenhouse gas emissions in their mode choice decision shippers require the ability to calculate the emissions from intermodal with only limited information, but relatively little data on the overall efficiency of intermodal as a mode is available. Vanek and Morlok (2000) used a simulation model to calculate the likely energy efficiency of intermodal to be in the range of 1200-2320 BTU/ton-mile. This would correspond to a carbon intensity of approximately 88-170 g CO\textsubscript{2}/ton-mile. The International Road Transport Union studied 19 routes in Europe, and estimated the average primary energy consumption of intermodal to be 20-50% less than trucking, with emissions savings at a slightly higher rate (IFEU and SGKV, 2002).

3. Methodology

A number of different definitions of intermodal transportation have been used in the literature, with no clear consensus having emerged (Bontekoning et al., 2004). Jones et al. (2000) identify the use of multiple modes of transportation to provide a single, seamless journey as a primary concept in their definition. These concepts capture the relevant factors for our research. To the shipper, who has the goods requiring movement, an intermodal shipment provides a single movement from origin to destination. The exact modes and intermediate routings are not important, as mode is judged on overall qualities such as speed, service, and cost. In this paper we limit our focus to the movement of freight through a combination of rail and trucking, which is a common use of the term intermodal (Taylor and Jackson, 2000; Spasovic and Morlok, 1993; Nierat, 1997; Harper and Evers, 1993; Evers, 1994; Nozick and Morlok, 1997).

We define an intermodal shipment to consist of an origin drayage movement performed by truck that takes the shipment from the origin location
to the origin ramp. At the ramp the shipment is transferred to rail and a linehaul between the origin and destination ramps occurs. At the destination ramp the shipment is transferred back to a truck and a destination drayage movement delivers the shipment to the consignee at the final destination. This is depicted in Figure 1.

We calculate the carbon footprint of an intermodal shipment by disaggregating the shipment into separate drayage and rail movements using 1.

\[
C_{1M} = d_{od} \times c_d + d_r \times c_r + d_{dd} \times c_d
\]  

(1)

where:

\begin{align*}
    d_{od} &= \text{distance of origin drayage} \\
    d_{dd} &= \text{distance of destination drayage} \\
    d_r &= \text{distance of rail haul} \\
    c_d &= \text{carbon efficiency of drayage} \\
    c_r &= \text{carbon efficiency of rail}
\end{align*}

We applied this method to a data set supplied by J.B. Hunt Transportation, the largest intermodal operator in North America. The data consisted of records for more 400,000 individual intermodal shipments covering more than 40,000 origin-destination lanes (grouped by zip code) in North America. Each record contained the locations of the origin, origin ramp, destination
ramp, and destination; the length of the origin and destination drayage; and the length of the rail haul. Additionally, the operator supplied a carbon efficiency parameter for drayage based on their own fuel efficiency, empty miles, and out of route miles. The length of the rail haul portion of each movement was provided by the contracted rail companies to the intermodal operator. When this data was not available the rail distance was calculated with the RailMILER commercial software program. The rail carbon efficiency parameter was calculated using efficiency numbers supplied by the rail companies per ton-mile. This value was then multiplied by the average weight of the intermodal shipments, including equipment, to get an efficiency parameter in terms of CO$_2$ per mile.

The calculation of the carbon footprint of an intermodal shipment in this manner is straightforward, but may be difficult for shippers to calculate in practice. Without knowledge of actual routing the relative distances of the drayage and rail haul movements are unknown. The respective carbon efficiency parameters, expressed in terms of CO$_2$ per unit of distance, can be estimated from sources such as the GHG Protocol. However, drayage movements tend to be less efficient than standard trucking due to age of equipment (Ang-Olson and Facanha, 2008) and higher empty miles (Spasovic and Morlok, 1993). The use of standard road emissions factors for both trucking and drayage will tend to overestimate the actual efficiency of intermodal shipments compared to trucking. Rail carbon efficiency numbers are generally given in units of CO$_2$ per ton-mile. These can be converted to distance based factors through a straightforward multiplication of the factor by the shipment weight, but the weight must be adjusted based on the type of equipment used.

These difficulties can be illustrated through a comparison of the calculation of the carbon footprint using actual operator data to a publicly available tool that makes use of limited information. The EPA’s SmartWay program provided a method for calculating the carbon footprint of intermodal shipments as part of their original SmartWay FLEET calculator. The tool is designed to help shippers estimate the potential savings of switching shipments from truck to intermodal. The calculator takes as parameters the distance between the origin and destination and the mix of rail service used (average, mixed freight, double stack, or trailer on flat car). Optionally users can provide specific information on drayage distance, shipment weight, and the percentage of empty drayage miles. The calculator provides an estimate of the carbon footprint of the shipment if moved by intermodal transport,
as well as by truckload. This allows the shipper to compare the results and calculate the savings achieved by switching from truckload to intermodal shipments.

The carbon footprint from the calculator was obtained by using the default values for drayage distance, drayage efficiency, and assuming 100% average rail service. Distance was calculated between the origin and destination by first geocoding the zip codes to latitude and longitude values using ESRI’s ArcGIS software. Next, the distance between the latitude and longitude points was calculated using the haversine great circle distance formula given by:

\[
D = r \times \left\{ 2 \arcsin \left( \sqrt{\sin^2 \left( \frac{\Delta \phi}{2} \right) + \cos \phi_o \cos \phi_d \sin^2 \left( \frac{\Delta \lambda}{2} \right)} \right) \right\} \tag{2}
\]

where \( \phi_o, \lambda_o, \phi_d, \) and \( \lambda_d \) are the latitude and longitude of the origin and destination locations and \( r \) is the radius of the Earth.

The results from the calculations for both the operator data and the SmartWay calculator are shown in Table 2.

From these results we can see that the SmartWay calculator underestimates the total CO\(_2\) by 30% compared to actual data. The large difference in emissions from drayage is mainly due to the SmartWay calculator significantly underestimating the number of drayage miles driven in practice. The SmartWay tool calculates total drayage miles using (3) where \( D \) is the distance between the origin and destination locations.

\[
drayage = 40 + \left( \frac{D}{400} \right)^2 \tag{3}
\]

This produces an average drayage distance of only 57 miles, with a maximum of 86 miles for a shipment with a great circle distance of 2,718 miles. In contrast the operator data shows the average total drayage distance to be
146 miles. The difference in rail CO\textsubscript{2} is driven by a lower rail circuity factor (20% to 27%) and higher estimated fuel efficiency (15 MPG to 13.8) for the SmartWay calculator.

In order to provide a comparison to other modes of transport we calculate the carbon efficiency of the intermodal shipments by dividing the total CO\textsubscript{2} emissions by the total number of net ton-miles worth of goods moved. Total net ton-miles were calculated by multiplying the shipment weight (excluding equipment) by the great circle distance between the origin and destination for each individual shipment, then summing the total for all shipments. By using the direct distance between origin and destination rather than the actual traveled distance we provide a consistent basis for comparing shipments across modes which have different amounts of circuity.

In addition to the calculated intermodal CO\textsubscript{2} we also include for comparison the estimated CO\textsubscript{2} for serving those same lanes by truckload service. The truckload calculations are again performed using both operator supplied data and the original SmartWay FLEET calculator. Calculations for the operator’s truckload emissions are based on data collected from their longhaul trucking business and are calculated using the follow equation:

\[
CF_{TL} = (d_{otr} + d_{ae}) \times c_{tl} \tag{4}
\]

where:

- \(d_{otr}\) = over the road distance
- \(d_{ae}\) = average empty distance per shipment
- \(c_{tl}\) = carbon efficiency of truckload transportation

The distance between the origin and destination zip codes is calculated using software that determines the actual over the road travel distance, eliminating the need to adjust the great circle distance using a circuity factor. The average empty miles is a fixed quantity based on dividing the total empty miles traveled by the number of shipments. Finally, the carbon efficiency factor is based on the actual fuel efficiency of the operator’s vehicles, an adjustment for out of route mileage variance, and the carbon content of diesel fuel.

The SmartWay calculator uses a slightly different method for estimating truckload emissions, given by:


\[
CF_{SWTL} = \left( d_{od} \times d_c \times \left( 1 + \frac{d_e}{1 - d_e} \right) \right) \times c_{swtl} \quad (5)
\]

where:

- \(d_{od}\) = straight line distance from origin to destination
- \(d_c\) = circuity factor adjustment
- \(d_e\) = percentage of empty miles
- \(c_{swtl}\) = carbon efficiency of truckload transportation

The SmartWay calculator provide default values for the circuity factor of 1.15, the empty miles as 20\%, and the carbon efficiency calculated by using a factor of 74.5 g CO\(_2\)/ton-mile and an assumed weight of 22 tons. The calculated emissions from intermodal shipping, truckload shipping, and the resulting efficiencies are shown in Table 3.

From these results we can see that while the SmartWay and operator intermodal calculations lead to significantly different results the estimates for truckload shipping are fairly consistent. When compared with data for other modes available from sources shown in Table 1 we can see that the calculated intensity of intermodal shipping fits in the expected range, with both calculation approaches showing a higher intensity than rail but lower than trucking. The estimated emissions from truckload shipping are consistent with estimates from other sources. Our calculated intensity falls below the range estimated from Vanek and Morlok (2000), but the estimated savings when compared to trucking are consistent with the average range found in by the IRU (2002).

Recall that the emissions from intermodal shipping can be broken up into three parts—the origin drayage, the rail linehaul, and the destination drayage movement. The drayage movements are generally considered to be less efficient than truckload shipping, while the rail haul is more efficient.
Table 4: Summary of Calculated CO₂ Intensity by Lane (g CO₂ per ton-mile)

<table>
<thead>
<tr>
<th></th>
<th>Operator</th>
<th>SmartWay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>29</td>
<td>47</td>
</tr>
<tr>
<td>Mean</td>
<td>72</td>
<td>49</td>
</tr>
<tr>
<td>Maximum</td>
<td>308</td>
<td>67</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>15</td>
<td>1.8</td>
</tr>
</tbody>
</table>

For the overall shipment to be more efficient than truckload the length of the linehaul must be long enough to make up for the lower efficiency of drayage and the increased circuity of the rail network compared to the straight point-to-point service provided by truckload shipping. Thus, on a specific shipment the actual efficiency of using intermodal transportation can vary depending on the actual distances involved for each of the three parts.

To show this variation we calculate the intensity of the intermodal movements on a lane-by-lane basis. Each lane is defined as a distinct origin-destination zip code pair, more than 40,000 of which are represented in the data set. For each lane the intensity was calculated by dividing the total CO₂ for the lane, as calculated using (1), by the total net ton-miles of cargo shipped. As a comparison a similar analysis was done using the SmartWay calculator. A summary of the results from this analysis is shown in Table 4. The distribution of the operator’s lane-by-lane intensities is shown in Figure 2. Due to the assumptions in the SmartWay calculator the calculated intensity shows a limited variation from the average value, with more than 99% of lanes falling within the range of 45-55 g CO₂/ton-mile.

From the results we can see that the actual intensity for a given lane can vary significantly, and in some cases the carbon intensity may actually be higher than if truckload shipping had been used. This is not true for the results from the SmartWay calculator, where no lane shows a greater intensity than if served by truckload and the calculated intensity always falls within a narrow range. This creates difficulty for shippers considering switching from truckload to intermodal, as there is considerable uncertainty about how much carbon savings can be obtained by switching individual lanes. In the next section we further examined the competitiveness of intermodal versus truckload shipping through the concept of the intermodal market area, and show how this concept can be used by intermodal operators to help shippers identify the lanes best suited for intermodal shipping.
Figure 2: Intermodal Carbon Intensity by Lane
3.1. Carbon Market Area

The reason for the lane-by-lane variance can be explained through the application of market area theory to intermodal transport. Nierat (1997) describes the market area of intermodal transportation as the region of space around a rail terminal in which intermodal transportation is the most competitive mode. The space is defined around a rail terminal because an intermodal shipment requires a fixed threshold cost to first be moved to the terminal via the origin drayage and rail line haul. The total cost to reach the destination is then this fixed cost plus the cost of the drayage move from the terminal to the final destination. This cost increases as the destination moves away from the terminal due to the longer drayage move at the destination. If the destination is too far from the terminal it may no longer be competitive to use intermodal transportation, instead a direct truckload shipment between origin and destination would be used.

A depiction of the choice faced between intermodal and rail is shown in Figure 3. The shipment begins at point A and is destined for point M. If the shipment is sent via intermodal it is first sent to the origin terminal by drayage truck and then to the destination terminal, point B, by rail. This represents the fixed cost portion of the shipment, as regardless of the where M is located the shipment must first be taken to point B. From B to M the final movement is again made by drayage truck. If the shipment is instead sent by truck it travels directly from A to M. The intermodal market area
for terminal B defines the range of space around B where M can be located and served more competitively by intermodal service than direct truckload shipment.

Formally Nierat (1997) defines this service area by calculating the costs for each shipment in the following manner. The cost to reach point M by road, defined as $C_r(M)$, is a combination of a fixed cost, $C_r(A)$, and a variable cost per unit of distance, $\omega_r$. The intermodal cost, $C_i(M)$, likewise consists of the fixed cost required to reach B, $C_i(B)$, plus a variable cost per unit of distance from B to M, $\omega_i$. The boundary of the market area can be found by setting the two costs equal to one another.

$$C_r(M) = C_i(M) \iff C_r(A) + \omega_r AM = C_i(B) + \omega_i BM$$  \hfill (6)

Rearranging the terms and substituting $\omega = \frac{\omega_r}{\omega_i}$ and $k = \frac{C_i(B) - C_r(A)}{\omega_r AB}$ gives the equation as:

$$AM - \omega BM = k AB$$  \hfill (7)

The parameter $\omega$ represents the relative cost of drayage operations to standard road trucking. When $\omega > 1$ the market area will have an oval shape oriented along the direction of travel from A to B. We note the similarity between the method used to calculate the cost of road and intermodal transportation by Nierat (1997) and our previous method for calculating the carbon footprint of shipments sent by those methods. With this in mind we extend this idea by defining the carbon market area of an intermodal terminal as the region of space around an intermodal terminal that can be served from a given origin with lower carbon emissions than by truckload transportation.

Recall that the carbon footprint of a truckload shipment is calculated using the following equation:

$$CF_{TL} = (d_{otr} + d_{ae}) \times c_{tl}$$  \hfill (8)

In this equation $c_{tl}$ and $d_{ae}$ are fixed quantities based on the operator’s actual efficiencies. If we define $C_r(A) = d_{ae} \times c_{tl}$, $\omega_r = c_{tl}$, and $d_{otr} = AM$ this equation becomes identical to the form used by Nierat (1997) to calculate the cost of truckload shipping.

Similarly, the carbon footprint of an intermodal shipment is calculated by:

$$C_{IM} = d_{od} \times c_d + d_r \times c_r + d_{dd} \times c_d$$  \hfill (9)
By defining $C_i (B) = d_{od} \times c_d + d_r \times c_r$, $BM = d_{dd}$, and $\omega_i = c_d$ this expression also becomes identical to the one used by Nierat for the cost of intermodal shipping. With those substitutions in place we can then rewrite the equation in the following form to describe the carbon market area for terminal B:

$$d_{otr} - c_{tl} \frac{d_{dd}}{c_{tl}} = \frac{d_{od} \times c_d + d_r \times c_r - d_{ae} \times c_{tl}}{c_{tl}}$$  \hspace{1cm} (10)

Unlike Nierat (1997) we consider shipments that do not originate at the origin terminal. For any given origin location we can find the carbon market area a destination terminal by first finding the origin ramp location that produces the minimum emissions to reach B. Once the origin terminal is found the expression on the right hand side is fixed. By simplifying the calculation of the over the road distances as $d_{otr} = d_{gc} \times c$, where $d_{gc}$ is the great circle distance between the origin and destination and $c$ is the road circuity factor, this again produces an oval region oriented along the line from the origin to the destination terminal. The carbon market area then provides an explanation for why the carbon efficiency of intermodal shipments varies on a lane-by-lane basis. For any given origin location only destinations that fall within the carbon market area of a terminal will produce lower emissions than truckload transportation. The use of an overall average fails to capture the location dynamics that affect the actual efficiency. Given the difficulty in accurately estimating emissions from intermodal shipping, even when an overall average efficiency is known, this represents an opportunity for operators to provide a service to shippers through their knowledge of the network. By applying the carbon market area theory intermodal operators can help shippers identify which lanes should be switched to intermodal.

The operator can then calculate not just the candidate locations, but the magnitude of the potential savings as well. The magnitude of the savings is necessary in order for shippers to properly tradeoff the carbon footprint of the shipment with the other criteria of the decisions, such as the cost, transit time, and service level. At any point within the market area the reduction in the carbon footprint is given by:

$$CF_{TL} - CF_{IM} = ((d_{otr} + d_{ae}) \times c_{tl}) - (d_{od} \times c_d + d_r \times c_r + d_{dd} \times c_d)$$  \hspace{1cm} (11)

Viewing the potential savings as contour lines surrounding the destination terminal we get a shape like that shown in Figure 4. The shaded oval
surrounding the terminal represents the carbon market area where emissions from intermodal are lower than those of trucking. The potential savings from intermodal increase as we move closer to the terminal, and the contour lines mark the regions with savings corresponding to 200, 400, and 600 kg CO₂.

Plotted in the x-y plane with the magnitude of the savings along the z-axis this produces the shape shown in Figure 5 for the carbon market area. The savings peak at the location of the destination terminal, and decrease as the destination moves away from the terminal. The savings decrease at a higher rate as the destination moves closer to the origin location.

The shape is the result of the intersection of two cones. The first, giving the carbon footprint associated with a truckload shipment, takes on a minimum value of \( C_r(A) = d_{ae} \times c_{tl} \) at the shipment origin and increases with a slope of as \( c_{tl} \) the destination moves away from the origin. The second cone, giving the carbon footprint of the intermodal shipment, takes on a minimum of \( C_i(B) = d_{od} \times c_{cd} + d_{r} \times c_{cr} \) at the destination terminal, and increases with slope \( c_{cd} \) as the final destination moves away from the terminal. Viewed in cross section along the line between the origin and destination.
Figure 5: Carbon Savings of Intermodal Switch

terminal the savings represent the difference between the two lines shown in Figure 6. This differs from other attempts to gauge the competitiveness of intermodal, such as the break-even approach used by Morlok and Spasovic, in that intermodal may be less competitive as the destination moves farther from the terminal, even as the distance from the origin increases.

Limbourg and Jourquin (2010) applied the intermodal market area concept to a hub and spoke network design problem, noting that a single terminal may have several overlapping market areas for shipments originating from different locations. Applying a similar idea we examine the case of a single origin having multiple markets around various destination terminals. Consider a shipper needing to move goods from an origin facility to a network of distribution locations. With the origin fixed the intermodal operator can determine the carbon market area for all of the possible destination terminal locations. Each destination terminal will have a carbon market area of different size and orientation, or possibly no market area at all. By identifying destinations that fall within the carbon market area of a terminal the operator can identify candidate locations for a switch from trucking to intermodal.

Evaluated across the entire intermodal network the operator is able to
identify the potential savings for any destination by selecting the mode and terminal that produce the lowest emissions. An example is shown in Figure 7. In this figure we show the potential savings for a shipment originating at a terminal location in Los Angeles by evaluating a network destination terminals. The threshold level of emissions required to reach each destination terminal from the origin is first calculated. Then the emissions required to reach a grid of destination points is calculated for intermodal shipments routed through each destination terminal, as well as a truckload shipment from the origin. The potential intermodal savings are calculated by finding the destination terminal that produces the lowest emissions to reach the final destination using an intermodal shipment, and this result is compared with the estimated truckload emissions. Finally, the map is created using ESRI’s ArcMap GIS software and applying interpolation to estimate the savings for all areas of the map. The figure demonstrates many of the results from the carbon market area concept. In general the savings tend to increase for destinations further from the origin, as the efficiency of the long rail haul increases the potential of intermodal. However, the savings are also dependent on the distance from the terminals and the direction of travel, giving rise to several distinct oval shaped regions of higher potential savings surrounding
Figure 7: Potential Intermodal Carbon Savings from Los Angeles

- a terminal and oriented along the direction of travel. As the destination moves away from the terminal the savings are reduced, even as the length of the journey may increase. A significant area in the Western portion of the United States does not fall within any carbon market area, due to the relatively short distance of the rail haul and the lack of nearby terminals.

This concept can be applied to multiple shipment origins, and in Figure 8 we see how the savings look for a shipment originating in Texas. The potential savings at any destination can be significantly different from that shown in Figure 7 due to the difference in origin location and length of rail haul. The areas of greatest potential savings now occur on both the West and East coast, while the region outside of any market area occurs in areas around Texas. Due to the shorter length of rail haul from an origin in Texas the
magnitude of possible savings are also reduced, as no destination provides as much savings as can be obtained by using intermodal to ship from Los Angeles to the East coast.

Based on the idea of the carbon market area we can see that the use of average efficiency values can be misleading when choosing between modes of transport. The actual efficiencies are dependent on a number of factors, including the origin and destination locations, the relative efficiencies of different modes of travel, and the design of the intermodal network.

4. Conclusions

Greenhouse gas emissions from transportation represent a major share of global emissions. Further, increased demand for freight transportation
and increased freight transportation intensity are associated with increases in GDP. This has significant implications for the future growth of emissions in both developed and emerging markets. Modal shifts towards more efficient modes of transportation is one approach to slowing or reducing this growth of freight transportation emissions, with intermodal representing an attractive option for shippers looking to combine the convenience of point-to-point truck service with the efficiencies of rail.

In this work we presented a method for calculating the overall efficiency of intermodal in comparison to standard truckload transportation. Our results confirm the assumption that intermodal transport provides a service that improves on the efficiency of truck transportation. The average carbon intensity of intermodal transport is estimated to be 70 g CO$_2$ per ton-mile, 44% lower than truckload. This estimate is lower than the range of 88-170 g CO$_2$/ton-mile based on the work of Vanek and Morlok (2000), but consistent with results from the IRU (2002) that show potential energy reductions of 20-50% compared to trucking. This methodology can have significant benefit to shippers looking to estimate their carbon footprint with limited information, as current standards provide little in the way of published data on intermodal efficiency. Our results show that a current publicly available calculator significantly underestimates the emissions from intermodal shipping in comparison to the actual efficiency achieved by an operator.

The SmartWay program has recognized the need for improved estimates of intermodal intensity, and the recent release of the SmartWay 2.0 tools provides a method for operators to share emissions estimates for intermodal transportation with shippers (EPA, 2012). The new multi-modal tool allows intermodal operators to report data on their overall intermodal performance and receive a score based on emissions per ton-mile. All multi-modal carriers are sorted into bins based on their performance level, and the score reported by SmartWay is based on the midpoint of each bin. Shippers who use intermodal transportation can enter activity data on the number of ton-miles shipped by each operator, and the tool estimates the total emissions using the score of each operator.

Though average emissions intensity information can be useful in estimating the potential of intermodal shipping to reduce emissions we show that intermodal shipping is more efficient than truckload only in a specific area surrounding an intermodal terminal, called the carbon market area. This result has implications for intermodal operators in a number of ways. First, calculating the actual emissions from intermodal shipping is difficult with-
out direct knowledge of the underlying rail and road network. Our results show that actual carbon intensity of intermodal shipping varies from 29-308 g CO$_2$/ton-mile depending on the lane under consideration. This represents an opportunity for intermodal operators to use their knowledge of the system to assist shippers in identifying lanes for a potential shift from truckload to intermodal. Providing detailed information regarding the potential savings can serve as a value added service, and may be useful in growing their intermodal business.

Second, by including the benefits of reduced greenhouse gas emissions the overall attractiveness of intermodal as a shipping mode can be increased. Fuller et al. (2011) provide an example of this when looking at the viability of a new intermodal terminal located in West Texas. Their results show the addition of the terminal has not just a financial benefit, but also an environmental benefit through reduced GHG emissions. When the positive benefits of the emissions reductions are included the overall attractiveness of intermodal as a mode is increased. This has a number of possible implications for other work on intermodal transportation, particularly in the area of terminal locations. Limbourg and Jourquin (2010) previously applied the market area concept to a terminal location problem, noting that traditional methods have failed to account for the actual shape of the market area by assuming a simple circular area. As seen in Figure 8 and Figure 7 the same principle applies to emissions, as the carbon savings vary not just based on distance from terminals, but also the direction of travel. Thus, the carbon market area concept helps identify regions where additional terminals have the greatest possibility of reducing emissions. This applies to operators, who can explore network changes that are most likely to improve service, and policy makers as well. When combined with national freight flows this methodology can be used to identify areas for potential infrastructure improvements to effectively reduce emissions.

5. Acknowledgements

The authors wish to thank J.B. Hunt Transportation Co. for their help and cooperation in this research. This research was partially supported by the Global Leaders for Environmental Assessment and Performance (LEAP) consortium http://leap.mit.edu/.

Ang-Olson, J., Facanha, C., 2008. Comparative evaluation of infrastructure strategies to reduce emissions from intermodal freight movement in south-
ern california. Transportation Research Record: Journal of the Transportation Research Board 2058, 15–22.


