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Environmentally-integrated optimization modeling of intermodal freight transportation: An Application of the I-95 corridor region

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ENVIRONMENTALLY-INTEGRATED OPTIMIZATION MODELING OF INTERMODAL FREIGHT TRANSPORTATION:

AN APPLICATION TO THE I-95 CORRIDOR REGION

Masters in Science, Technology and Public Policy Thesis Submitted in Fulfillment of the Graduation Requirements for the

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Abstract

Freight transportation is essential to economic health in the United States in that it transports all types of goods and materials that support commerce and meet consumer demands. However, the literature strongly suggests that the demand for freight transportation is expected to increase, and at a rate that exceeds the capacities to support such demand. The national highway network was built to accommodate a far smaller national population, and its limited capacity and expansion, coupled with a strong and steady population increase over the last century has borne a myriad of congested highways, increased travel time, increased transportation costs, and significant amounts of harmful air pollutants emitted into the air. Furthermore, the literature also calls for increased inclusion of environmental interactions in transportation decision-making; and this thesis attempts to contribute to that field.

This thesis centralizes on the development of a network flow model that utilizes optimization to achieve minimization of travel time, travel costs, and emissions of six ambient air pollutants associated with freight transportation within the I-95 Corridor Region. This model utilizes the Microsoft Excel application and the Premium Solver Platform, and it enables the model user to utilize the powerful tool of optimization to explore intermodal transportation options that quantify variances in emissions outputs, total travel time, and total travel cost. Furthermore, this model intends to demonstrate that the inclusion of environmental emissions in freight transportation planning is a useful, necessary, and beneficial tool in modern transportation decision-making.

1.0. Background

1.1. Overview of Intermodal Freight Transportation

Freight transportation is essential to economic health in the United States in that it transports all types of goods and materials that support commerce and meet consumer demands. The demand for freight transportation has elevated in response to population increases and expansions in economic activity in the U.S. and abroad. The Bureau of Transportation Statistics (BTS) (2005) found that the amount of ton-miles of freight via single modes[1] transported rose 32.4 percent from 1993 to 2002, and 12.2 percent for multimodal freight transport in the same time period (2005). Globalization also plays a key role in reinforcing the growth in demand; the Government Accountability Office (2005) has estimated that domestic production paired with international trade will spur a 70 percent increase in freight traffic by the year 2020. This trend in freight transportation activity is expected to continue, and in its wake other issues of concern have emerged and thus intensified.

With much credit due to globalization, modern long-distance freight transportation systems are largely intermodal. Intermodalism, a term sometimes used interchangeably with *multimodalism*, is defined by the Transportation Research Board (TRB) (1998) as “the transport of goods in containers that can be moved on land by rail or truck and on water by ship or barge” (p. 14). Modern intermodalism offers increased flexibility in shipment options because it involves the use of more than one mode to transport goods in containers, thus allowing for better service efficiency. Many logistics providers have transitioned from single-mode transportation to multiple-mode because they recognize that it produces cost savings and other benefits. Furthermore, some state agencies have recognized it as a means of controlling pollution,

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[1] Such as trucks, rail, water, air, and pipeline.

relieving highway congestion, and controlling highway costs (TRB, 1998). Congestion, in particular, is a notoriously chronic and debilitating constraint to ensuring consistent service efficiency.

Congestion is a major cause of delay in transportation, and its presence is apparent in some of the nation's larger cities that lie on Interstate 95 (I-95), a key trade corridor connecting Maine and Florida. In its 2005 Urban Mobility Study, the Texas Transportation Institute estimated that congestion on major highways caused over 112.3 million hours of delay for passenger car and truck drivers in the Philadelphia area, 62.4 million hours in Baltimore, and 8.3 million hours in Richmond (Schrank & Lomax, 2005). Additional travel time incurred by highway congestion also prompts excess fuel consumption, which subsequently drives costs up for highway users. Table 1-1 shows selected cities, all of which are of close proximity to I-95, according to the total travel delay, excess fuel consumed, and congestion cost, as well as their rankings in each category.

Table 1-1. Congestion in Selected Urban Areas Along I-95 in 2003

	Travel Delay[1]		**Excess Fuel Consumed**[2]		**Cost of Congestion**[3]	
Urban Area	*1,000 hours*	*Rank*	*1,000 gallons*	*Rank*	*$ millions*	*Rank*
New York, NY-Newark, NJ	623,796	2	198,217	2	6,780	2
Washington, D.C.-VA-MD	145,484	7	87,567	5	2,465	7
Philadelphia, PA	112,309	10	60,323	15	1,884	10
Baltimore, MD	62,436	17	39,502	16	1,057	17
Jacksonville, FL	16,850	38	10,159	39	285	38
Richmond, VA	8,305	51	4,763	52	140	51
Charleston, SC	6,364	59	3,879	57	107	59
Columbia, SC	2,029	74	1,331	75	34	74

[1] Travel Delay – Travel time above that needed to complete a trip at free-flow speeds

[2] Excess Fuel Consumed – Increased fuel consumption due to travel in congestion rather than free-flow conditions.

[3] Congestion Cost – value of travel time delay (estimated at $13.45/hour of person travel and $71.05/hour of truck time) and excess fuel consumption (estimated using state average cost per gallon)

[4] Out of 85 urban areas that were ranked in this study.

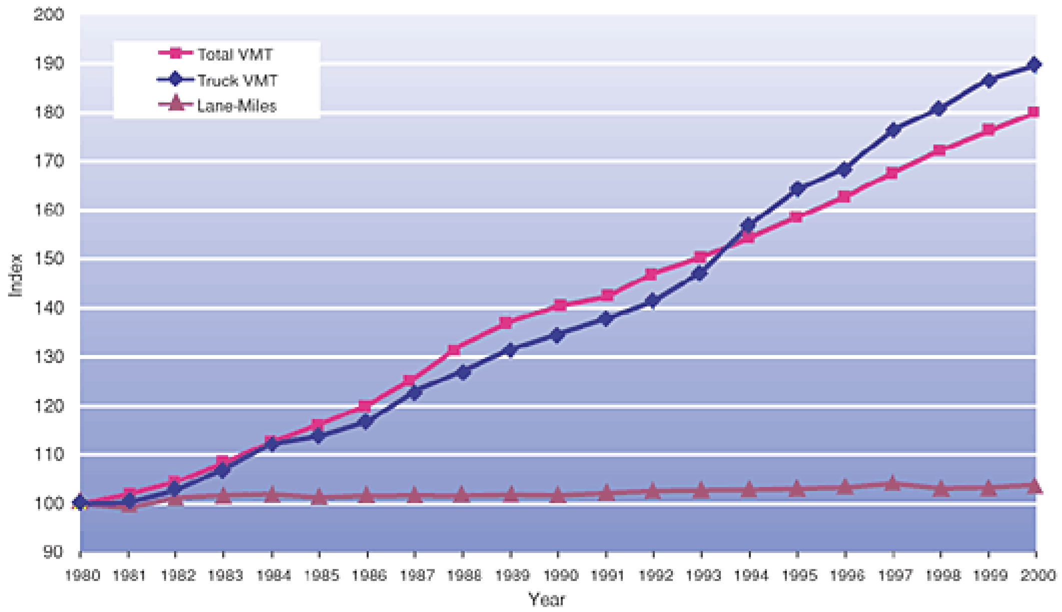
Source: (Schrank & Lomax, 2005, pp. 14-15)

The rise in demand for freight transportation has spurred increased congestion, and such congestion further exacerbates air pollution from engines. In areas of high traffic, engines can spend considerable amounts of time at slow speeds or idling, which translates into wasted fuel and emissions.

The performance of freight transportation services is highly, if not critically, dependent upon highways, which are the prime connectors to rail and port terminals, and distribution centers. Those highways are not expanding at a rate sufficient to support the increase in highway travel. The Federal Highway Administration (FHWA) (2002) indicated that, from 1980 to 2000, the number of truck vehicle-miles traveled (VMT) soared 80 percent, while the number of highway lane-miles increased by only 2 percent. Perhaps more interestingly, regardless of the fact that less than 10 percent of all vehicle-miles of travel is made up of commercial vehicles, the growth rate of truck traffic is more than twice that of passenger traffic (Federal Highway Administration, 2002; Ostria, 2004).

Highway congestion and capacity problems are also strong issues in modern transportation planning. As shown in Figure 1-1, the total VMT from 1980 to 2000 has consistently been above the lane-miles, which indicates that there are more drivers on the highway than the highway is built to support. Figure 1-1 demonstrates that the aggregate amount of highway lane-miles has not increased to support the rapidly climbing total VMT. As the gap widens between the total VMT and total lane-miles, the frequency and severity of congestion intensifies. Hence, highway congestion and capacity problems are important driving forces behind incentives to the research and development of better, more efficient transportation systems.

Figure 1-1. Vehicle-Miles Traveled (VMT) and Highway Lane-Miles: 1980-2000



Source: U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics* (Washington, DC: Various years).

Source: (Sedor & Caldwell, 2002, p. 12)

Commensurate with the rate of overall VMT nationwide, the overall VMT within the I-95 Corridor Coalition[2] region has far exceeded highway capacity. Following a 37 percent population increase within the Coalition region between 1970 and 2004, overall VMT has soared 140 percent in the same time period (Cambridge Systematics Inc., 2005). The population growth spurt also spurred a 34 percent increase in containerized freight movements between 1999 and 2004, resulting in significant mobility, economic, and environmental impacts as recognized by the Coalition (Cambridge Systematics Inc., 2005). Figure 1-2 demonstrates the sharp contrast in annual VMT and annual delay to population and highway mileages.

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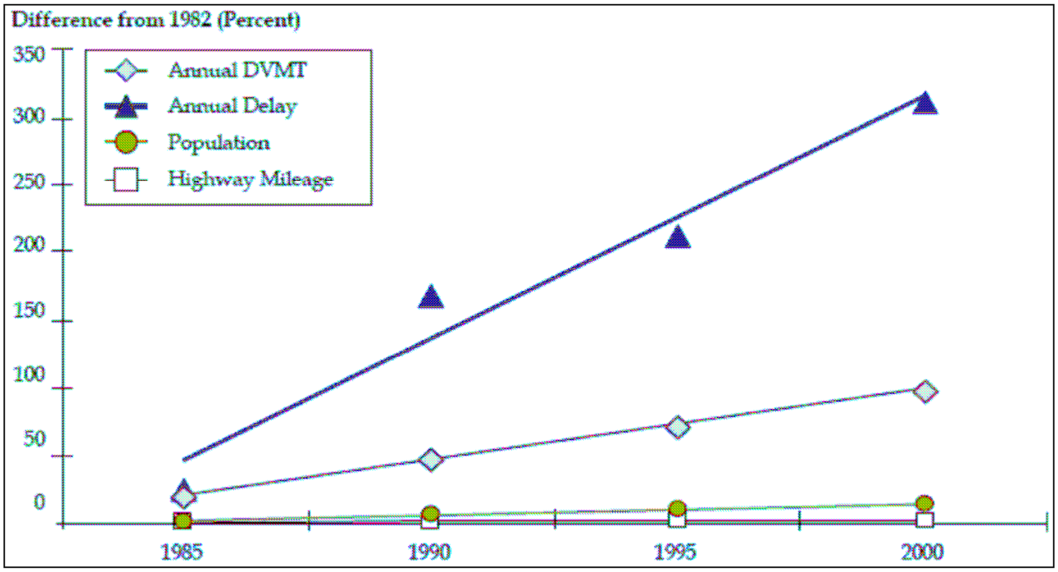
[2] The I-95 Corridor Coalition is an alliance of transportation agencies and related organizations representing Eastern states ranging from Maine to Florida, and its multijurisdictional nature allows for collaboration on improving transportation policies within the region, as well as management and operations. For more information, see *www.i95coalition.org*.

Figure 1-2. Population, VMT, Highway Mileage, and Delay in the I-95 Corridor Region (1985-2000)



Source: (Cambridge Systematics Inc., 2005, Ch. 1, p. 2)

1.2. Emissions from Transportation Sources

Emissions from transportation sources are a major precursor to poor air quality in many regions. A significant amount of air pollution comes from the thousands of diesel-powered heavy-duty trucks, railroads, and ships that transport goods all over the nation, and emissions from diesel engines are a significant source of air pollutants that adversely affect air quality. Air pollutants emitted from freight trucks, rail and ships used in freight transportation include nitrogen oxides (NO_x) and carbon dioxide (CO_2), two common greenhouse gases widely believed to be responsible for the onset of global warming. Other pollutants include volatile organic compounds (VOC) and sulfur dioxide (SO_x), which combine with heat and light to form ground-level ozone and smog. Additionally, particulate matter[3] (PM) and carbon monoxide (CO) are major contributors to illnesses and ailments in humans, including cancer.

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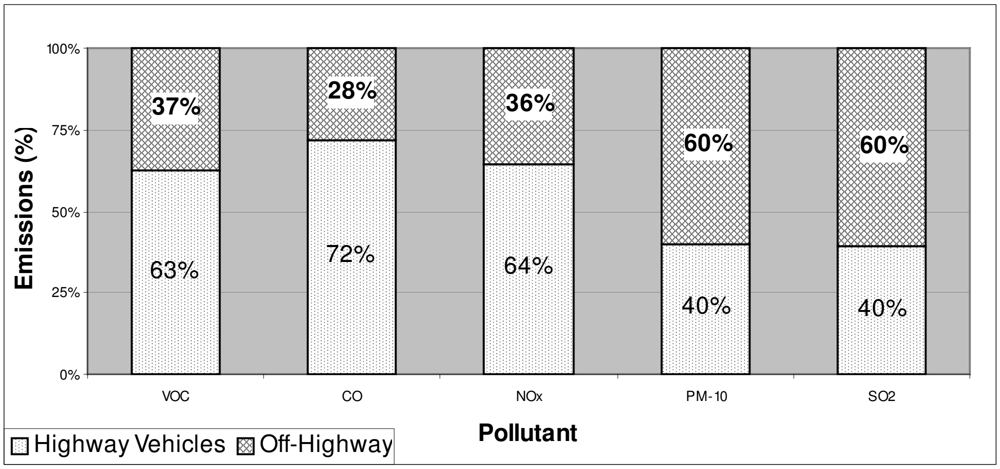
[3] Two categories of particulate matter exist: PM10 are particles that range from 2.5 to 10 micrometers (µm) in diameter and are known as *inhalable coarse particles*, and particles smaller than 2.5 µm are refered to as *fine particles*. For purposes of this paper, all references to PM are to inhalable coarse particles, or PM10.

Gasoline- and diesel-powered cars and trucks make up a significant portion of the national emissions inventory. Figure 1-3 shows the variation in emissions shares between highway vehicles (e.g., diesel trucks and passenger cars) and off-highway vehicles (e.g., marine vessels, railroads, and construction vehicles). Highway vehicles make up the majority of VOC, CO, and NO_x emissions at 63 percent, 72 percent, and 64 percent, respectively. Off-highway sources emit 20 percent more PM_{10} and SO_2 emissions than highway sources, at 60 percent each.

Figure 1-3. Contribution to National Emissions from Mobile Sources, 2002



Source: (U.S. Environmental Protection Agency (EPA), 2005a)

Emissions from freight have been dubbed the “elephant in the corner” in many emissions debates (Massachusetts Institute of Technology & Charles River Associates (MIT & CRA), 2001). The largest increase in emissions rates by any major transportation mode has been attributed to the emissions of carbon dioxide by freight trucks, which increased by 69 percent from 1990 to 2005[4] (EPA, 2007b). Figure 1-4 shows the percentage of greenhouse gas (GHG) emissions (presented as terragrams of CO_2 equivalents) from the freight transportation sector in 2004. Heavy-duty trucks were the largest contributor, with 77 percent, followed by marine

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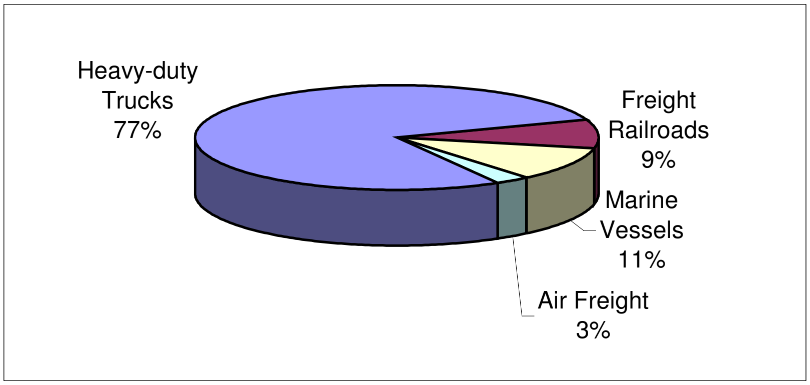
[4] Also, during this time, fuel economy was stable although the number of truck vehicle-miles rose 51 percent (EPA, 2007b).

Figure 1-4. Freight Sector Contributions of Greenhouse Gas Emissions (Tg CO_2 Equivalent)

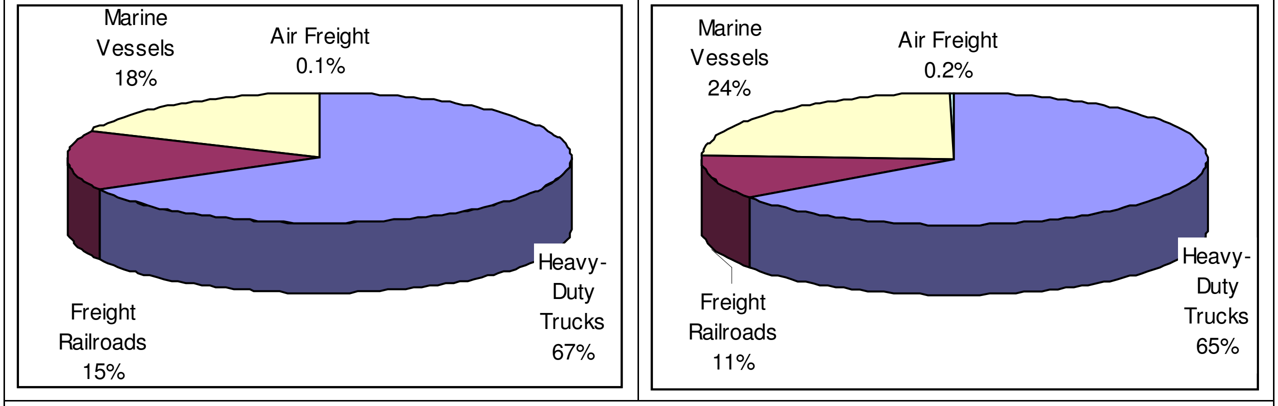


Source: (Cambridge Systematics Inc., 2005, p. 29)

vessels at 11 percent, freight rail at 9 percent, and air freight at 3 percent. Overall, the freight sector is responsible for 24.7 percent of all GHG emissions from transportation sources.

Heavy-duty vehicles make up a large portion of national emissions from freight. As shown in Figure 1-5, heavy-duty vehicles produce two-thirds of total NO_x and PM_{10} emissions. Marine vessels are the second-largest contributor, accounting for 18 percent of freight NO_x emissions and 24 percent of freight PM_{10} emissions. Railroads follow at 15 percent and 12 percent of total emissions, respectively.

Figure 1-5. Freight Sector Contribution of NO_x and PM_{10} Emissions, 2002


a.) NO_x Emissions

b.) PM_{10} Emissions

Source: (Ang-Olson & Ostria, 2005, p. 26)

2.0. Literature Review

2.1. Congestion and Capacity Issues

Two of the most important business assets in a successful freight carrier business are reliability and service predictability. However, capacity constraints, deferred maintenance of highways and railroad networks, rising fuel prices, and other factors are barriers to ensuring just-in-time operations[5], and consequentially, reliability and predictability is compromised (Ortiz et al., 2006). Freight operations are now more susceptible to increased delays and disruptions that cut into the bottom line. This is most notable on highways, where congestion is onslaught by too many vehicles operating on a fixed network.

Highways are not the only transportation mode faced with stressed capacities. The freight rail system is an important link, as it serves both the trucking and shipping industries. An important partnership between the trucking and railroad industries has historically provided the bulk of transportation services, and many states have sought to maximize their utility by researching and implementing strategies to enhance freight rail services in order to offset congestion on highways (American Association of State Highway and Transportation Officials, 2003; Bryan, Weisbrod, Martland, & Wilbur Smith Associates Inc., 2006). However, the rail network in the Northeast region is rendered one of the nation's most complex systems, and investments in rail logistics have been increasing despite the fact that the railroad network is as finite as the highway system, and rail capacity already is showing signs of reaching its maximum (Cambridge Systematics Inc., 2005; Coffey, 2004).

The capacity constraints faced by landside transportation modes, including congestion and capacity issues, are generally less pronounced in waterborne freight. The nation's

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[5] Just-in-time operations is the practice of carrying as little inventory as possible in order to match the demand for a product; this requires a high degree of predictability and reliability in the time and cost required to support such flows (Ortiz et al., 2006). Examples include the automobile industry and laptop computers built to order.

intracoastal waterways remain relatively free flowing, but heavy traffic and bottlenecks are frequent at urban port terminals and harbor entrances (Coffey, 2004), and delays due to congestion on railroads and highways can influence the efficiency of waterborne freight. The lack of reliable arrival of shipments at port terminals can cause further delays, which in turn can cause long lines at port entrances and exits and reinforce further service inefficiencies (Cambridge Systematics Inc., 2005). Thus, attention to the congestion problem is often deflected to the even bigger problem of limited capacity.

It is well documented that the transportation network is running at very near its full capacity; however, the repercussions of elevated demand levels for freight transportation are compounded by current strains on modal capacities (i.e., rail, roads, and ports), and the relatively limited response to expanding those capacities (Ang-Olson & Ostria, 2005; Sedor & Caldwell, 2002; U.S. Government Accountability Office, 2005). The central difficulty is that improving transportation infrastructure to relieve congestion is costly, and time-consuming. For example, FHWA (2002) reported to Congress that the average annual cost to improve the nation's highway and bridges from 2001 to 2020 would be $106.9 billion[6], while the average annual cost of maintenance would be $75.9 billion[7]. In addition to this, Ostria (2004) reports that the cost of transporting freight will increase if investments in infrastructure improvements do not meet the rise in demand. However, expanding and improving highway and railroad infrastructure is a short-term approach and is likely to be "marginal at best;" Flott (2004) suggests that the true challenge is to "find new ways to add freight capacity without relying solely on the existing land-based road and rail systems" (p. 20). This suggests diversification of the freight transportation system, and short-sea shipping has emerged as an alternative to landside transportation.

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[6] In 2000 dollars.

[7] Also in 2000 dollars.

2.2. Short-Sea Shipping and Intermodalism

The potential of short-sea shipping as a means of transporting freight has been increasingly noted for its capacity to offset some of the freight that would otherwise be transported on land and consequently relieve some traffic congestion, and thus, reduce emissions of harmful air pollutants. Unfortunately, analysis on the role of short-sea shipping in freight transportation is limited. In an industry dominated by heavy-duty trucks and freight rail, few studies have evaluated the integration of short-sea shipping in freight operations and its potential effects on transportation systems on the micro and macro levels (Cambridge Systematics Inc., 2005). However, certain regions have peaked interest in short-sea shipping, such as Southern California, and the methods in which short-sea shipping can be beneficial are unique.

2.2.1. Short-Sea Shipping in Southern California

The Port of Los Angeles and Long Beach is a major component in the trade of containerized cargo with Asia, a market that has made the Southern California economy one of the world's largest (Le-Griffin & Moore, 2006). However, the Port of Los Angeles and Long Beach is heavily congested and port capacity is becoming increasingly limited, and the problem is exacerbated by a recent projection that container volume at the Port is to increase three-fold by 2030 (Southern California Association of Governments, 2005). Furthermore, rail and truck infrastructure is worsening, and with zero funding for capacity improvements and opposition by local communities, the Southern California region is faced with serious questions as to how to remain competitive in the midst of a surface transportation infrastructure challenge. In response, the California Department of Transportation evaluated short-sea shipping as a method to offset and relieve congested landside transportation systems (Le-Griffin & Moore, 2006).

Le-Griffin and Moore (2006) also explained in their report that short sea shipping was a viable alternative to landside transportation because short-sea shipping could transport empty containers from overloaded ports to alternative commercial corridors, thereby removing the need for truck trips through congested urban corridors. Furthermore, Le-Griffin and Moore (2006) concluded that short-sea shipping was sufficiently beneficial in that it could enhance the reliability of the regional transportation system, and they recommended further evaluation to implement short-sea shipping into the regional port system.

2.2.2. Short-Sea Shipping in the I-95 Corridor Region

The I-95 Corridor Coalition, an alliance of transportation agencies and related organizations representing Eastern states ranging from Maine to Florida, recently published a report that contained significant insight regarding industry perspectives on short-sea shipping along the Atlantic coast. While some ports utilize short-sea shipping services, such as the Ports of New York and New Jersey and the Port of Albany, some pre-existing issues and conditions exist that hinder the expansion of short-sea shipping services across long distances.

One of the most noted obstacles is a limited understanding of the costs and benefits associated with short-sea shipping. According to interviewees, short-sea shipping would benefit regional highway networks by offsetting some traffic, but it is difficult to quantify the extent of such reductions (Cambridge Systematics Inc., 2005). Furthermore, ports were described as "parochial," with each acting in its own interest, leading to the dominance of larger, more industrious ports (Cambridge Systematics Inc., 2005). With this lack of collaboration, state

DOTs and MPOs are inclined to fund and support individual or nearby ports, as opposed to regional ports (Cambridge Systematics Inc., 2005).

Another notable finding from the I-95 Corridor Coalition interview with short-sea shipping stakeholders is that there is a need for a pilot project to demonstrate that short-sea shipping can be effective. Although many interviewees were familiar with the concept of short-sea shipping, and were interested in learning more about its applicability, interviewees stated that a demonstration project may be necessary to exhibit the feasibility of short-sea shipping, as well as set the momentum for other related projects (Cambridge Systematics Inc., 2005).

2.3. Mitigating Freight Transportation's Impacts on Air Quality

Public and private sector interests in freight transportation and its effects on air quality have heightened considerably in recent years. Consequently, emissions reductions have become a higher priority; a number of technological and operational strategies now exist to mitigate emissions of criteria pollutants as well as to improve energy efficiency of engines.

Technological strategies are targeted at reducing the emissions of vehicles by "intervening with the vehicles being used and the fuels they are burning" (Gorham, 2002, p. 5). This entails the modification or advancement of equipment, such as retrofitting an engine, or altering the type of fuel used, such as adapting to alternative, low-sulfur fuel (Ang-Olson & Ostria, 2005). EPA has recently proposed and implement new, more stringent emissions standards for NOx, PM10, CO, fuel sulfur, and hydrocarbons (HC) for marine diesel engines, locomotives, and heavy-duty trucks. Most of these new standards have already begun to take effect, and freight shippers can accommodate by using technological strategies to reduce fleet emissions (Wachs, 1999).

Operational strategies are aimed at reducing engine emissions by changing how trucks, rail, and ships operate, and examples of such methods include reduced highway speeds, refraining from taking excessive, lengthy, or circuitous routes, or engine idling time (Ang-Olson & Ostria, 2005). Operational methods can help improve system efficiency, which can alleviate congestion and thus reduce excessive and unnecessary emissions from engine idling. This implies that advance planning and analysis on improving traffic flows, including the evaluation of shortest routes and reducing vessel speed, can impact both congestion and emissions in a beneficial way.

Cost reduction and operating at optimal service speeds are the cornerstones of productivity. Cost reduction has been a key catalyst in the shift towards larger, cheaper, and more efficient vehicles; vehicles that have greater capacity are more fuel-efficient because they are able to carry more in a single trip (MIT & CRA, 2001). Thus, rail is more energy-efficient than trucks, and ships are more efficient than both rail and trucks.

Some studies indicate that shifting freight from trucks to rail would be more economically and environmentally beneficial. For instance, Union Pacific Railroads (n.d.) stated in a white paper that, if 25 percent of the freight transported via trucks were shifted to freight rail by the year 2025, nearly 800,000 tons of air pollution would be spared, as well as 16 billion gallons of fuel saved, and 2.8 billion less hours of travel forsaken on congested highways. Furthermore, Scott and Sinnamon (2006) reported that annual fuel use would be reduced by 3 percent if highway freight within a given city were shifted to rail. Despite such assertions, Greene and Schaefer (2003) explain, “because different modes offer different services in terms of cost, speed, and performance, the differences in energy intensity are greatly reduced when one compares modes based on equivalent levels of service” (p. 37).

To a decision-maker whose top priority is to choose a transportation mode that produces the least emissions, it would be ideal to select the most energy-efficient transportation modes. However, in the realm of freight transportation, shifting freight to more energy-efficient modes is challenging, particularly when speed and cost factors play a major role in logistics decisions (Greene & Schafer, 2003). If transportation costs and general demand are pertinent for the fastest transport possible, then it may be difficult to promote greater use of more energy-efficient modes unless those energy-efficient modes can be cost- and service-competitive (MIT & CRA, 2001). The dramatic increase in double-stack container trains demonstrates this point because their costs and service standards are ideal (MIT & CRA, 2001).

2.4. Overview of Transportation Planning

Freight transportation is a joint enterprise between government and industry. Government controls and manages highways, airports, and waterways and harbors-- the major components of the transportation network. The private sector, or transportation companies, operate on these components and provide services. Government infrastructure and other programs affecting freight must be flexible to match the dynamism of the industry (TRB, 1998). However, transportation planning is often not a collaborative effort between government and the private sector. Three reasons for this exist: (1) the freight sector is generally underrepresented in the planning process, (2) exclusiveness of data exchange within the freight sector and between the freight sector and public transportation agencies, and (3) differences in planning processes.

Freight transportation is a minor constituency compared to passenger transport (Sedor & Caldwell, 2002). In transportation planning, freight is not paid nearly as much attention as passenger travel, and much of the data related to passenger travel is inappropriately used in a freight context. This implicates the need for increased exchange of information, "improved freight data, and the use of quantitative planning tools to assess the needs for and benefits of freight improvements are important mechanisms for fully integrating freight into the planning process" (Sedor & Caldwell, 2002, p. 17).

The freight transportation system is predominantly private, and much of the freight data are confidential and unavailable for purposes of planning and decision-making by other entities. The Bureau of Transportation Statistics, which has been an important force in transportation-related data collection and management, identified important information gaps in freight movements, particularly "insufficient information on international trade, commodity movements for some industries and modes, and on system time, cost, and reliability" (Neumann, 1999, p. 13). The lack of adequate representation prevents the proper evaluation of transportation policy options, which may include infrastructure development, performance monitoring, and congestion mitigation efforts (Neumann, 1999), all of which can benefit efficiency of freight services.

The characteristics of the planning process in the public and private sectors are disproportionate to one another. In the public sector, where funding is public, planning requires the involvement of a wide range of stakeholders, from state and local governments to transit authorities to the general public, and yields a bureaucratic, structured, and lengthy process that can take months to years (Sedor & Caldwell, 2002). Planning within the private sector can take as little as three to six months, mostly because external parties are usually excluded. These different timeframes further complicates collaboration in creating more effective transportation policies. Despite these differences, representation of the freight sector in the transportation industry has markedly improved in the last two decades.

2.5. Freight Modeling Relative to Passenger Modeling

Transportation planning is largely demand-driven. Although travel demand is a portion of the freight transportation planning process as a whole, its representation is a vital determinant of improvements in logistics planning and relevant policies, particularly pertaining to infrastructure investments (Pendyala, 2002). Thus, many models are developed to forecast and measure demand, oftentimes with commodity flow data. As previously mentioned, much of the principles of modeling done on behalf of the freight sector has been according to that of passenger modeling.

Research on freight mobility is greatly unsurpassed by the research in passenger modeling. On the metropolitan, state, and national levels, the scope of tools and methods of data collecting, travel forecasting, and evaluation and tradeoff analyses is much more prevalent in passenger travel than for freight (Neumann, 1999). Among the several cited reasons for this, the lack of freight-related data is most prevalent. Available data are aggregately published to maintain confidentiality of freight shippers (Tatineni & Demetsky, 2005) and as a result, public access of such data is restricted.

Many MPOs and state transportation planners have nonetheless relied on alternative sources of data for their freight modeling efforts. Most frequently used is commodity flow data, which details the characteristics of the commodities being shipped out from economic sectors, used especially in modeling of transportation demand. Other data sources include employment and land use data, and vehicle inventory and use surveys, shipper and receiver surveys, as well as warehouse and terminal site surveys (Pendyala, 2002). Furthermore, the dynamics and characteristics of freight transportation are innately more complex than passenger transportation, which adds to the relative complexity of freight systems modeling.

2.6. The Four-Step Model Structure

Many of the transportation forecasting models used today embody the four-step model structure, which encompasses four components of transportation: trip generation, trip distribution, mode choice, and trip assignment. The four-step model structure is a fundamental concept in passenger modeling, and to some degree, successfully applied in the field of freight modeling. In the context of freight modeling, the four step process includes the following, as described by Barth and Norbeck (1996), de Jong, Gunn, Walker, and Widell (2001) and Marcial Echenique and the WSP Group (2002):

- *Trip Generation:* In trip generation models, the objective is to define the total magnitude of travel activity in a zone or region. The goal is to identify the drivers behind the production and attraction of these trips, and estimate the economic activity based on demographic variables. Economic data and input-output tables are used to estimate the quantity of each commodity that is produced and consumed in each geographic unit in the model.
- *Trip Distribution*. Distribution models determine the commodity flow between origins and destinations; that is, essentially determining how much of the commodity is transported to— and from— which locations (e.g., intermodal terminals, distribution centers) according to trade flows determined by the trip generation portion of the four-step model.
- *Mode choice/modal split*. In modal split, or mode choice models, portions of the commodity flow are distributed and allocated to modes (e.g. trucks, rail, combined transport, inland waterways).

- *Trip assignment*. Once the commodity flows have been measured and allocated to modes, they are assigned to routes or networks.

Freight modeling requires the inclusion of certain factors in logistics operations that are not necessarily relevant to passenger transportation. Such components include the diverse characteristics of freight shipments (e.g., shipment size, value, perishability), the diversity of the decision-makers (e.g., shippers, receivers, carriers), and the different prices for service as negotiated in individualized contracts (Jong, Gunn, Walker, & Widell, 2001; Tatineni & Demetsky, 2005). For these reasons, in many cases it is not appropriate to directly apply the principles of passenger demand modeling on that of freight.

2.7. Applications of Freight Models

Current literature boasts a myriad of transportation models that are of microscale nature, most of which focus on a particular entity or mode, but they can generally be classified in two groups. In a review of European, Australian, and North American freight models, freight models in the U.S. were broadly classified as typically being commodity flow models used at the state and national level, and urban roadway congestion models used by urban planners to study economic competitiveness and efficiencies (Marcial Echenique & Partners & WSP Group, 2002). There are a number of states, including Kansas and Wisconsin, that use forecasting models to predict commodity flows through their states in order to predict infrastructure use and the intensity of commodity flows via trucks (Cambridge Systematics Inc., COMSIS Corporation, & University of Wisconsin-Milwaukee, 1996).

The complex and dynamic nature of freight transportation logistics makes it difficult to collect and manipulate data into a single, all-in-one model. Many MPOs and state DOTs have created sets of models that operate as a cohesive and iterative system that ultimately functions as a strategic planning tool (Amekudzi & Meyer, 2005; Crainic, 2002). Many states have developed or adopted forecasting models for purposes of measuring commodity flows, and planning for capacity and operational efficiencies. Many of those transport demand models are not stand-alone models; they are instead linked to passenger demand models (Pendyala, 2002). The following sections present examples of such models.

2.7.1. Puget Sound Regional Council Travel Demand Forecasting Model

The Puget Sound Regional Council (PSRC) travel demand forecasting model is a set of models purposed toward economic forecasting, land use forecasting, vehicle availability, trip generation, distribution, mode choice, and trip assignment— the elements of the four-step concept—as well as a time-of-day model (Cambridge Systematics Inc., 2006). Although the PSRC model is primarily passenger-based, the PSRC developed a distinct, although integrated, forecasting model for commercial trucks, called the FASTrucks model. In this model, the PSRC recognized that modeling truck trips required using economic data that seeped beyond the passenger route network. To address this, the FASTrucks model produces measures of consumption and production rates, disaggregated by truck type (e.g., light, medium, heavy) and employment category. Furthermore, the model integrates passenger and freight truck trips by using a conversion factor to equalize truck volumes and speeds with passenger vehicles, which contributes to forecasting effects on capacity and congestion in the region.

2.7.2. Freight Modeling in Florida

In Florida, intermodal freight connectivity is a noted priority, and state transportation planners have recognized the need to study the operational efficiency of its highways within proximity of its major seaports. In response, Al-Deek, Klodzinski, El-Helw, Sarvareddy, and Emam (2002) developed a network flow model, derived from components of other simulation and trip generation models, to forecast the influx of freight trucks on intermodal connectors in the Ports of Tampa and Cape Canaveral in Florida. The model used actual traffic volume data in both ports and on its highway feeder routes to simulate and forecast freight activity in a five-year period. Average travel time and average delay time estimates were used. Although the state of Florida has an extensive modeling toolbox, it does not have a model component for freight. The Florida Statewide Model Task Force has stated their intentions to research and develop a tool that can model freight activity compatibly with its other models (Florida Statewide Model Task Force Blue Ribbon Panel, 2002; Pendyala, 2002).

2.8. Multimodal Transportation Modeling

Although multimodalism is recognized as having significant potential in alleviating transportation's most pressing problems, only a few state studies have addressed multiple modes and how multimodalism can contribute to a more streamlined freight network system. In transportation decision-making, Neumann (1999) implies that improved tools (e.g., models) for comparing tradeoffs between multiple modes are critically needed. Even so, no state has reported developing a statewide freight forecasting model for a single mode other than trucks—and intermodal pairings, such as truck-rail or ship-rail were not addressed (Horowitz, 2006). The lack of attention to intermodal freight as an integrated system in statewide freight models is a significant hindrance to effectively creating well-formulated transportation policies (Surface Transportation Environmental Cooperative Research Program Advisory Board (STEC), 2002, p. 27). Absent the knowledge of how intermodalism can contribute to air quality improvement efforts, cost savings, or a more streamlined shipping and delivery system, freight transportation planning remains rather limited. The same may be said regarding environmentally integrated transportation models, which will be discussed in upcoming sections.

2.9. Environmentally Integrated Transportation Modeling

2.9.1. State of the Practice

In every aspect of transportation—whether it is the actual transport of goods, the unloading and loading of such goods, or in infrastructure improvements, every decision made therein has a consequence on the environment (CH2M HILL, 2000). In current practices, there is significant variation among consulting firms and MPOs pertaining to the research on freight transportation impacts on the environment, particularly air quality, and such research is rendered scarce and scattered (STEC, 2002; Wachs, 1999). Although at varying degrees, environmentally integrated decision-making in the transportation arena is a perpetually strengthening presence in state DOTs and MPOs. While many agencies remain traditional in the sense that they address environmental issues as an externality rather than as an integral component of a system, some states, such as California and Florida, have emerged as leaders by making environmental stewardship a core presence in the planning, development, construction, maintenance, and operation of transportation projects (Repine, Gerstle, & Wakeman, 2002).

2.10. The Need for a Paradigm Shift in Transportation Planning

Amekudzi and Meyer (2005) discuss two separate paradigms of environmental decision-making: traditional, and sustainable development-oriented. The characteristics, as well as the tools and methods, used in both paradigms are very different because the foundation of science is different in each respect. For the sake of better understanding of the traditional planning philosophy and comparing it to the more modern, and more ideal, paradigm, Table 2-1 depicts selected differences relevant to this discussion.

Table 2-1. Comparison Between the Traditional and Sustainability-Oriented Planning Processes

Characteristic	Traditional Process	Process Oriented toward Sustainable Development
Scale	- Regional and network level	- Local, state, national and global
Focus of Planning and Investment	- Traffic flow theory - Network analysis - Travel behavior	- Ecology - Systems theory
Government Economic Policies	- Accommodate travel demand - Promote economic development - Enhance system safety - Catch up to sprawl	- Efficient use/management of existing infrastructure - Provide transportation capacity where appropriate (from ecology perspective) - Reduce material consumption & throughput
Focus of Technical Analysis	- Trip-making and systems characteristics between origins and destinations - Air-quality conformity - Benefits defined in economic terms	- Relationships between transportation, ecosystem, land use, economic development and community social health - Secondary and cumulative impacts
Types of Issues	- Congestion - Mobility and accessibility - Macroscale environmental impact - Economic development - Little concern for secondary/cumulative impacts	- Global warming and greenhouse gases - Biodiversity and economic development - Community quality of life - Energy consumption
Types of Strategies	- System expansion/safety - Efficiency improvements - Traffic management - Demand management (from perspective of system operating more smoothly) - Intelligent transportation systems	- Maintenance of existing system - Traffic calming and urban design - **Multimodal/intermodal** - Transportation–land use integration - Demand management (from perspective of reducing demand)

Source: (Amekudzi & Meyer, 2005, p. 17)

The traditional planning processes address discrete units of a system and make decisions that affect those units. However, as previously discussed, the transportation system is no longer a collection of discrete units, and today much of it operates cohesively as a multimodal system. In planning processes oriented toward sustainable development, the interactions of transportation as a system within its environment, such as an ecosystem, is evaluated. As Table 2-1 indicated, multimodalism is cited as one of the types of strategies employed in transportation planning that is oriented toward sustainable development include multimodal transportation.

Current literature urges for increased utilization of systems thinking in environmentally integrated transportation planning. In spite of reasonably well-developed modeling practices in traffic impact studies, air quality conformity analyses, and infrastructure development studies, these models tend to be designed for a single mode. Furthermore, Amekudzi and Meyer (2005) noted that "current literature promotes the closer evaluation of environmental considerations in transportation decision-making, but largely remains mum on the techniques and methods of analyzing these interactions (pp. 15-16). The lack of appropriate tools and best practices that allow for comparison of environmental impacts between modes is well noted and is frequently cited as a need in transportation planning (Amekudzi & Meyer, 2005; Repine, Gerstle, & Wakeman, 2002; STEC, 2002).

2.11. Transportation-Related Emissions and Air Quality Models in Use

The U.S. Environmental Protection Agency (EPA) has been a leader in developing emissions models. One of their better-known developments is the MOBILE6 model, which calculates past, current and future emissions for highway vehicles including passenger cars, trucks, buses, and motorcycles (EPA, 2003). It also allows for the accounting of conditions that influence rates of emissions output from engines, such as ambient temperatures and traffic speeds. Although the MOBILE6 model can be used to evaluate emissions of heavy-duty diesel trucks, MOBILE6 does not include emissions analysis for other transportation modes that are significant contributors of air pollutants, particularly freight rail or barges and container ships. However, the MOBILE6 model has been used as a companion with many other models, such as in the state of Wisconsin, in which the model was used to measure emissions impacts of statewide traffic congestion.

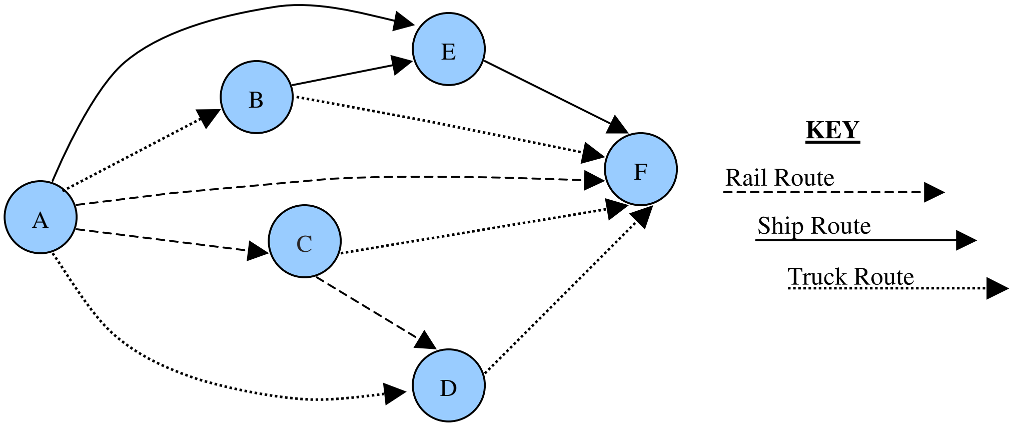
The EPA also produced an emissions model that calculates emissions estimates for nonroad equipment, such as construction equipment, tugboats, snowmobiles, and other recreational equipment. The NONROAD model is versatile in its ability to concentrate on geographical areas, different periods in time, and a range of pollutants (EPA, 2005b). However, the NONROAD model is not equipped to analyze emissions for commercial marine, locomotives, and aircraft, and thus limits the scope of transportation and emissions analysis.

Through the EPA's SmartWay Transport Partnership, freight carriers can use the Freight Logistics Environmental and Energy Tracking (FLEET) Performance Model, a tool that assesses either a trucking or rail carrier's environmental performance with respect to CO_2, NO_x, and PM emissions. The FLEET Performance Model also enables the evaluation of tradeoffs associated with emissions reduction strategies and fuel savings, demonstrating the financial and environmental benefits of reducing their emissions (EPA, 2004).

2.12. Network Optimization Models

Optimization models are often used to plan the operations of a system. A network flow model is a type of optimization model in which the network is a graphical representation of a collection of nodes and arcs, with nodes representing physical locations (i.e., origin or destination cities, distribution centers, etc.), and arcs representing the routes that connect two or more nodes. The use of network optimization modeling allows for the most optimal flow of a commodity according to the maximization or minimization of a decision variable, such as cost, on a multimodal transportation network of any scale, from regional to international (Crainic, 2002). An example of a multimodal network flow diagram is depicted in Figure 2-1. In this network, there are several ways to get from node A (the origin) to node F (the destination) via a single mode or a combination, and the route choice in a network flow model is determined by an objective. In Figure 2-1, the objective is to get from A to F by a series of truck, rail, and ship routes, but one may ask, what's the best way to get from A to F at least cost? Network flow models are plentiful in the realm of transportation modeling because they are useful for assisting decision-making processes and contributing to evaluation and selection of policies. Crainic (2002) offers a thorough review of network design models and the variations in its applications.

Figure 2-1. Example Network Flow Diagram



3.0. Thesis Purpose and Goals

In modern transportation planning, where environmental interactions have earned their place among the top priorities of many decision-makers in the transportation industry, it is now more necessary than ever that analytical tools have the capacity to integrate freight transportation planning with environmental impacts. However, the literature review has indicated that this is not yet the case; many existing freight transportation models do not incorporate environmental factors. The ability to use such a tool would enable decision-makers to make more informed decisions about how to better plan the transport of freight over long distances while maintaining environmental, monetary, and temporal interests. This thesis intends to demonstrate such capabilities, and contribute to paving the way to better, more improved integration of environmental factors into transportation-related decision analysis.

The primary deliverance of this thesis is a spreadsheet model, built with Microsoft Excel, which demonstrates the feasibility and environmental impacts of freight transportation options. This model is designed to mimic a realistic network of rail and waterway freight routes connected to I-95, and it enables the user to explore multimodal transportation options that quantify variances in emissions outputs, total travel time, and total travel cost. Furthermore, this model intends to demonstrate that the inclusion of environmental emissions in freight transportation planning is a useful, necessary, and beneficial tool in evaluating the tradeoffs between, for instance, reducing several tons of harmful SO_x emissions and a few additional dollars in cost.

Short-sea shipping is highly intermodal insofar that it relies on other modes such as railroads and trucks that are locally accessible, and its application to several areas on the East coast has become more frequent. Thus, when applied to the freight transportation industry, a short-sea shipping company may need a transportation model that is inclusive of air pollution, and this model delivers a framework for such application.

Furthermore, the goal is to merge transportation logistics and transportation planning with minimizing environmental pollution—two fields of analysis that have historically remained independent of each other. Ultimately, this type of model will demonstrate that studying the environmental, temporal, or financial tradeoffs of using one freight mode over another is possible, beneficial, and necessitates a higher level of integration in modern transportation planning.

4.0. Model Structure & Data Collection

4.1. Overview

The model, designed with a Microsoft Excel interface, is equipped to perform nonlinear optimization of travel time, travel cost, and emissions of VOC, CO, NO_x, PM, SO_x, and CO_2. The core function of the model is to optimize for a decision objective by performing calculations that yield a combination of nodes and route segments that produce the most optimal scenario according to the objective. The model then produces a trip itinerary listing the details of where and how freight is to be transported, along with other data.

The model is outfitted with two main worksheets: the *Inputs* worksheet, and the *Solver* worksheet. The *Inputs* worksheet is the source of all interchangeable data used in the optimization process, which takes place on the *Solver* worksheet. On the *Solver* worksheet, optimization of travel time, travel cost, and emissions of VOC, CO, NO_x, PM, SO_x, and CO_2 take place. The following section describes the components of the *Inputs* worksheet, the source of the data therein, and the functions in the *Solver* worksheet.

Please note that the Tables and Figures in the following section are the same datasets that are stored on the *Inputs* worksheet (and also in the same order), and in this paper the entire *Inputs* worksheet may be viewed in Appendix A. Furthermore, some of the datasets contain cells shaded in gray; these cells retain sensitive formulas that directly affect calculations in optimization. If altered, calculation errors may occur. The model user can alter data in non-shaded cells only.

4.2. Route Data

Route data is perhaps the most important element of the model. Its components are the building blocks of the models. This is because the selection of certain nodes and routes segments, as well as their distances, are major factors in determining the model outcome, as all are directly related to the travel time, travel cost, and the amount of emissions produced from transporting freight. Route data are stored in the Node Reference List and Master Route List.

The Node Reference List is depicted in Table 4-1 below, and it displays all of the nodes, each attributed by an identifier number, the city, state, and abbreviation. Additionally, the user has the option of blocking nodes; this is done by entering a value of 1 (indicating the node is open) or a value of zero (indicating the node is blocked) in the *Allow Node?* column. These nodes, arranged in a combination of origins and destination nodes, constitute the route segments as shown in Table 4-2.

Table 4-1. Node Reference List

Node	City Abbreviation	City Name	State
1	NYC	New York	NY
2	PHL	Philadelphia	PA
3	WLM.DE	Wilmington	DE
4	BLT	Baltimore	MD
5	RCH	Richmond	VA
6	NFK	Norfolk	VA
7	WLM.NC	Wilmington	NC
8	FLO	Florence	SC
9	CHL	Charleston	SC
10	SAV	Savannah	GA
11	JAX	Jacksonville	NC

The Master Route List, as shown in Table 4-2, contains the characteristics of each route segment, including a unique Route ID, mode, the origin and destination nodes and cities, and segment distances. Distances are disaggregated by: (1) the distance in the origin state, (2) the distance in the destination state, and (3) the distance in through-states (for land-based routes) and on the open sea (for water-based routes). Distances in through-states are indicated for routes that pass through a state other than the origin and destination state. Similarly, ship routes are separated by the distances traveled within the origin or destination port or harbor, and the distance on open sea[8]. Because speeds may vary by state or port, through-state and open sea distances must be considered.

Table 4-2. Master Route List and Distances[9]

							Distances *(mi)*			
Route ID	**Mode**	**Origin Node**	**Origin City**	**Destination Node**	**Destination City**	**Through-State/ Open Sea (OS)**	*Origin State*	*Destination State*	*Thru State/ Open Sea*	**Total**
1	Rail	1	NYC	2	PHL	NJ	10	23	20	53
2	Truck	1	NYC	2	PHL	NJ	5	21	58	84
3	Ship	1	NYC	6	NFK	OS	18	44	339	401
4	Ship	1	NYC	7	WLM.NC	OS	18	80	319	417
5	Ship	1	NYC	9	CHL	OS	18	58	618	694
6	Ship	1	NYC	10	SAV	OS	18	72	681	771
7	Ship	1	NYC	11	JAX	OS	18	103	769	890
8	Rail	2	PHL	3	WLM.DE	None	8	7	0	15
9	Truck	2	PHL	3	WLM.DE	None	25	10	0	35
10	Ship	2	PHL	6	NFK	OS	105	44	166	315

4.2.1. National Transportation Atlas Database

The National Transportation Atlas Database (NTAD) was a major source of data used in the selection of nodes and route segments. The 2005 version of NTAD contains a comprehensive collection of transportation-related geospatial data, which provided information about highway, railway, and waterway routes, and their distances (Bureau of Transportation Statistics & Research and Innovative Technology Administration, 2005). Furthermore, NTAD data designated route capacities, their purposes, (e.g., which waterways were for deep-sea vessels only), their operating conditions (e.g., open, closed, or under construction), and more.

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[8] With regard to the distance headings in Table 4-2, it is necessary to clarify that a single port cannot be attributed to a single state, as in the case of the Ports of New York and New Jersey, which are consolidated into a single port. Thus, origin state distances for ship routes as referenced in Table 4-2 are indicative of the distance within that port, and not necessarily that state.

[9] Only the first 10 routes are shown; for the full list, please see Appendix A.

These data were collected extensively by various entities, including the U.S. Army Corps of Engineers, the Federal Highway Administration, the Research and Innovative Technology Administration's Bureau of Transportation Statistics, the Federal Railroad Administration, as well as the U.S. Bureau of the Census and the Bureau of Economic Analysis.

NTAD data were mapped using ArcGIS, a geographical information systems software. Because freight transportation using I-95 along the Eastern seaboard was a major element of this model, the entire stretch of I-95, starting in New York City and ending in Jacksonville, FL, was isolated on a map using ArcGIS and used as the basis for selecting nodes, and truck, rail, and waterway routes.

4.2.2. Node and Route Selection

The eleven nodes selected, shown in Table 4-1 in the previous section, were selected primarily on the basis of their close proximity to I-95 and their accessibility to ports via highway and railway. NTAD data provided information regarding the characteristics of intermodal terminals and facilities, and the diversity of transportation services (e.g., drayage, storage, and on-site cargo lifts and transport) in the region of these nodes were also criteria in selection. Selected nodes represent well-populated cities with an abundance of intermodal terminals where cargo exchanges take place.

Route data provided by NTAD, particularly route types and distances, for the most part, guided the selection and omission of highway, railway, and waterway routes. For instance, interstate or U.S. highway connectors from I-95 to port nodes were preferred over state highways because they are more likely to have higher speed limits and vehicle capacities.

The national railroad system as mapped on ArcGIS with NTAD data is enormous. It was necessary to select rail routes that was representative of an authentic freight carrier. Thus, railroad routes provided by NTAD were screened for those that were currently active (i.e., unabandoned) and primarily owned or operated by CSX Transportation, Inc. (CSX). Because CSX is an intermodal company serving several major ports in the East, it was a reliable guide in selecting commercial rail routes for the model.

Regarding waterway routes, NTAD data differentiated routes by its function, its type, and its direction. Waterway routes used by deep-draft vessels were selected over those that were for shallow-draft vessels or for pleasure crafts. Those attributed as sea lanes, intracoastal waterways, and harbor lanes were also selected. Additionally, some routes were identified as northbound only lanes; care was exercised to select only southbound lanes and differentiate incoming lanes to ports between outgoing lanes from ports.

It is important to acknowledge that the availability of services by actual intermodal freight services on the East coast was not a criterion in the selection of nodes. This is because the affiliations and intermodal services of freight transportation companies vary by location. For instance, CSX and Norfolk Southern are the two major railroads operating on the East coast; in the port of Philadelphia, CSX may have truck-rail-maritime services, but Norfolk Southern may only have truck-maritime services. An important attribute about the highway, railway, and waterway routes selected for the model is that they are actual commercial routes, but they do not necessarily represent actual points of intermodal transfers for every mode. Routes for each mode were selected for different reasons, although combined they attempt to imitate a real-life collection of transportation modes and options.

An important factor driving the selection of nodes and routes is the ability to have options of routes and modes. The model is designed for optimization of 52 route segments, of which the number of possible connecting segments via any one mode at each node is not the same throughout. For example, one may travel from Florence (FLO) to Charleston (CHL) via rail or truck, but the only options out of CHL are via rail or ship, not truck. These slight variations in segment options make it more likely for the model to evaluate intermodal route segments.

4.3. Data Relevant to Travel Time

4.3.1. Defining Speed Limits

Modal speeds are a vital component in determining the travel time of a trip; Table 4-3(a) below depicts the maximum and adjusted speed limits for each state and port, disaggregated by mode. Instead of specifying the speed limits for each node, speed limits are specific to states and ports. The speed limits for ports and full cruise on open water were difficult to obtain, so assumptions were made according to designations made by port authorities as well as relevant literature. The same was done for rail speeds. Furthermore, highway speed limits were provided by the National Institute for Highway Safety (2007).

In reality, freight carriers may not travel at the maximum speed at all times during travel. Thus, the model user has the opportunity to designate a more accurate representation of actual travel speeds for each mode. By defining a percentage of the maximum allowable speed limit, the user can define a more realistic travel speed that better reflects actual conditions such as traffic and capacity restrictions. The percentage can be differentiated by mode, however, the default for each in the model is 85 percent, as shown in Table 4-3(b). Thus, the values shown in the *Adjusted Speed* column are adjustments of the maximum speed limit according to the percentage as specified by the user; the model will extract and utilize those speeds shown in Table 4-3(c) in travel time calculations.

Table 4-3. State- and Port-Specific Speed Limits & Speed Adjustments

a). Maximum State- and Port-Specific Speed Limits

	Speed Limits *(mph)*		
State/Port	**Rail**	**Ship**	**Truck**
NY	70		50
NJ	70		55
PA	70		55
DE	70		55
MD	70		55
VA	70		55
NC	70		55
SC	70		60
GA	70		55
FL	70		65
NYC		25	
PHL		25	
WLM.DE		25	
BLT		25	
NFK		25	
WLM.NC		25	
CHL		25	
SAV		25	
JAX		25	
OS		50	

b). Percentage of Max. Speed Limits

Mode	% of Max. Speed Limit
Rail	85%
Ship	85%
Truck	85%

c). Adjusted State- and Port-Specific Speed Limits

	Estimated Travel Speed *(mph)*		
State/Port	**Rail**	**Ship**	**Truck**
NY	60		43
NJ	60		47
PA	60		47
DE	60		47
MD	60		47
VA	60		47
NC	60		47
SC	60		51
GA	60		47
FL	60		55
NYC		21	
PHL		21	
WLM.DE		21	
BLT		21	
NFK		21	
WLM.NC		21	
CHL		21	
SAV		21	
JAX		21	
OS		43	

4.3.2. Drayage Time

The second time-related input is that of drayage. Drayage time is the accumulated time spent handling the cargo in-between modes—more specifically, it is the receiving, storage of, and loading of freight from one mode to another. In some cases, cargo can be transported for some distance to a different warehouse or location. Drayage time is an essential component in calculating total travel time, because it is a significant source of temporal delay in the transport of intermodal freight. The default dray time values shown in Table 4-4 are estimates only, and reflect the number of hours required for freight to be transferred from the starting mode to the ending mode.

Table 4-4. Drayage Time

	Ending Mode		
Starting Mode	Rail	Ship	Truck
Rail	0.00	1.25	0.60
Ship	0.75	0.00	1.00
Truck	0.50	1.10	0.00

Furthermore, the model accounts for drayage time only when the modes of two connecting route segments are different. Thus, there is no temporal penalty for drayage for two route segments with the same mode. However, in some cases, the user may decide to impose a penalty on same-mode segment connections. This will be demonstrated as a case study in the *Model Demonstration and Case Studies* section.

4.3.3. Congestion Index

The final time-related input is that of the Congestion Index (CI), which is an indicator of the extra time it takes to travel in peak-period conditions over free-flow conditions. The temporal delay associated with congestion is factored into this model by means of the CI; each node and/or route segment is assigned a CI as a measure of the level of congestion in that region. The CI for each mode at a certain node will determine the extra time that it takes to travel through that node. For instance, a CI of 1.6 indicates that a 30-minute trip in free-flow conditions will result in a 60 percent delay, or 18 minutes, in peak-period conditions. Table 4-5 shows the base CI for each node as provided by the Texas Transportation Institute's 2005 Urban Mobility Study (Schrank & Lomax, 2005)[10]. Because the study did not provide an index for all the cities used in this model, cities with no CI were assigned a proxy CI according to the nearest city of relative size with its own CI.

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[10] In the Urban Mobility Study, the CI is referred to as the Travel Time Index (TTI).

Table 4-5. CI at Each Node

		Base CI *(hours)*		
Node	**City**	Rail	Ship	Truck
1	NYC	1.00	1.00	1.43
2	PHL	1.00	1.00	1.36
3	WLM.DE	1.00	1.00	1.36
4	BLT	1.00	1.00	1.37
5	RCH	1.00	1.00	1.08
6	NFK	1.00	1.00	1.22
7	WLM.NC	1.00	1.00	1.18
8	FLO	1.00	1.00	1.06
9	CHL	1.00	1.00	1.18
10	SAV	1.00	1.00	1.18
11	JAX	1.00	1.00	1.17

For route segments, the Average CI is the calculated average of the CI for the origin and destination nodes, as shown in Table 4-6. . In the case that a proxy CI is preferred, the user can insert a new CI in the *User-Defined CI* column. By default, the CI is available only in truck routes, but the user has the option of inserting a user-defined CI for any node and/or route segment, including those for rail and ship. The *Final CI* column reflects the CI that will be used according to the cell value in the *Use User-Defined CI?* column.

Table 4-6. CI for Each Route Segment

Route ID	Mode	Origin Node	Origin City	Destination Node	Destination City	Base CI in Origin City	Base CI in Destination City	Average CI	User-Defined CI	Use User-Defined CI? *(1=yes 0=no)*	Final CI *(hours)*
1	Rail	1	NYC	2	PHL	1.00	1.00	1.00	1.00	0	1.00
2	Truck	1	NYC	2	PHL	1.43	1.36	1.40	1.00	0	1.40
3	Ship	1	NYC	6	NFK	1.00	1.00	1.00	1.00	0	1.00
4	Ship	1	NYC	7	WLM.NC	1.00	1.00	1.00	1.00	0	1.00
5	Ship	1	NYC	9	CHL	1.00	1.00	1.00	1.00	0	1.00
6	Ship	1	NYC	10	SAV	1.00	1.00	1.00	1.00	0	1.00
7	Ship	1	NYC	11	JAX	1.00	1.00	1.00	1.00	0	1.00
8	Rail	2	PHL	3	WLM.DE	1.00	1.00	1.00	1.00	0	1.00
9	Truck	2	PHL	3	WLM.DE	1.36	1.36	1.36	1.00	0	1.36
10	Ship	2	PHL	6	NFK	1.00	1.00	1.00	1.00	0	1.00

4.4. Data Relevant to Travel Cost

4.4.1. Rate-per-Mile

The first cost-related input is the rate-per-mile (RPM) for each mode. The RPM is an often-used cost measure in freight transportation. The RPM may be specified differently for each mode, as shown in Table 4-7.

Table 4-7. Rate-per-Mile

Mode	RPM
Truck	$1.61
Rail	$1.37
Ship	$1.12

RPM data was extracted from a National Ports and Waterways Institute (NPWI) (2004) report entitled *The Public Benefits of the Short-Sea Intermodal System*. The report focused on intermodalism and the role of short-sea shipping along points on the East coast. The study used a computer model to generate freight rates that took into account the cost of vessels, financing options, labor costs, and fuel costs. This report is one of the very few studies done on intermodal costs, thus the data provided was heavily relied upon.

The *Public Benefits* report estimated the RPM of coastal ferry service that included the cost of drayage, as well as operating costs and fuel costs. The report listed the RPM for several trips, including New York City to Norfolk, VA; Norfolk to Charleston, SC; and Charleston to Miami, FL. The RPM for each of these trips was the same, thus the RPM as determined in this study was used as a proxy cost for container shipping in this model. For trucking routes, the *Public Benefits* report calculated the RPM for several northbound, southbound, and average trips for two major truck shipping companies and a “street” rate, using a fuel adjustment factor and pickup and delivery costs. For purposes of this model, the truck RPM was derived as the average of the three rates for a southbound journey from Newark, NJ to Miami. Finally, the

RPM cost for rail service was not explicitly given. However, the report stated that, depending on route distance, truck-rail service is usually approximately 15 to 20 percent lower than all-truck service (NPWI, 2004, p. 20). Therefore, the RPM for rail service was determined as 15 percent lower than the trucking rate of $1.61/mile.

4.4.2. Drayage Cost

Another cost component in travel cost calculation is drayage cost, which is the cost of an intermodal cargo transfer from one mode to another. The cost of drayage is separate from the actual shipping cost, and is generally consisted of fuel surcharges, costs associated with waiting times (i.e., time the container is at rest and waiting to be moved), access charges, labor, and other cost factors. Additionally, the structure of the drayage rate may vary by the freight company offering the service, and by local unions. Table 4-8 displays the drayage costs used in the model. Similar to dray time, there is no dray cost for two connecting route segments with the same mode. For instance, if the model selected Routes 2 (NYC to PHL via truck) and 9 (PHL to WLM.DE via truck), there would be a $0 drayage cost, according to the truck-truck dray cost in Table 4-8. Alternatively, if the model selected Routes 2 and 10 (NYC to PHL via truck, then PHL to NFK via ship), then there would be a cost penalty of $225.

Table 4-8. Drayage Cost

	Ending Mode		
Starting Mode	Rail	Ship	Truck
Rail	$0	$275	$300
Ship	$275	$0	$225
Truck	$300	$225	$0

In a report titled *Cross Border Short-sea Shipping Study*, conducted by Cambridge Systematics, Inc. (2007), the drayage rates, inclusive of fuel surcharges, were collected for short-sea shipping carriers in the Cascades region of the U.S. Pacific Northwest and Canada. These rates were used as the drayage rates for truck-ship and ship-truck service in the model. Ship-rail and rail-ship drayage rates were provided in a report titled, *Inland Port Feasibility Study* (Tioga Group Inc., Railroad Industries Inc., & Cambridge Systematics Inc., 2003). This report encompassed a market analysis of intermodal transportation, particularly between ships and rail, in the San Joaquin Valley and the Port of Oakland, CA. With respect to truck-rail and rail-truck drayage rates, specific data were not available, so an estimate was used.

4.4.3. Cost Factors in Intermodal Transportation

The cost system is inherently complex and sensitive to market changes. According to Mr. Steve Plauche, the manager of the Cost and Economic Analysis department at CSX Intermodal, Inc., a large freight carrier operating on the East coast, some of the costs of intermodal transportation include the following shown in Table 4-9.

Table 4-9. Typical Cost Factors for CSX Intermodal, Inc.

Variable Costs	**Fixed Costs**
- Lift costs - Fuel costs - Maintenance-of-Way (track) costs - Damaged lading costs - Port switching costs - Trucking costs - Rail car costs - Container/trailer costs - Repositioning of empty container/trailers - Equipment maintenance - Crew costs	- Terminal switching - Terminal lease - Terminal depreciation - Terminal overhead - Track access

Source: (Plauche, 2006)

Mr. Plauche also indicated that providing an all-inclusive cost to their customers is customary. Additionally, the cost breakdown of freight transportation services is rarely available as public information. Thus, this model will not attempt to incorporate each of these elements, but instead use an all-inclusive cost that is representative of all the fixed and variable costs. It is for this reason that the model incorporates a single, per-mile cost factor for all three modes.

4.5. Data Relevant to Emissions

Another component of the *Inputs* worksheet is emissions data for VOC, CO, NO_x, PM, SO_x, and CO_2, including emission factors. Emissions data for each were derived from a variety of sources, including two transportation-related models. The first model, developed in 1995 by the U.S. Department of Energy's Office of Transportation Technologies and Argonne National Laboratory, is the *GREET* model (Wang, Wu, & Elgowainy, 2005). *GREET* is an analytical tool that estimates total fuel-cycle energy use and emissions associated with transportation technologies and fuels. *GREET* provided emissions in grams per million Btu (g/mBtu) for diesel-powered locomotives and in grams per mile for heavy heavy-duty diesel trucks[11].

The second model used was the Total Energy & Emissions Analysis for Marine Systems (*TEAMS*) model, developed in 2005 by a team from Rochester Institute of Technology and the University of Delaware (Winebrake, Corbett, & Meyer, 2005). *TEAMS* is similar to *GREET* with the exception that it calculates total fuel-cycle emissions and energy consumption for marine systems, including ferry boats and container ships. *TEAMS* provided the emission factors for both the main and auxiliary engines of a residual oil-powered container ship in grams per ship-mile (g/ship-mi).

Both models were used to extract emissions factors for VOC, CO, NO_x, PM, SO_x, and CO_2. With the exception of CO_2, tailpipe emissions were extracted for all pollutants. Tailpipe

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[11] The emission factors extracted from GREET are specific for heavy heavy-duty diesel trucks. However, the term "heavy-duty vehicles," as used throughout this paper, is an umbrella term for different weight classes of diesel-powered heavy-duty vehicles, including light heavy-duty, medium heavy-duty and heavy heavy-duty.

emissions are the final emissions produced in a total fuel-cycle, accounted as the emissions from end-use, such as from diesel trucks or construction equipment. CO_2 emissions, on the other hand, are accounted over the total fuel-cycle, which runs from fuel extraction through production and consumption. CO_2 is not a regulated pollutant; when it is emitted in the air, it does not remain concentrated in the region where it sourced as opposed to the other pollutants. Thus, it is more appropriate to consider the impact of CO_2 emissions during all stages of the fuel cycle, and it is for this reason that the optimization of CO_2 emissions in the model incorporates total fuel-cycle emissions of CO_2.

Emissions factors were collected in units of grams per TEU-mile. This is a measure of the emissions output, in grams of pollutant, for each mile one TEU[12] is transported. In this model, the standard dimensions of a TEU are considered. The inclusion of tons per TEU enables the consideration of different weights carried per TEU—because they are not always the same, depending on the goods carried, and the mode used. As shown in Tables 4-10, 4-11, and 4-12, conversions are made from the original measurement units into g/TEU-mi, shown in gray cells.

Table 4-10. Rail Emission Factors

	Rail Emission Factors					
	VOC	CO	NO_x	PM_{10}	SO_x	CO_2
g/mBtu	73.948	213.328	1,517.110	35.940	17.259	78,363.233
Btu/ton-mi	370	370	370	370	370	370
tons/TEU	5.0	5.0	5.0	5.0	5.0	5.0
g/TEU-mi	0.14	0.39	2.81	0.07	0.03	144.97

Table 4-11. Ship Emission Factors

	Ship Emission Factors					
	VOC	CO	NO_x	PM_{10}	SO_x	CO_2
grams/ship-mi	1,493.444	6,869.444	39,626.045	1,173.381	19,559.318	1,464,151.000
TEU/ship	5,000	5,000	5,000	5,000	5,000	5,000
g/TEU-mi	0.30	1.37	7.93	0.23	3.91	292.83

---

[12] A TEU, or twenty-foot equivalent unit, is a commonly used measure of containerized cargo capacity. At its standard, it is 20 feet long, 8'6" feet high and 8 feet wide (EPA, 2006). Although there are several standard container sizes in use, as is the 40-foot container commonly used in the U.S., the model will measure capacity in TEUs.

Table 4-12. Truck Emission Factors

	Truck Emission Factors					
	VOC	CO	NO_x	PM_{10}	SO_x	CO_2
g/mBtu	0.678	3.274	13.726	0.237	0.443	2,002.000
TEU/truck	2	2	2	2	2	2
g/TEU-mi	0.34	1.64	6.86	0.12	0.22	1,001.00

To measure emissions output during drayage, idling emission factors were collected from a variety of reports from EPA and Argonne National Laboratory. Idling emissions factors for trucks for the pollutants VOC, CO, NOx, and PM were obtained from EPA (1998a) in g/hr. The idling truck emission factor for CO_2 was obtained—also in g/hr— from a report titled *Analysis of Technology Options to Reduce Fuel Consumption of Idling Trucks* by Argonne National Laboratory (Stodolsky, Gaines, & Vyas, 2000). Furthermore, because the idling emission factor for SO_x was unable to be located among the literature, a rough estimate was devised by calculating the original SO_x emission factor value with the engine size of a typical idling engine and the power load at idling.

The idling ship emissions factors for VOC, CO, NOx, and PM were taken from a regulatory impact analysis by EPA concerning marine engines (EPA, 2007a, p. 10); the value for VOC was converted from the hydrocarbon (HC) emission factor provided by the report, using a conversion factor. The idling emission factor values for ship engines for SO_x and CO_2 were extracted from TEAMS under idling engine conditions.

For locomotive rail engines, all idling emission factors were obtained from a study on diesel fuel effects on locomotive emissions (Fritz, 2000), as well as a regulatory support document for locomotive emissions standards by EPA (1998b).

Some unit conversions to g/hr were required, so the constants used in conversions were established. Tables 4-13 and 4-14 depict the constants used as well as the conversions to g/hr for idling rail and ship engines. Table 4-15 depicts idling emission factors for trucks (where conversions were not required).

Table 4-13. Emission Factors and other Designates for Idling Rail Engines

a.) Constants Used in Conversions for Rail

Constants (Rail)	
g/bhp-hr to g/kW-hr	1.341
hp/kw	0.746
Engine Power @ Idle (hp)	17.00
Energy Production @ Idle (kW)	12.677

b.) Emission Factors for Idling Rail Engines

	Emission Factors for Idling Rail Engines					
	VOC	CO	NO_x	PM_{10}	SO_x	CO_2
g/bhp-hr	0.27	1.28	4.95	0.18	0.09	589.54
g/kW-hr	0.37	1.72	6.64	0.24	0.12	790.57
g/hr	4.66	21.76	84.15	3.06	1.58	10,022.01

Table 4-14. Emission Factors and other Designates for Idling Ship Engines

a.) Constants Used in Conversions for Ship

Constants (Ship)	
Energy Production @ Idle (kW)	1176.0

b.) Emission Factors for Idling Ship Engines

	Emission Factors for Idling Ship Engines					
	VOC	CO	NO_x	PM_{10}	SO_x	CO_2
g/kWh	0.43	1.60	5.70	0.23	N/A	N/A
g/hr	508.03	1,881.60	6,703.20	270.48	15,507.00	1,065,151.00

Table 4-15. Emission Factors for Idling Truck Engines

	Emission Factors for Idling Truck Engines					
	VOC	CO	NO_x	PM_{10}	SO_x	CO_2
g/hr	12.55	94.30	55.85	2.59	0.045	10,397.00

5.0. Using Solver to Run the Model

5.1. Overview of the *Solver*

At the core of this model is the Premium Solver, a spreadsheet optimization tool developed by Frontline Systems for Microsoft. This thesis utilized the Premium Solver for Education version, an upgraded version of the standard that is bundled with Microsoft Excel. The Solver is a proven and effective tool that performs optimization on many types of linear and nonlinear models. According to Frontline Systems, the Premium Solver Platform can handle up to 500 decision variables and 250 constraints in a smooth nonlinear model (Frontline Solvers, 2006). Thus, it is possible to drastically expand the current version of the model for more thorough, or more specialized analysis.

The Solver's purpose is to find the best—or most optimal— solution with the variables it is given, that either maximizes or minimizes the objective, and satisfies all constraints (Frontline Solvers, 2006). In this model, Solver optimizes for eight distinct decision objectives: travel time, travel cost, and emissions output of VOC, CO, NO_x, PM, SO_x and CO_2. For any one objective, the Solver searches within a feasible region, which consists hundreds of different possible solutions, and selects one that best satisfies the objective function. A feasible region is the "set of points or values that the decision variables can assume and simultaneously satisfy all the constraints in a problem" (Ragsdale, 2001, p. 29). Constraints are important in a model, because they further define the limits on a decision variable, and consequently shift the feasible region. If the constraints are too restrictive, the Solver may not find any feasible solution. Components of the Solver are discussed further in the following sections.

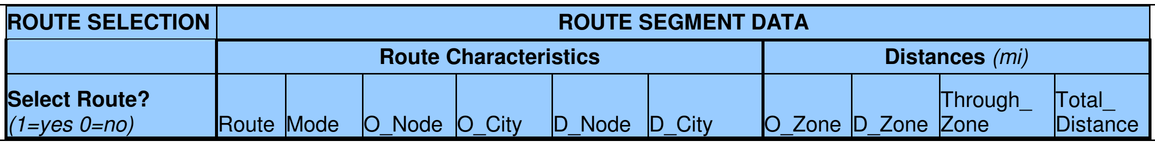
5.2. Functions on the Solver Worksheet

The Solver worksheet is divided into five main categories that performs a specific set of calculations or provides data for calculations: *Route Selection*, *Route Segment Data*, *Travel Time Optimization*, *Travel Cost Optimization*, and *Emissions Optimization*. Each category has a set of columns, each with its own function. The following sections are devoted to explaining the components within each category, beginning with Route Selection.

5.2.1. Route Selection & Route Segment Data

Components within the Route Selection and Route Segment Data categories are described below Figure 5-1.

Figure 5-1. Route Selection and Route Segment Data



ROUTE SELECTION	ROUTE SEGMENT DATA									
	Route Characteristics						Distances *(mi)*			
Select Route? *(1=yes 0=no)*	Route	Mode	O_Node	O_City	D_Node	D_City	O_Zone	D_Zone	Through_ Zone	Total_ Distance

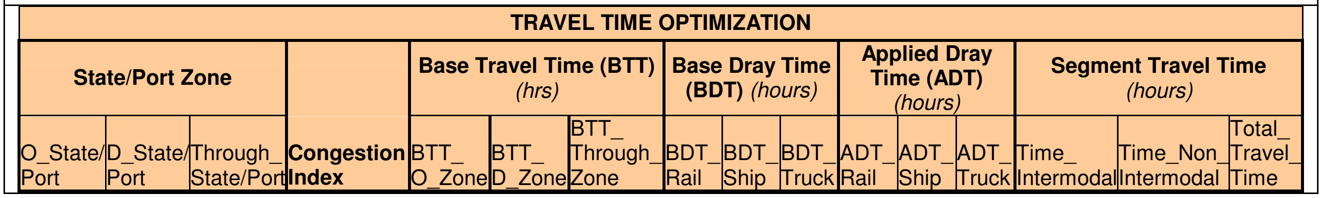
- **Route Selection.** The Route Selection column contains the *Select_Route?* function, which consists of binary decision variables representing route segments. Each route segment either picks up a value of 1, indicating the segment is selected, or 0 if otherwise. The optimization process centralizes on these decision variables.
- **Route Characteristics.** The Route Characteristics function contains important information characterizing each route segment, including:
    - the *Route* number, a unique numerical reference for each route segment;
    - the *Mode*, indicating the mode used;
    - the *O_Node* and *O_City*, which indicates the node and city of origin; and
    - the *D_Node* and *D_City*, which indicates the destination node and city.

- **Distances.** The Distances category disaggregates the number of miles in the zone of origin (*O_Zone*), the destination zone (*D_Zone*) and the Through-Zone (*Through_Zone*)

5.2.2. Travel Time Optimization

Figure 5-2 displays the set of functions within the Travel Time Optimization category.

Figure 5-2. Solver Section on Travel Time Optimization



TRAVEL TIME OPTIMIZATION															
State/Port Zone				**Base Travel Time (BTT)** *(hrs)*			**Base Dray Time (BDT)** *(hours)*			**Applied Dray Time (ADT)** *(hours)*			**Segment Travel Time** *(hours)*		
O_State/Port	D_State/Port	Through_State/Port	**Congestion Index**	BTT_O_Zone	BTT_D_Zone	BTT_Through_Zone	BDT_Rail	BDT_Ship	BDT_Truck	ADT_Rail	ADT_Ship	ADT_Truck	Time_Intermodal	Time_Non_Intermodal	Total_Travel_Time

Each function is also described below.

- **State/Port Zone.** This function essentially identifies ship routes with port zones and truck and rail routes with state zones. The *O_State/Port* and *D_State/Port* values indicate, for rail and truck routes, the state in which the origin node and destination node resides. For ship routes, this refers to the distance between the origin port and the gateway to the open sea, and the distance between the gateway to the open sea and the destination port. The *Through_State/Port* depicts, for rail and truck routes, the state that lays in-between the origin and destination states, if one exists. For ship routes, this is the distance on the open sea.
- **Congestion Index (CI).** The CI indicates the index value that is appropriate to the region in which the route segment belongs. This value is obtained directly from the *Final CI* as determined on the *Inputs* sheet.
- **Base Travel Time (BTT).** The BTT, measured in hours, is indicative of the travel time spent in actual travel, and does not account for drayage time. Speed, distance, and

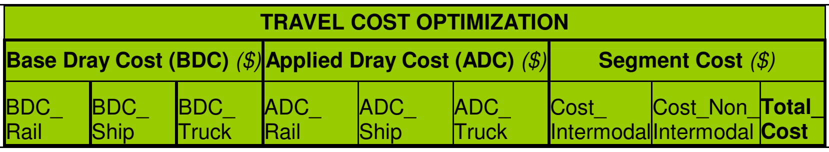
congestion factors are calculated for each zone: *BTT_O_Zone*, *BTT_D_Zone*, and *BTT_Through_Zone*. The sum of all zones is reflected as *Time_Non_Intermodal* (shown under the *Segment Travel Time* function).

- **Base Dray Time (BDT).** The BDT identifies the drayage time for the mode used in the corresponding route segment, whether or not the route segment is actually selected. The BDT value shows the dray time for each of the three modes (*BDT_Rail*, *BDT_Ship*, and *BDT_Truck*) if freight were to be transferred to each from the primary mode used in the route segment. It is used for reference purposes only.
- **Applied Dray Time (ADT).** The *ADT* is equal to the BDT value. The ADT is the BDT value multiplied by the binary value in *Select_Route?* so it is shown only if the Solver selects that particular mode and route segment. Furthermore, the ADT shows the total time of the applied intermodal transfer; if its value is zero, then it indicates either that the particular route segment is not selected, or that no intermodal transfer is to take place. The ADT is also reflected as the value of *Time_Intermodal* (shown under the *Segment Travel Time* function).
- **Segment Travel Time.** The Segment Travel Time is consisted of the *Time_Non_Intermodal* (the sum of the BTT), the *Time_Intermodal* (the ADT) and the *Total Travel Time* (the sum of the BTT and the ADT).

5.2.3. Travel Cost Optimization

The fourth category on the Solver worksheet is Travel Cost Optimization, as shown in Figure 5-3.

Figure 5-3. Solver Section on Travel Cost Optimization



TRAVEL COST OPTIMIZATION								
Base Dray Cost (BDC) *($)*			**Applied Dray Cost (ADC)** *($)*			**Segment Cost** *($)*		
BDC_ Rail	BDC_ Ship	BDC_ Truck	ADC_ Rail	ADC_ Ship	ADC_ Truck	Cost_ Intermodal	Cost_Non_ Intermodal	**Total_ Cost**

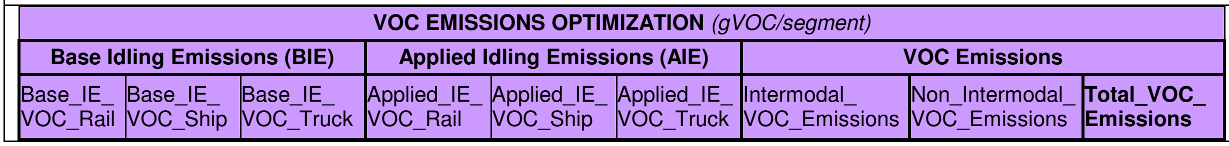
The following describes the functions within this category.

- **Base Dray Cost (BDC).** Similar to the BDT, the BDC identifies the dray cost for an intermodal switch to rail, ship, and truck, according to the mode used in the route segment. It is shown for each as *BDC_Rail*, *BDC_Ship*, and *BDC_Truck*, and dray costs are obtained from the *Inputs* sheet. Additionally, the sum of all BDC values are reflected in the *Cost_Non_Intermodal* (shown under the *Segment Cost* function), as it does not reflect the cost of intermodal drayage.
- **Applied Dray Cost (ADC).** Similar to the ADT, the *ADC* is the *BDC* value that is applied to the total cost of the route segment if the optimal solution consisted of an intermodal switch from that particular route segment to the next. The sum of the *ADC* columns in each route segment (shown as *ADC_Rail*, *ADC_Ship*, and *ADC_Truck*) is equal to the *Cost_Intermodal*, which is under the *Segment Travel Cost* function.

5.2.4. Emissions Optimization

The last category on the Solver worksheet is that of Emissions Optimization**.** There are six sub-categories, where each sub-category is devoted to a single pollutant. Figure 5-4 shows the VOC sub-category and its components; the format is the same for all other emissions in their respective sub-categories.

Figure 5-4. Solver Section on Emissions Optimization: VOC Sub-Category



VOC EMISSIONS OPTIMIZATION *(gVOC/segment)*								
Base Idling Emissions (BIE)			**Applied Idling Emissions (AIE)**			**VOC Emissions**		
Base_IE_ VOC_Rail	Base_IE_ VOC_Ship	Base_IE_ VOC_Truck	Applied_IE_ VOC_Rail	Applied_IE_ VOC_Ship	Applied_IE_ VOC_Truck	Intermodal_ VOC_Emissions	Non_Intermodal_ VOC_Emissions	**Total_VOC_ Emissions**

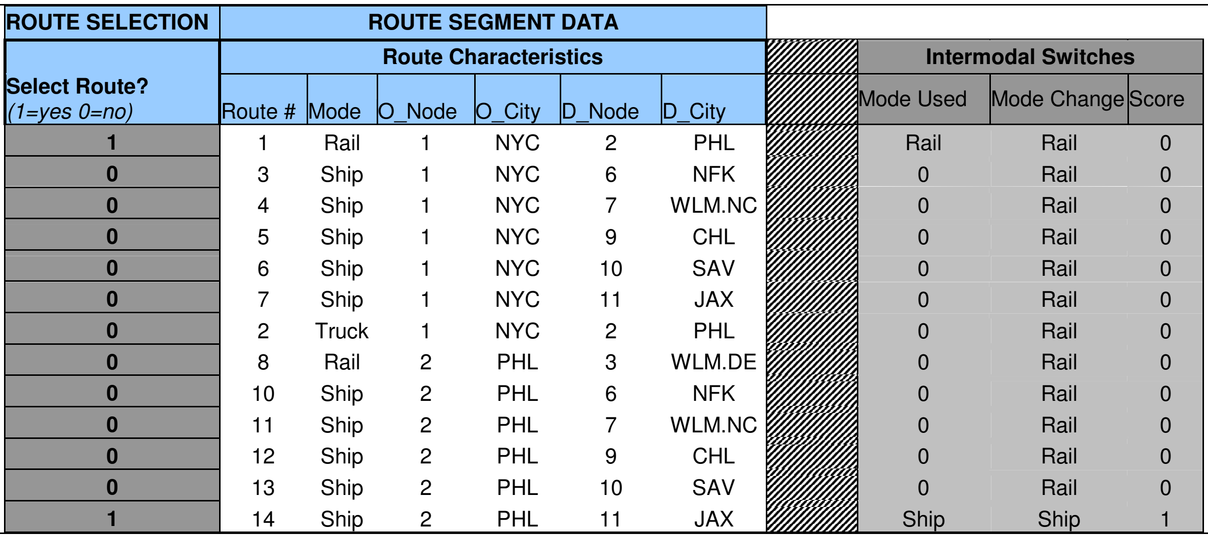
The following offers descriptions for each function in emissions optimization.

- **Base Idling Emissions (BIE).** The BIE function shows the base idling emissions, shown as gVOC/segment, for each route segment according to the idling time, in hours, during drayage, and the emissions factor for the corresponding pollutant, given as grams per hour (both of which are determined on the *Inputs* sheet). It is shown for each mode, under the *Base_IE_VOC_Rail*, *Base_IE_VOC_Ship*, and *Base_IE_VOC_Truck* columns. Furthermore, the BIE shows the emissions output for each route segment if an intermodal switch is made at any other connecting route segment whether or not the route segment is actually selected. Thus, it is used for reference purposes only.
- **Applied Idling Emissions (AIE).** The AIE shows the idling emissions for each route segment if and only if the current route segment and the connecting route segment both have a *Select_Route?* value of 1. The final AIE is shown under the *Intermodal_VOC_Emissions* column (shown under the *VOC Emissions* function).
- **VOC Emissions**. The VOC Emissions section shows the subtotals in *Intermodal_VOC_Emissions* column, the *Non_Intermodal_VOC_Emissions* column, as well as the total emissions output in the *Total_VOC_Emissions* column.

5.2.5. Regarding Intermodal Switches

The Solver worksheet is also outfitted with the ability to identify where and when intermodal switches take place within the itinerary of the final solution. This calculation is separate from the optimization process and serves as an informational resource only. When the Solver solves for an optimal solution, a tally of the intermodal switches is revealed in the Solver Results Summary, which shows the totals for travel time, cost, and each of the six emissions, and is discussed in the next section. Below, in Figure 5-5, an example trip itinerary is shown for a trip from NYC>PHL via rail and PHL>JAX via ship.

Figure 5-5. Identifying Intermodal Switches With a Example Trip Itinerary

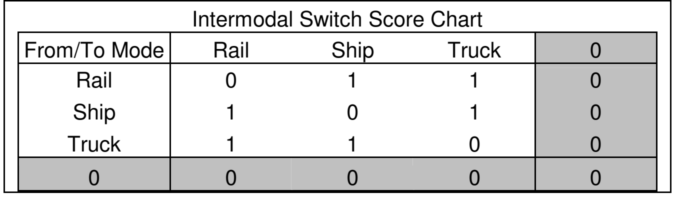


ROUTE SELECTION	**ROUTE SEGMENT DATA**								
	Route Characteristics						**Intermodal Switches**		
Select Route? *(1=yes 0=no)*	Route #	Mode	O_Node	O_City	D_Node	D_City	Mode Used	Mode Change	Score
1	1	Rail	1	NYC	2	PHL	Rail	Rail	0
0	3	Ship	1	NYC	6	NFK	0	Rail	0
0	4	Ship	1	NYC	7	WLM.NC	0	Rail	0
0	5	Ship	1	NYC	9	CHL	0	Rail	0
0	6	Ship	1	NYC	10	SAV	0	Rail	0
0	7	Ship	1	NYC	11	JAX	0	Rail	0
0	2	Truck	1	NYC	2	PHL	0	Rail	0
0	8	Rail	2	PHL	3	WLM.DE	0	Rail	0
0	10	Ship	2	PHL	6	NFK	0	Rail	0
0	11	Ship	2	PHL	7	WLM.NC	0	Rail	0
0	12	Ship	2	PHL	9	CHL	0	Rail	0
0	13	Ship	2	PHL	10	SAV	0	Rail	0
1	14	Ship	2	PHL	11	JAX	Ship	Ship	1

Within the *Mode Used* column, which is the first of the three in the Intermodal Switches section, each cell first identifies whether or not its corresponding *Select_Route?* cell is selected; if it is, the cell returns the mode used in that route segment, and a value of 0 otherwise. In the *Mode Change* column, the purpose of each cell is to look at the *Mode Used* cell and return the value shown. If the *Mode Used* cell has a value of 0, it indicates that the next corresponding route segment—if one exists—has not yet been identified, so the *Mode Change* cell continues to return the same value as the cell above it until the Mode Used value is different. As shown in Figure 5-5, the *Mode Change* value for Route 1 is *rail*, but because the *Mode Used* values in all the routes in-between up until Route 14 have a *Select_Route?* value of 0, the *Mode Change* cells continue to return the same value, indicating that one route segment has been selected so far. However, in Route 14, a second route segment has been selected, and the *Mode Used* cell identifies the mode used as *ship*, and the *Mode Change* cell changes to show *ship* as the new, current mode.

The *Score* column is responsible for assigning a score of 1 or 0 according to whether a mode pair between two route segments are different. It queries the value of the *Mode Used* cell for Route 14, and matches it with the *Mode Change* value in Row 13 (which the model "thinks" is the current mode) and cross-references the pair in the Score Chart shown in Figure 5-6. A rail-ship transfer has a score of 1, so the *Score* column returns a value of 1. The sum of the *Score* column is the total number of intermodal switches, and this sum is shown in the Solver Results Summary, which is discussed in the next section.

Figure 5-6. Intermodal Switch Score Chart



Intermodal Switch Score Chart

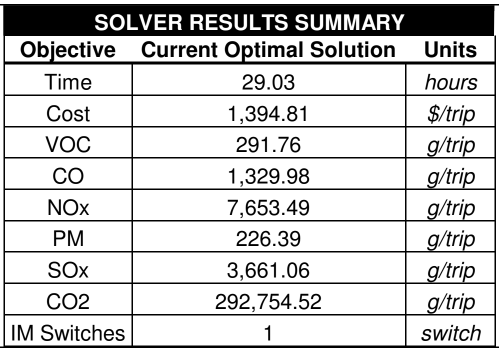
From/To Mode	Rail	Ship	Truck	0
Rail	0	1	1	0
Ship	1	0	1	0
Truck	1	1	0	0
0	0	0	0	0

5.2.6. Solver Results Summary

When the Solver has completed the optimization process and found an optimal solution, the final values for each objective are displayed in the Solver Results Summary. Figure 5-7 shows the solution values for each objective as well as the total number of intermodal switches, for the NYC>PHL>JAX via rail and ship example trip discussed in the previous section. Each cell within the *Current Optimal Solution* column indicates the sum of the optimization columns for each objective, and the *Units* column indicates the units for that objective value.

Furthermore, the *IM Switches* cell indicates the number of intermodal switches that are applied in the *Current Optimal Solution*.

Figure 5-7. Example Solver Results Summary



SOLVER RESULTS SUMMARY		
Objective	**Current Optimal Solution**	**Units**
Time	29.03	*hours*
Cost	1,394.81	*$/trip*
VOC	291.76	*g/trip*
CO	1,329.98	*g/trip*
NOx	7,653.49	*g/trip*
PM	226.39	*g/trip*
SOx	3,661.06	*g/trip*
CO2	292,754.52	*g/trip*
IM Switches	1	*switch*

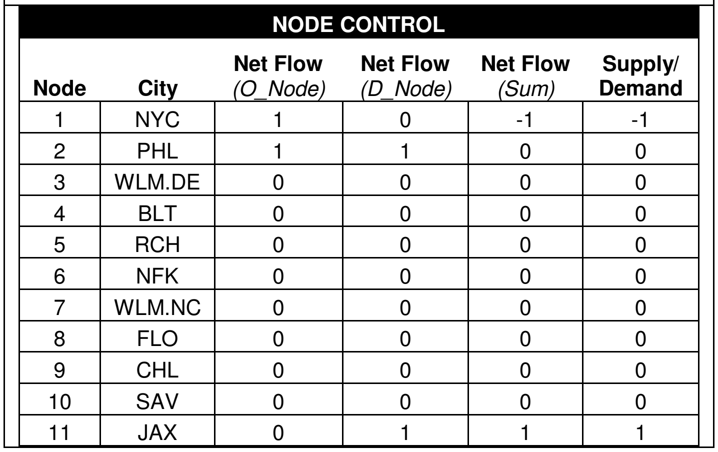
5.3. Constraints

Constraints are used to help shape the parameters and define solutions, and in models, these control variables can be expressed mathematically. These constraints allow for the evaluation of possible scenarios, of which assists in decision-making. The following sections discuss the two default constraints used for this model.

5.3.1. Net Flow Constraints

In a network flow model, where there is a web of nodes connected by arcs, there is a balance of supply and demand at each node that directs the flow from an origin node to a destination node. As shown in the Node Control section within Figure 5-8, each of the 11 nodes used in the model are set with its own supply or demand value that indicates whether it is a “sending” node, a “through” node, or a “receiving” node. For instance, node 1 (NYC) has a supply of 1 (which makes it a “sending” node), and node 11 (JAX) has a demand of –1 (which makes it a “receiving” node). Nodes 2 through 10 are nodes that stand between NYC and JAX, and their values are 0, indicating that the flow must continue through all these nodes (which makes each a “through” node).

Figure 5-8. Node Control



NODE CONTROL					
Node	**City**	**Net Flow** *(O_Node)*	**Net Flow** *(D_Node)*	**Net Flow** *(Sum)*	**Supply/ Demand**
1	NYC	1	0	-1	-1
2	PHL	1	1	0	0
3	WLM.DE	0	0	0	0
4	BLT	0	0	0	0
5	RCH	0	0	0	0
6	NFK	0	0	0	0
7	WLM.NC	0	0	0	0
8	FLO	0	0	0	0
9	CHL	0	0	0	0
10	SAV	0	0	0	0
11	JAX	0	1	1	1

The assignment of supply and demand values at each node instructs the model that the net flow (inflow minus outflow) at each node must be equivalent to its supply or demand. In other words, each network flow constraint indicates that the flow into a given node less the flow out of that same node must be equal to the supply or demand at that node. Thus, the Solver is required to optimize for an objective by choosing the most optimal route that begins at node 1 and ends at node 11, and for all other nodes, there must be an incoming and an outgoing arc at that node. The mathematical structure of each arc constraint is shown below in Table 5-1.

Suppose after running the mode for travel time minimization, the Solver chose the trip layout as shown in Table 5-2. If this combination of route segments were chosen, all the node constraints would be satisfied, as shown in Table 5-3. Arc X_{12} has a value of –1, satisfying the node 1 constraint. Arcs X_{12} and $Y_{2,10}$ yield a sum of zero, also satisfying the node 2 constraint.

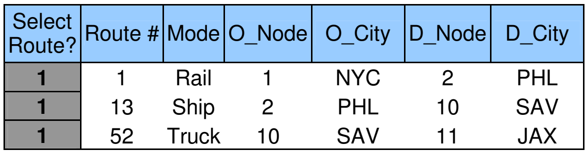
Table 5-1. Mathematical Representation of Net Flow Constraints

Constraint	*Mathematical Representation*
Node 1	$-X_{12} - Y_{16} - Y_{17} - Y_{19} - Y_{1,10} - Y_{1,11} - Z_{12} = -1$
Node 2	$+X_{23} + Y_{26} + Y_{27} + Y_{29} + Y_{2,10} + Y_{2,11} + Z_{23} - X_{12} - Z_{12} = 0$
Node 3	$+X_{34} + Y_{36} + Y_{37} + Y_{39} + Y_{3,10} + Y_{3,11} + Z_{34} - X_{23} - Z_{23} = 0$
Node 4	$+X_{45} + Y_{46} + Y_{47} + Y_{49} + Y_{4,10} + Y_{4,11} + Z_{45} - X_{34} - Z_{34} = 0$
Node 5	$+X_{56} + X_{57} + X_{58} + Z_{56} + Z_{57} + Z_{58} - X_{45} - Z_{45} = 0$
Node 6	$+X_{68} + Y_{67} + Y_{69} + Y_{6,10} + Y_{6,11} + Z_{68} - X_{56} - Y_{16} - Y_{26} - Y_{36} - Y_{46} - Z_{56} = 0$
Node 7	$+Z_{79} + Z_{7,10} + Z_{7,11} - X_{57} - Y_{17} - Y_{27} - Y_{37} - Y_{47} - Y_{67} - Z_{57} = 0$
Node 8	$+X_{89} + Z_{89} + Z_{8,10} - X_{58} - X_{68} - Z_{58} - Z_{68} = 0$
Node 9	$+X_{9,10} + Y_{9,10} + Y_{9,11} - X_{89} - Y_{19} - Y_{29} - Y_{39} - Y_{49} - Y_{69} - Y_{79} - Z_{89} = 0$
Node 10	$+X_{10,11} + Y_{10,11} + Z_{10,11} - X_{9,10} - Y_{1,10} - Y_{2,10} - Y_{3,10} - Y_{4,10} - Y_{6,10} - Y_{7,10} - Y_{9,10} - Z_{8,10} = 0$
Node 11	$-X_{10,11} - Y_{1,11} - Y_{2,11} - Y_{3,11} - Y_{4,11} - Y_{6,11} - Y_{7,11} - Y_{9,11} - Y_{10,11} - Z_{10,11} = 1$

Notes:

1. X=arc assigned to rail mode; Y=arc assigned to ship mode; Z=arc assigned to truck mode. Each arc takes on a value of 1 or 0, depending on whether it is selected by the Solver.
2. The subscript numerals refer to the origin and destination nodes in that particular arc. For instance, X_{12} indicates an arc from node 1 to node 2 via rail. Similarly, $Z_{2,11}$ indicates an arc from node 2 to node 11 via ship.

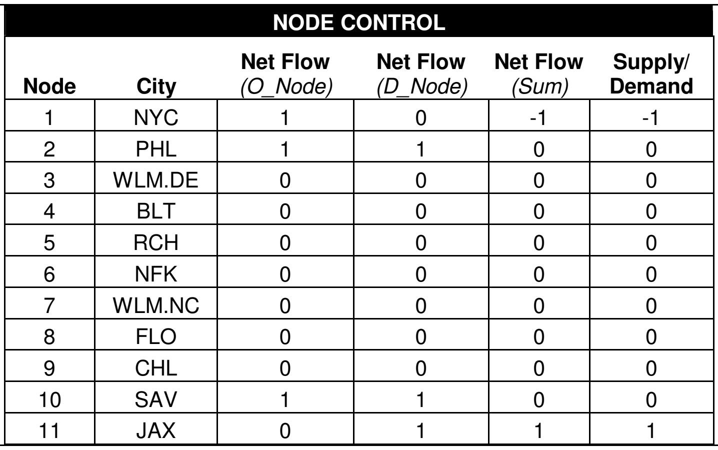
Table 5-2. Example Trip Layout



Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	13	Ship	2	PHL	10	SAV
1	52	Truck	10	SAV	11	JAX

The node 11 constraint is also satisfied because arc $Z_{10,11}$ yields a sum of 1. Thus, maintaining the balance of flow in these constraints is imperative in ensuring the effectiveness of the model during optimization. It ensures that the Solver always chooses a combination of routes, or arcs, that have the origin and destination nodes as specified by the model user.

Table 5-3. Example Solution Depicting Satisfied Net Flow Constraints



NODE CONTROL					
Node	**City**	**Net Flow** *(O_Node)*	**Net Flow** *(D_Node)*	**Net Flow** *(Sum)*	**Supply/ Demand**
1	NYC	1	0	-1	-1
2	PHL	1	1	0	0
3	WLM.DE	0	0	0	0
4	BLT	0	0	0	0
5	RCH	0	0	0	0
6	NFK	0	0	0	0
7	WLM.NC	0	0	0	0
8	FLO	0	0	0	0
9	CHL	0	0	0	0
10	SAV	1	1	0	0
11	JAX	0	1	1	1

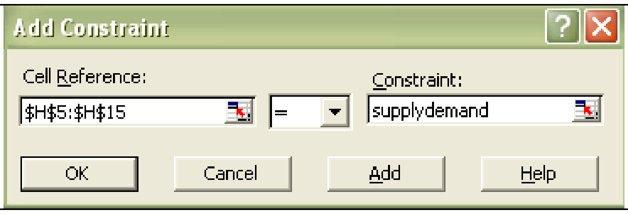
5.3.2. Binary Constraints

Binary constraints are vital to the effectiveness of the model are binary constraints. Binary constraints are applied to the decision variables; they ensure that the values of each changing cell is restricted to either 1 or 0 to indicate wither or not a route segment has been selected, essentially acting as an “on/off” switch in each changing cell.

5.4. Constraints as Shown on the Solver Parameters Dialog

In the model, there is a range of cells that represent the net flow value for each of the 11 nodes, and this array is called *netflow*. Additionally, there is a range of cells that contain the supply or demand value, and this array is named *supplydemand.* As shown in Figure 5-9, the constraint may be entered as cell range (i.e., *J15:J15*) or typing out its assigned name. The same applies for the *selectroute=binary* constraint, which should be entered as shown in Figure 5-10.

Figure 5-9. Entering the *netflow=supplydemand* Constraint



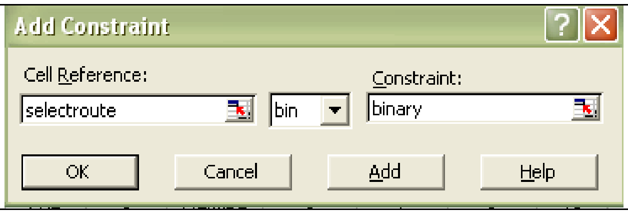
Add Constraint

Cell Reference: $H$5:$H$15

=

Constraint: supplydemand

Figure 5-10. Entering the *selectroute=binary* Constraint



Add Constraint

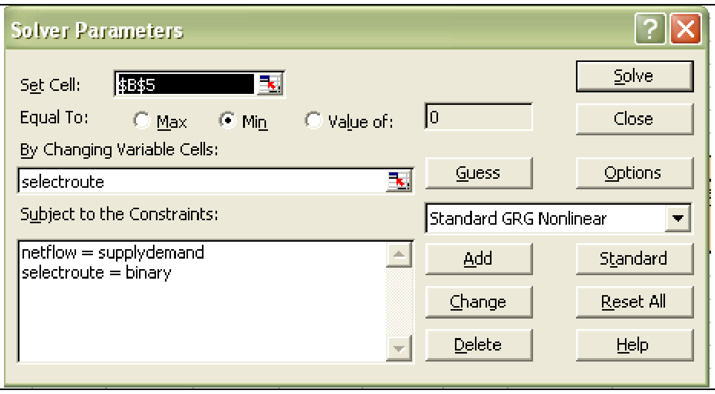
Cell Reference: selectroute

bin

Constraint: binary

In any optimization run, the Solver Parameters Dialog should contain both the *netflow*=supplydemand and *selectroute=binary* constraints, as discussed in the previous section, and they should be displayed in the Solver Parameters dialog box as shown in Figure 5-11.

Figure 5-11. Constraints as Shown in the Solver Parameters Dialog Box



Solver Parameters

Set Cell: $B$5

Equal To: ○ Max ● Min ○ Value of: 0

By Changing Variable Cells: selectroute

Subject to the Constraints:

netflow = supplydemand
selectroute = binary

Standard GRG Nonlinear

In addition, the *Set Cell*, shown in the top left corner of Figure 5-11, contains the cell reference to the decision objective on the *Solver* worksheet that the Solver is to optimize, and it is important to ensure that the appropriate reference cell is assigned before optimization commences.

Regarding Solver engines, there are three Solver engines are available for use: the Standard GRG Nonlinear engine, the Standard Simplex LP engine, and the Standard Evolutionary engine. In all optimizations relevant to this thesis, the Standard GRG Nonlinear engine should be used, as shown in the center right section of the image in Figure 5-11.

6.0. Optimization of Decision Objectives & Constraints

6.1. Optimization of Decision Objectives

In this section, each of the decision objectives—travel time, travel cost, and six pollutant emissions— are discussed further in detail and the mathematical representations are explained. Note that these mathematical representations are translated into Excel formulas and may not follow the makeup of the equations.

6.2. Travel Time as the Decision Objective

The total travel time *T* is calculated as the sum of the Base Travel Time (BTT) and the Applied Dray Time (ADT) for each route segment (see Equation 6-1(a)). The BTT is calculated as the travel speed *k* and distance *d* within each of the three travel zones *z*—origin zone, destination zone, and through-zone— multiplied by the congestion index *I* for route segment *s* using mode *m*. The BTT is then multiplied by the *Select_Route?* variable X_s, which equals "1" only if route segment *s* has been selected; if the route segment *s* is not selected, the BTT will not be calculated. Equation 6-1(b) depicts the equation for the BTT.

Equation 6-1. Calculation of Total Travel Time

6-1(a). Total Travel Time

$$T = \sum_{(X_s=1)} \left(BTT_s + ADT_s \right)$$

Where:

T Is the Total Travel Time for all route segments *s*.
s Is a single route segment *s*.
BTT_s Is the Base_Travel_Time for route segment *s*.
ADT_s Is the Applied_Dray_Time for route segment *s*.

6-1(b). Base Travel Time

$$BTT_s = \sum_z \left(\frac{d_{s,m}}{k_{m,z}} \cdot I_{s,m} \right) \cdot X_s$$

Where:

BTT_s	Is the Base Travel Time for route segment *s*.
z	Is the set of travel zones where 1=origin zone, 2=destination zone, and 3=through-zone.
$d_{s,m}$	Is the distance *d* of route segment *s* via mode *m*.
$k_{m,z}$	Is the travel speed *k* for mode *m* used in travel zone *z*.
$I_{s,m}$	Is the congestion index *I* for route segment *s* via mode *m*.
X_s	Is a binary variable equal to "1" if route segment *s* is selected, and "0" otherwise.

6-1(c). Applied Dray Time

$$ADT_s = \sum \left(X_s \cdot dt_t \cdot Y_m \right)$$

ADT_s	Is the Applied Dray Time for route segment *s*.
X_s	Is a binary variable equal to "1" if route segment *s* is selected, and "0" otherwise.
L_m	Is the drayage time *dt* used in route segment *s*.
Y_m	Is a set of binary variables that represent the set of possible connecting route segments with the same mode *m*, if any, and whose value will be equal to "1" if a segment within the set is selected, and "0" otherwise.

Furthermore, the ADT, whose equation is shown in Equation 6-1(c), is calculated as the dray time *dt* for a route segment *s*, multiplied by its X_s variable and the set of next possible connecting route segments Y_{sm} that share the same mode, which are also binary variables.

The ADT for a route segment is generated only if the current segment is selected, and if the route segment that follows employs a different mode than the previous. Thus, for each route segment, the *Y* variable represents three different sets of possible connecting route segments for each mode, resulting in different possible dray times. The inclusion of the *Y* variable enables the correct dray time to be applied.

6.3. Travel Cost as the Decision Objective

The total travel cost is comprised of the Base Travel Cost (BTC) and the Applied Dray Cost (ADC), as shown in Equation 6-2(a), for all selected route segments X_s=1. The BTC is essentially the total segment distance d (or the sum of the distance in each travel zone z) multiplied by the rate-per-mile r for the mode m used, and multiplied again by the *Select_Route?* variable, which is a binary variable that equals "1" when the route segment is selected, and "0" otherwise. The BTC equation is shown in Equation 6-2(b).

Equation 6-2. Calculation of Total Travel Cost

6-2(a). Total Travel Cost

$$C = \sum_{(X_s=1)} \left(BTC_s + ADC_s \right)$$

Where:

C	Is the total travel cost C for all selected route segments where X_s=1.
X_s	Is a binary variable equal to "1" if route segment s is selected, and "0" otherwise.
$B\ TC_s$	Is the Base Travel Cost of route segment s.
ADC_s	Is the Applied Dray Cost of route segment s.

6-2(b). Base Travel Cost

$$BTC = X_s \cdot r_m \cdot \sum \left(d_z \right)$$

Where:

r_m	Is the rate-per-mile r of mode m.
d_z	Is the distance d in zone z.

6-2(c). Applied Dray Cost

$$ADC_s = \sum \left(X_s \cdot dc_t \cdot Y_m \right)$$

Where:

ADC_s	Is the Applied Dray Cost of route segment s.
X_s	Is a binary variable equal to "1" if route segment s is selected, and "0" otherwise.
dc_s	Is the drayage cost dc used in route segment s.
Y_m	Is a set of binary variables that represent the set of possible connecting route segments with the same mode m, if any, and whose value will be equal to "1" if a segment within the set is selected, and "0" otherwise.

Furthermore, the ADC, whose equation is shown in Equation 6-2(c), is calculated as the dray cost dc for a route segment s, multiplied by its X_s variable and the set of next possible connecting route segments Y_{sm} that share the same mode, which are also binary variables. Similar to its purpose in travel time calculations, the Y variable represents three different sets of route segments, each grouped by mode. The appropriate *dc* is applied when the current route segment and another route segment from one of the *Y* sets both equal “1.”

6.4. Pollutant Emissions as the Decision Objective

In the case of emissions, optimization is performed individually for each of the six pollutants, VOC, CO, NO_x, PM, SO_x, and CO_2. Equation 6-3(a) depicts the general equation for the total emissions output of a given pollutant, whose structure follows those of total travel time and total travel cost. The total emissions output for a given pollutant E_p is equal to the sum of the Base Emissions Output (BEO) and the Applied Idling Emissions (AIE).

Equation 6-3. Calculation of Total Emissions Output for a Given Air Pollutant

6-3(a). Total Emissions Output

$$E_p = \sum_{(X_s=1)} \left(BEO_s + AIE_s \right)$$

Where:

E_p	Is the total emissions output *E* of a given air pollutant *p*, for all selected route segments where X_s=1.
X_s	Is a binary variable equal to “1” if route segment *s* is selected, and “0” otherwise.
BEO_s	Is the Base Emissions Output of route segment *s*.
AIE_s	Is the Applied Idling Emissions of route segment *s*.

6-3(b). Base Emissions Output

$$BEO_s = X_s \cdot v_{p,m} \cdot \sum \left(d_z \right)$$

Where:

BEO_s	Is the Base Emissions Output of route segment *s*.
X_s	Is a binary variable equal to “1” if route segment *s* is selected, and “0” otherwise.
$v_{p,m}$	Is the emission factor *v* for the pollutant *p* using mode *m*.
d_z	Is the distance *d* in zone *z*.

6-3(c). Applied Idling Emissions

$$AIE_s = \sum \left(X_s \cdot w_m \cdot Y_m \right)$$

Where:

AIE_s	Is the Applied Idling Emissions of route segment *s*.
X_s	Is a binary variable equal to "1" if route segment *s* is selected, and "0" otherwise.
w_m	Is the idling emission factor *w* used with mode *m*.
Y_m	Is a set of binary variables that represent the set of possible connecting route segments with the same mode *m*, if any, and whose value will be equal to "1" if a segment within the set is selected, and "0" otherwise.

The BEO is the product of the *Select_Route?* variable for a route segment, X_s, the emission factor v for the pollutant p using mode m, and the total distance d_z for all travel zones within the segment. The BEO equation is shown in Equation 6-3(b). Additionally, the AIE, shown in Equation 6-3(c), is derived as the product of the idling emission factor w used with mode m, the *Select_Route?* variable depicted by X_s, and the set of next possible connecting route segments that share the same mode, represented by the set of binary variables Y_m.

6.5. Regarding Objective Formulae in Optimization Columns

The Total Travel Time, Total Segment Cost, and all five of the emissions optimization columns (as shown in Figures 5-2, 5-3, and 5-4) contain sensitive formulas that, when altered, can cause the model to optimize incorrectly. In those columns, the cells are uniquely set up so that they all direct to the same group of possible secondary route segments. This is because the destination node in the primary segment becomes the origin node in the secondary segment. Therefore, care should be exercised in ensuring that each formula are directed to the correct set of cells; otherwise, the Solver will not evaluate all segment options that are actually available. This is the reason why the Master Route List on the *Solver* worksheet does not list the route segments in the exact order by *Route_ID*. Instead, the list is sorted using the Sort function on

Excel by first the *O_Node*, the *Mode*, and then the *D_Node*. *If the order of this route list is altered, the formulae in each of the cells within the Total Travel Time and Total Segment Cost columns will not direct to the correct decision variables in the* Select_Route? *column, and thus the model will not perform correctly.*

7.0. Model Demonstration and Case Studies

7.1. Case Study 1: Basic Demonstration of Model

This case study attempts to demonstrate several basic model functions by exploring time-optimal solutions with constraints on other variables. However, a base case scenario must first be established.

In the base case scenario, travel time is optimized with no constraints other than the two default constraints, which are the *netflow=supplydemand* and *selectroute=binary* constraints. With the *Set Cell* on the Solver Parameters dialog set to the decision objective— total travel time—the Solver performed optimization and produced a time-optimal solution of 15.65 hours; the summary results are shown in Table 7-1 and the trip itinerary is shown in Table 7-2.

Since the time-optimal solution was 15.65 hours, a next step might be to find the next optimal solution, for comparison purposes. In order for the model to search for the best possible solution with a trip time that is longer than 15.65 hours, Scenario 1A consists of the constraint *time* ≥ 15.66 hours. In Scenario 1B, the time constraint is changed to *time* ≥ 17.41 hours. In Scenario 1C, the time constraint is *time* ≥ 17.51 hours. The solutions and itineraries for all three scenarios are summarized below in Tables 7-1 and 7-2.

Table 7-1. Summary Results of the CS1 Base Case Scenario and Scenarios 1A, 1B and 1C

		Base Case	Scenario 1A	Scenario 1B	Scenario 1C
Time	*hours*	15.65	16.94	17.20	17.51
Cost	*$/trip*	1,275.47	1,769.57	1,524.28	1,894.12
VOC	*g/trip*	127.36	165.16	156.34	145.34
CO	*g/trip*	367.43	623.75	547.13	472.99
NOx	*g/trip*	2,612.99	3,275.24	3,188.59	2,881.67
PM	*g/trip*	61.90	70.93	69.99	67.87
SOx	*g/trip*	29.73	62.75	56.57	42.98
CO2	*g/trip*	134,968.91	290,052.67	257,629.03	177,919.87
IM Switches		0	2	1	2
Constraints *(Cell References[13])*		1. Netflow=supplydemand *(I5:I15=J5:J15)*	1. Netflow=supplydemand *(I5:I15=J5:J15)*	1. Netflow=supplydemand *(I5:I15=J5:J15)*	1. Netflow=supplydemand *(I5:I15=J5:J15)*
		2. Selectroute=binary *(A21:A72=binary)*	2. Selectroute=binary *(A21:A72=binary)*	2. Selectroute=binary *(A21:A72=binary)*	2. Selectroute=binary *(A21:A72=binary)*
			3. Time ≥ 15.66 hours *(B5 ≥ 15.66)*	3. Time ≥ 16.95 hours *(B5 ≥ 16.95)*	3. Time ≥ 17.21 hours *(B5 ≥ 17.21)*

At a glance, the Results Summary shows little disparity in the time sub-optimal solutions from Scenarios 1A, 1B and 1C. The itineraries show a combination of predominantly rail-based route segments, with slight variations in single-leg truck routes.

Table 7-2. Itineraries from the CS1 Base Case Scenario and Scenarios 1A, 1B and 1C

Base Case

Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

Scenario 1A

Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	46	Truck	8	FLO	10	SAV
1	50	Rail	10	SAV	11	JAX

Scenario 1B

Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	52	Truck	10	SAV	11	JAX

Scenario 1C

Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	9	Truck	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

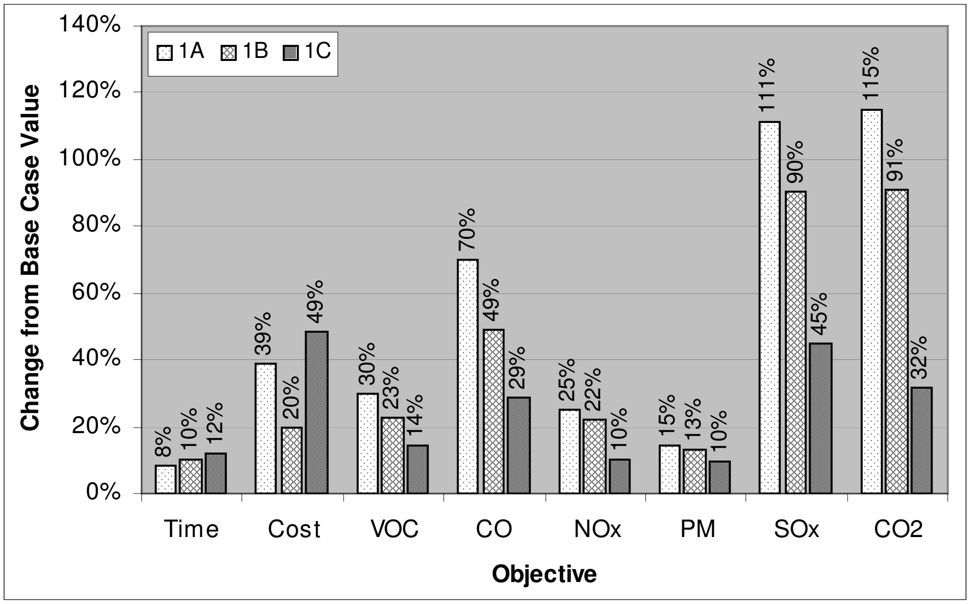
---

[13] Cell references indicate how the constraint was entered in the Solver Parameters dialog box.

Figure 7-1, shown below, depicts the percentage change of each objective from the base case value according to each scenario. Perhaps the most noticeable aspect is how, for such small incremental changes in time, relatively dramatic changes occur in all the other variables. While travel time—the decision objective in this case—is the only variable that increases in percentage change in each subsequent scenario, all the emissions objectives decrease in percentage change. This suggests that small tradeoffs in travel time can reap considerable emissions savings. For instance, there is a difference of 4 percent in travel time between Scenarios 1A, 1B and 1C, but the difference in CO_2 within these scenarios can range as much as 83 percent.

In contrast to the gradual increase in time and the gradual decrease of emissions, Figure 7-1 also shows some disparity between the cost values in each scenario. Scenario 1A is 39 percent more costly than the base case scenario, and Scenario 1C is 49 percent more costly; however, quite oddly, Scenario 1B is least costly, at 20 percent. This suggests that, for small changes in travel time, cost values can be quite volatile.

Figure 7-1. Percentage Deviation of Each Variable in CS1 Base Case Scenarios



If we continue to assume that the base case scenario is unacceptable, and that an alternative time-optimal scenario needs to be selected, one might want to continue running the model to find other time sub-optimal solutions that yield more reasonable cost values while keeping CO_2 emissions low. Thus, Scenarios 1D and 1E were run, where the constraint on time was set as *time* ≥ 17.52 hours and *time* ≥ 18.42 hours for each scenario, respectively. Table 7-3 shows the resulting values of each objective, and Table 7-4 shows the itineraries for each.

Table 7-3. Summary Results of Scenarios 1D and 1E

		Scenario 1D	Scenario 1E
Time	*hours*	18.41	19.06
Cost	*$/trip*	1,858.52	1,553.58
VOC	*g/trip*	167.91	155.14
CO	*g/trip*	613.88	447.54
NOx	*g/trip*	3,334.12	3,182.75
PM	*g/trip*	73.52	75.40
SOx	*g/trip*	59.54	36.21
CO2	*g/trip*	275,638.23	164,398.23
IM Switches		2	0
Constraints *(Cell References)*		1. Netflow=supplydemand *(I5:I15=J5:J15)* 2. Selectroute=binary *(A21:A72=binary)* 3. Time ≥ 17.52 hrs *(B5 ≥ 17.52)*	1. Netflow=supplydemand *(I5:I15=J5:J15)* 2. Selectroute=binary *(A21:A72=binary)* 3. Time ≥ 18.42 hrs *(B5 ≥ 18.42)*

Table 7-4. Itineraries from Scenarios 1D and 1E

Scenario 1D

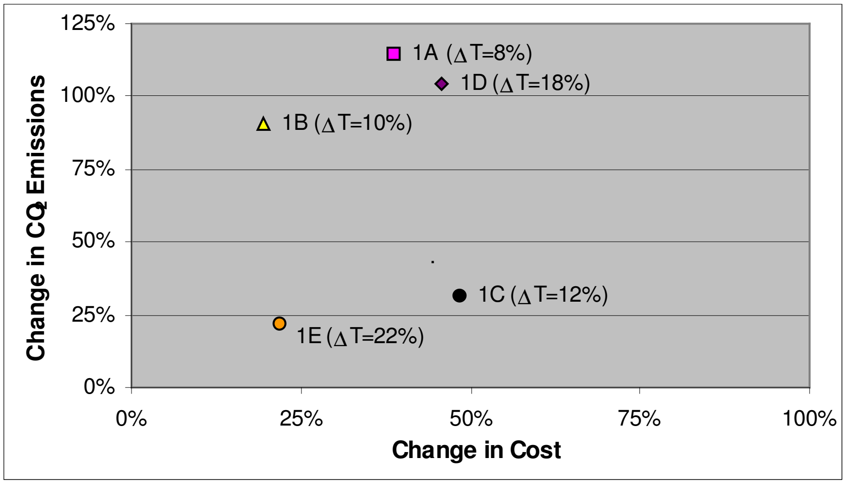
Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	23	Truck	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

Scenario 1E

Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	29	Rail	5	RCH	6	NFK
1	36	Rail	6	NFK	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

To distinguish the tradeoffs between cost and CO_2 solutions from Scenarios 1A-1E, a graph was generated, and is shown below in Figure 7-2. Each point on the graph indicates the intersection of the percentage change in cost and CO_2 for an individual scenario. The label at each point indicates the scenario, and enclosed in parentheses is the percentage change in time for that one scenario from the time-optimal base case (i.e., ΔT=8% indicates that Scenario 1A is 8 percent longer than the travel time in the base case scenario). Figure 7-2 shows that Scenarios 1D and 1E produce dramatically less CO_2 emissions than Scenarios 1A-1C (but not less than the CS1 base case). With regard to cost, Scenario 1D emerged as the second most costly scenario, at 46 percent, and produces the second highest amount of CO_2 emissions, at 104 percent. However, 1E greatly differs in that it offers less differential cost from the base case, at 22 percent, and the lowest CO_2 emissions of all 5 scenarios at 22 percent. The tradeoff for the low cost and CO_2 emissions is a 22 percent increase in travel time.

Figure 7-2. Cost and CO_2 Tradeoffs Between Time-Optimal Solutions in CS1



Note: Refer to Section C-8.0 in Appendix C for the data table.

Assuming a 22 percent increase in trip length is acceptable, Scenario 1E would emerge as the most preferable scenario. For whichever range in acceptable travel times is applicable, a decision-maker is able to use this optimization model to derive different scenarios and make better decisions.

The worksheet containing Solver results, itineraries, and associated graphs from Case Study 1 are shown in Appendix C.

7.2. Case Study 2

Suppose that a transportation planner for a major freight company learns that rail and truck freight services in the Florence, SC region has been terminated, and he is instructed to eliminate the FLO node altogether. The transportation planner is also instructed to explore time-optimal scenarios and evaluate how the overall emissions payload would be affected. To examine what would be the new time-optimal base case, the planner would run the model for time under a set of new constraints.

Table 7-5 shows all the routes that contain the FLO node, and their respective cell references. Those route segments are to be "blocked," or removed, from the field of possible routing options. Table 7-6 indicates the solution values for the original time-optimal base case scenario as well as the new CS2 time-optimal solution, and the percentage change in between.

The original base case solution is the original time-optimal solution that arises with default data values on the *Inputs* worksheet, and default constraints. Under the CS2 time-optimal solution, the aforementioned route segments were entered into the Solver dialog box using their respective cell references and were set to zero.

Table 7-5. Routes Containing the FLO Node

Route #	Mode	O_Node	O_City	D_Node	D_City
33	Rail	5	RCH	8	FLO
34	Truck	5	RCH	8	FLO
36	Rail	6	NFK	8	FLO
40	Truck	6	NFK	8	FLO
44	Rail	8	FLO	9	CHL
45	Truck	8	FLO	9	CHL
46	Truck	8	FLO	10	SAV

Table 7-6. Summary Results of the Time-Optimal Base Case and CS2 Base Case Scenarios

Objective	Units	Original Base Case	CS2 Base Case	% Δ from Base Case
Time	*hours*	15.65	23.46	49.91%
Cost	*$/trip*	1,275.47	1,426.29	11.82%
VOC	*g/trip*	127.36	587.56	361.32%
CO	*g/trip*	367.43	2,331.30	534.50%
NOx	*g/trip*	2,612.99	10,790.97	312.97%
PM	*g/trip*	61.90	363.59	487.37%
SOx	*g/trip*	29.73	13,190.77	44274.85%
CO2	*g/trip*	134,968.91	961,778.43	612.59%
IM Switches		0	1	100.00%
Constraints *(Cell References)*		1. Netflow=supplydemand *(I5:I15=J5:J15)* 2. Selectroute=binary *(A21:A72=binary)*	1. Netflow=supplydemand *(I5:I15=J5:J15)* 2. Selectroute=binary *(A21:A72=binary)* 3. Blocked routes # 33-34, 36, 40, & 44-46 *(A51=0, A54:A55=0, A60=0, & A64:A66=0)*	

Table 7-7. Itineraries from the Time-Optimal Base Case and CS2 Base Case Scenarios

Original Base Case

Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

CS2 Base Case

Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	5	Ship	1	NYC	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

As Table 7-7 reveals, the new itinerary for the CS2 base case solution consists of a ship route from NYC to CHL, and switches to rail mode for the remainder of the trip to JAX. In terms of travel convenience, the new itinerary may not be much different from the all-rail trip in the base case scenario. However, as indicated by the percentage change values in Table 7-6, the new trip time increased 49.9 percent to 23.46 hours, and the trip cost rose 11.8 percent to $1,426.29. Emissions of each of the six pollutants leap to percentage changes that are in the hundreds and thousands, such as a 361.3 percent increase in VOC, 534.5 percent increase in CO, and quite strikingly, a 44,274.8 percent increase in SO_x emissions.

The transportation planner decides that the CS2 optimal solution produces unacceptable levels of SO_x emissions. He decides to evaluate two possible options:

- **Option A:** Obtain the next best time-optimal solution and determine whether the cost and SO_x emissions tradeoff is better than the base case solution.
- **Option B:** Seek an alternate trip that will produce no more than half of the SO_x emissions in the CS2 optimal solution, with a single condition: that the new trip cost not exceed 25 percent of the time-optimal cost value. In the condition that it does, the transportation planner must rescind the Option.

For Option A, the second best time-optimal solution is sought, and a new constraint is added where $time \geq 23.47$ hours. For Option B, a different solution is sought where the SO_x value is no more than half of the value obtained in the CS2 base case solution of 13,190.77 g/trip; a constraint was inserted in the Option B scenario where $SO_x \leq 6{,}595$ grams.

The summary results for the CS2 base case scenario, and Options A and B, as well as the percentage change in solution values in both Options from the CS2 base case are shown in Table 7-8. Table 7-9 shows the itineraries for each.

As shown in Table 7-9, the itineraries in Options A and B both consist of rail-ship intermodal routes, where Option A is a ship-to-rail trip where an intermodal switch is made in SAV, and Option B consists of a rail-to-ship trip where an intermodal switch is made in WLM.NC. With respect to trip length, Option B is 8.5 percent longer than Option A, which is 0.4 percent longer than the CS2 base case trip time. However, Option A produces 2.3 percent.1 percent more SO_x emissions than the CS2 base case, but Option B produces 87.0 percent *less* SO_x emissions than the CS2 base case, which is a significant drop. With regard to cost, Option

A produces 5.7 percent less total cost, and Option B produces 9.2 percent additional cost, which remains within the 25 percent limit set by the transportation planner's criteria for Option B.

Table 7-8. Summary Results and Percentage Changes in Solution Values from CS2 Scenarios

		CS2 Base Case	**CS2 Option A**		**CS2 Option B (Run #2)***	
Objective	**Units**	*Solution Values*	*Solution Values*	*% Δ from Base Case*	*Solution Values*	*% Δ from Base Case*
Time	*hours*	23.46	23.55	0.4%	**25.55**	8.9%
Cost	*$/trip*	1,426.29	1,345.39	-5.7%	**1,557.72**	9.2%
VOC	*g/trip*	587.56	593.87	1.1%	**214.53**	-63.5%
CO	*g/trip*	2,331.30	3,659.02	57.0%	**875.35**	-62.5%
NOx	*g/trip*	10,790.97	11,058.80	2.5%	**5,169.63**	-52.1%
PM	*g/trip*	363.59	373.55	2.7%	**144.06**	-60.4%
SOx	*g/trip*	13,190.77	13,488.09	2.3%	**1,720.42**	-87.0%
CO2	*g/trip*	961,778.43	966,639.78	0.5%	**222,767.49**	-76.8%
IM Switches		1	1	0.0%	0.0%	**0.0%**
Constraints *(Cell References)*		1. Netflow=supplydemand *(I5:I15=J5:J15)*	1. Netflow=supplydemand *(I5:I15=J5:J15)*		1. Netflow=supplydemand *(I5:I15=J5:J15)*	
		2. Selectroute=binary *(A21:A72=binary)*	2. Selectroute=binary *(A21:A72=binary)*		2. Selectroute=binary *(A21:A72=binary)*	
		3. Blocked routes # 33-34, 36, 40, & 44-46 *(A51=0, A54:A55=0, A60=0, & A64:A66=0)*	3. Blocked routes # 33-34, 36, 40, & 44-46 *(A51=0, A54:A55=0, A60=0, & A64:A66=0)*		3. Blocked routes # 33-34, 36, 40, & 44-46 *(A51=0, A54:A55=0, A60=0, & A64:A66=0)*	
			4. Time ≥ 23.47 hours *(B5 ≥ 23.47 hours)*		4. % Δ SOx ≤ 50% *(B11 ≤ 6,595 grams)*	

* *Only Run #2 is shown because its solution value for time was better than the solution value in Run #1.*

Table 7-9. Itineraries from CS2 Options A and B

CS2 Option A Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	6	Ship	1	NYC	10	SAV
1	50	Rail	10	SAV	11	JAX

CS2 Option B Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	31	Rail	5	RCH	7	WLM.NC
1	43	Ship	7	WLM.NC	11	JAX

Despite the differences in travel time between Options A and B, the transportation planner decides to decides to evaluate the differences in cost and SO$_x$ emissions to assist in making his decision.

Table 7-10, shown below, reveals the solution values for cost and SO$_x$ for the base case and in Options A and B. To assess the value of SO$_x$ emissions, the total SO$_x$ output for each dollar in the cost of a particular trip was calculated. In the CS2 base case, which costs

$1,426.29, the tradeoff is 9.25 grams of SO_x for each dollar in trip cost. For Option A, the SO_x output is 10.03 grams of SO_x per dollar, and 1.10 grams of SO_x per dollar in Option B.

Table 7-10. Relationship Between Cost and SO_x Emissions Across CS2 Scenario Options

	CS2 Base Case	Option A	Option B
SOx (g)	13,190.77	13,488.09	1,720.42
Cost ($)	1,426.29	1,345.39	1,557.72
SOx Output Per Dollar (g)	9.25	10.03	1.10

Within the three scenarios shown in Table 7-10, which represent the scenarios with the least travel time possible given its own particular set of constraints, Option B reveals itself to be the scenario that will emit the least amount of SOx emissions for each dollar it costs to produce that trip. This suggests that using rail as the primary mode for most of the trip will produce these emissions benefits, and with the additional 9.2 percent in travel time, the tradeoff between SOx emissions and cost may be the more appealing choice for the transportation planner. If the transportation planner chooses that a 0.4 percent increase in trip time is worth the 5.7 percent reduction in trip cost and the additional SOx output per dollar, then Option A may be ideal.

The worksheet containing Solver results, itineraries, and associated graphs from Case Study 2 are shown in Appendix D.

7.3. Case Study 3

In this case study, let's assume that there is a freight carrier that wants to impose a cost penalty on two connecting route segments that share the same mode. By default, the model does not apply a cost penalty to same-mode connections. This is based on the assumption that the cargo remains on board during such connections, and that there is no stop made at the connection point. However, in this case study, let us assume that cargo rates have changed, and there is a drayage cost at all same-mode route connections.

The freight carrier wants to know the difference in cost, so the model is used to evaluate several sub-optimal scenarios where cost is the decision objective. To perform this, the *drayage cost* for same-mode connections must be assigned a penalty value for each mode. The changes are made in the on the *Inputs* sheet in Section 3.2. Thus, the drayage cost for rail-rail connections was assigned a penalty of $300, ship-ship connections was penalized $400, and $250 for truck-truck connections, as shown in Table 7-11.

Table 7-11. Drayage Costs Used in CS3

	Ending Mode		
Starting Mode	*Rail*	*Ship*	*Truck*
Rail	$300	$275	$300
Ship	$275	$400	$225
Truck	$300	$225	$250

Because the same-mode drayage cost for rail and ship are higher than intermodal dray costs, two outcomes may be expected: (1) the route selected is a single leg from origin to destination using any single mode, or (2) two or more route segments with intermodal switches will be selected. The objective values yielded from the base case scenario and Scenarios 3A, 3B, and 3C are summarized in Table 7-12 below. Scenario 3A was run with a cost constraint where *cost* ≥ $1,353.80, a penny more than the base case value. Similarly, Scenarios 3B and 3C were run with cost constraints set at a value rounded up to the nearest dime from the previous cost solution. Furthermore, the itineraries for each scenario are shown in Table 7-13.

Table 7-12 indicates that the first assumption previously mentioned—regarding direct, single-leg routes— did not occur, and instead, the model yielded a ship-ship route with a stop in WLM.NC, valued at $1,353.79. The itineraries for Scenarios 3A-3C as shown in Table 7-13 reflect intermodal trips, which concur with the second assumption. The base case and all 3 scenarios all demonstrate a variety of possible route layouts, and Figure 7-3 below further illustrates the differences across cost and the other objectives by showing the percentage change of each objective from its base case value.

Table 7-12. Summary Results of the CS3 Base Case Scenario and Scenarios 3A, 3B, and 3C

		Base Case	**Scenario 3A**	**Scenario 3B**	**Scenario 3C**
Time	*hours*	26.65	30.52	31.48	29.04
Cost	*$/trip*	1,353.79	1,366.28	1,613.68	1,649.29
VOC	*g/trip*	254.36	320.17	788.98	304.07
CO	*g/trip*	1,170.00	1,515.45	3,272.94	1,425.31
NOx	*g/trip*	6,749.11	8,041.85	14,085.59	7,654.08
PM	*g/trip*	199.85	231.94	463.92	224.04
SOx	*g/trip*	3,331.34	3,676.26	17,197.86	3,546.67
CO2	*g/trip*	249,374.20	368,173.27	1,431,101.37	323,141.93
IM Switches		0	1	2	2
Constraints *(Cell References)*		1. Netflow=supplydemand *(I5:I15=J5:J15)*	1. Netflow=supplydemand *(I5:I15=J5:J15)*	1. Netflow=supplydemand *(I5:I15=J5:J15)*	1. Netflow=supplydemand *(I5:I15=J5:J15)*
		2. Selectroute=binary *(A21:A72=binary)*	2. Selectroute=binary *(A21:A72=binary)*	2. Selectroute=binary *(A21:A72=binary)*	2. Selectroute=binary *(A21:A72=binary)*
			3. Cost ≥ $1,353.80 *(B6 ≥ 1353.8)*	3. Cost ≥ $1,366.30 *(B6 ≥ 1366.3)*	3. Cost ≥ $1,613.70 *(B6 ≥ 1613.7)*

Table 7-13. Itineraries from the CS3 Base Case Scenario and Scenarios 3A, 3B and 3C

CS3 Base Case

Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	4	Ship	1	NYC	7	WLM.NC
1	43	Ship	7	WLM.NC	11	JAX

Scenario 3A

Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	2	Truck	1	NYC	2	PHL
1	14	Ship	2	PHL	11	JAX

Scenario 3B

Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	2	Truck	1	NYC	2	PHL
1	13	Ship	2	PHL	10	SAV
1	52	Truck	10	SAV	11	JAX

Scenario 3C

Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	9	Truck	2	PHL	3	WLM.DE
1	21	Ship	3	WLM.DE	11	JAX

Figure 7-3 shows that cost can range from 0.9 to 21.8 percent above the base case value across Scenarios 3A-3C. While cost continuously increases after each scenario, so do all the other objectives in Scenario 3B, which consists of two intermodal switches. However, in 3B, where cost is 19.2 percent above the base case value, the values of all the emissions objectives dramatically increase, particularly with CO_2, where CO_2 rose to 474 percent and VOC by 210 percent. The time objective did not differ as much with an 18 percent increase.

Figure 7-3. Percentage Change of All Objectives in CS3 Base Case Scenarios 3A-3C

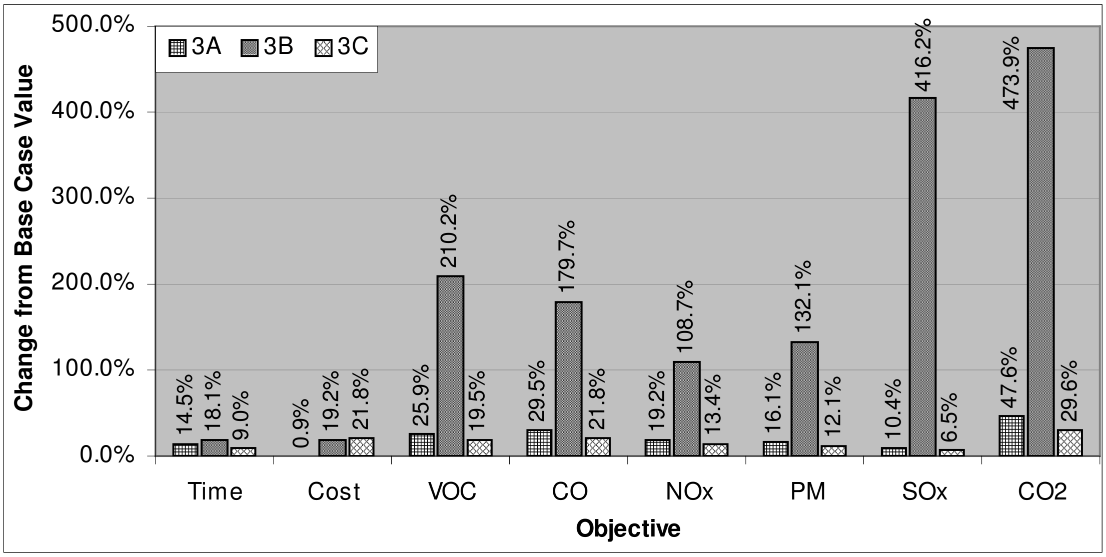


Figure 7-3 also shows that, in Scenario 3C, all objectives other than cost actually dip to a percentage change that is less than Scenario 3A. For instance, time is 9 percent, and SO_x is at 6.5 percent, but cost continues to increase to 21.8 percent. Scenario 3C also produces two intermodal switches.

As predicted, the model seems to favor trip itineraries that consist of one or more intermodal switches, and this is most likely attributed to the higher dray cost of same-mode route connections. The question now becomes: is it possible to find another cost-optimal scenario that consists of only one intermodal switch or less, and how would that scenario compare to the others in terms of emissions output?

Scenario 3D was run in the model with a new constraint on the number of intermodal switches, where *IM Switch* ≤ 1. A new constraint on cost was also entered, where *cost* ≥ \$1,366.30[14]. Table 7-14 below depicts the summary results and itinerary.

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[14] If there were no cost constraint, the model would produce the same results as in Scenario 3B. This is because 3B already has one intermodal switch. Thus, in order to find the next best possible solution with one intermodal switch, the model needs to contain a constraint that forces it to find a solution other than that of 3B.

In Scenario 3D, the Solver was able to find a new solution that yielded zero intermodal switches and quite surprisingly, a cost value of 12.8 percent above the base case value—less than that of Scenarios 3B and 3C. Figure 7-4 demonstrates how the results of Scenario 3D compare to that of 3A and 3C for the other objectives.

Table 7-14. Scenario 3D Summary Results and Trip Itinerary

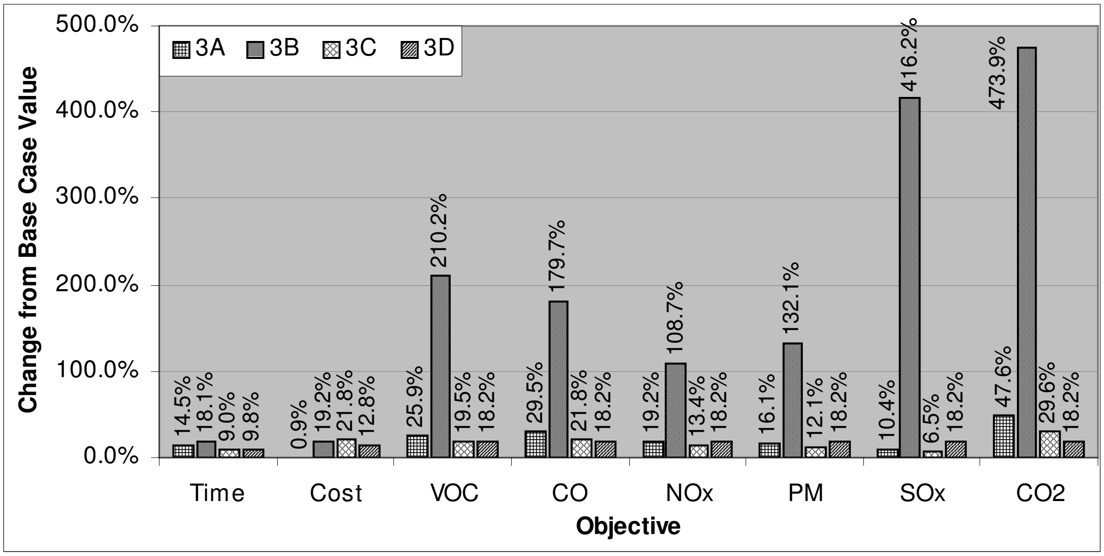
Summary Results

		Scenario 3D
Time	*hours*	29.27
Cost	*$/trip*	1,527.62
VOC	*g/trip*	300.72
CO	*g/trip*	1,383.23
NOx	*g/trip*	7,979.10
PM	*g/trip*	236.27
SOx	*g/trip*	3,938.46
CO2	*g/trip*	294,821.45
IM Switches		0
Constraints *(Cell References)*		1. Netflow=supplydemand *(I5:I15=J5:J15)*
		2. Selectroute=binary *(A21:A72=binary)*
		3. Cost ≥ $1,366.30 *(B6 ≥ 1366.3)*
		4. IM Switch ≤ 1 *(B13 ≤ 1)*

Itinerary

Select Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	5	Ship	1	NYC	9	CHL
1	49	Ship	9	CHL	11	JAX

Figure 7-4. Percentage Change of All Objectives in Scenarios 3A-3D from the Base Case



For the time objective, Scenario 3D takes 9.8 percent less time than the base case value—only 0.8 percent less than the shortest trip in 3C. With regard to VOC, CO, and CO_2 emissions, Scenario 3D produces less emissions output than any other scenario. Emissions outputs for NO_x, PM, and SO_x are still within reasonable ranges, where the difference between the value in Scenario 3D and the scenario with the least output is 4.8 percent for NO_x, 6.1 percent for PM and 11.8 percent for SO_x. These differences are relatively reasonable, given the fact that these output levels could starkly change as it did in Scenario 3B.

For the decision-maker whose primary objective is to minimize cost and the number of intermodal switches, Scenario 3A might be the most preferable. However, if trip time and emissions outputs are also deciding factors, one might consider Scenario 3D as most ideal, because it also produces relatively low cost, has no intermodal switches, and produces less overall emissions.

The worksheet containing Solver results, itineraries, and associated graphs from Case Study 3 are shown in Appendix E.

8.0. Model Limitations

As with all first-version models such as this one, several limitations exist. The following sections discuss the limitations attributed to this model, how they influence optimization efficiency and the integrity of the solutions yielded. Some of the aforementioned limitations are not necessarily barriers or obstructions to successful model use, but it is necessary to indicate and explain the issues that may arise during optimization, and present methods of overcoming or bypassing such situations.

8.1. "Good" vs. "Optimal" Solutions

The Solver provides several types of solutions, and it is important to differentiate each. The first is a *feasible solution*, which is a solution where all the constraints used by the Solver are satisfied. A feasible solution can also be an optimal solution; this is true when the objective function value is maximized or minimized. The best type of optimal solution is the *globally optimal solution*, which is when the Solver selects a feasible solution with the best possible objective function values; when no better solution exists. Finally, a *locally optimal solution* is when a feasible solution with the best objective function values within the immediate feasible region (in some cases, there may be several feasible regions, so a locally optimal solution is one where the best feasible solution within its "vicinity" is selected)[15]. "The kind of solution the Solver can find depends on the nature of the mathematical relationships between the variables and the objective function and constraints (and the solution algorithm used)" (Frontline Solvers, 2006, p. 55). To expand on this point, let's briefly review the modeling conditions from CS3.

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[15] For further details, see (Frontline Solvers, 2006, p. 55).

In CS3, a drayage cost for same-mode route connections was applied. In the CS3 base case, which was the cost-optimal scenario under the new drayage costs, the optimal solution was a ship-ship route with a stop in WLM.NC, valuated at $1,353.79. However, if we recall from previous cost solutions, another cost solution exists that is more optimal than the CS3 base case solution, and that is the single-leg trip from NYC to JAX via ship, valued at $996.80. Even with the new drayage costs applied in CS3, the $996.80 solution should have remained an eligible cost-optimal solution because it is a direct route with no drayage. The model proceeded to select the $1,353.79 solution regardless.

In finding the cost sub-optimal solution in CS3, the cost constraint would be established with $1,353.79 as the lower limit, and a new optimal solution would result in $1,366.28 (as was in Scenario 3A). However, if the $996.80 solution was the original CS3 base case solution, and the sub-optimal scenario was run with the cost constraint as *cost* ≥ $996.81, the new solution would result in $1,353.79. If not for the discovery of the $996.80 solution, a freight carrier might have proceeded with the more expensive option. The central significance in this is that the model will not always find the *most* optimal solution. However, with more time to fine-tune the model, the effectiveness of the optimization process may be improved.

8.2. Model Design & Solution Times

Nonlinear models, such as this one, are generally more difficult to solve than linear models, which translates into longer solution times and decreased likelihood of obtaining a globally optimal solution. In some cases, the Solver can continue to perform optimization for as long as twenty minutes, which can be an inconvenience with particular regard to the need for speed and efficiency in project planning. Solution times can vary greatly depending on the design of the spreadsheet model, the nature of the constraints (i.e., whether they are entered as a constant or as a cell reference containing a formula), the type of Solver engine used, and even the version of Solver used. With regard to the model developed in this thesis, the Nonlinear GRG Engine—one of three engines available for use in the student version of the Premium Solver Platform— was the most appropriate. In spite of the inconsistencies regarding optimal solutions, the Solver nonetheless offers a way to evaluate various transportation options. Further improvements in model design and upgrading the Solver software to a higher version can improve the quality of the solutions.

8.3. Inconsistency with Regard to Constraint Values

In some cases, the Solver is finicky with regard to whether it can find a feasible solution under the constraints it is given. If a constraint is placed on an objective so that the objective value cannot exceed a certain amount, a pop-up dialog will sometimes announce that the "Solver cannot find a feasible solution." In the case that this happens, several solutions can be tried. First, the constraint value can be increased or decreased by some degree, such as by one-tenth. Sometimes the constraint value will need to be incrementally increased or decreased several times before the Solver is able to find a feasible or optimal solution. Another solution is to run Solver *without resetting the decision variables*[16]. Another solution is to use the *Automatic Scaling* feature on the Solver Options dialog[17]. The reason for this inconsistency is unclear, but the aforementioned methods can alleviate this problem and deliver a solution.

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[16] This was done in several of the runs in Case Studies 1 and 2.

[17] For more details regarding the AutoScale feature, please refer to (Frontline Solvers, 2006).

8.4. Limited Resources

In the development of the model as part of this thesis, delivering a solid overall design and layout of the model was a priority. However, it was not possible to obtain direct, human assistance from Frontline Systems, the creator and developer of the Solver; due to costs being outside the budget for this thesis. Additionally, resources and literature related to building optimization models using the Solver application were limited. Thus, the major source of information and guidance was from the *Premium Solver Platform User Guide*[18]. The current design and layout is effective, but the efficiency in terms of solution time has much room for improvement.

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[18] See (Frontline Solvers, 2006).

9.0. Policy Implications and Applications for Future Research

Maintaining an efficient transportation system—on highways, railways and waterways—is imperative to economic health, and the current problems with congestion and capacity are important policy issues that must be addressed.

Freight transportation provides the movement of goods that drives the U.S. economy; however, it is well-documented in current literature that the nation's transportation system is becoming increasingly choked, as a result of increased traffic volume spurred by population increases and economic expansion. Many highway infrastructure that are connectors between major intermodal freight terminals, including ports, do not have the capacity to support increased freight volumes, and the U.S. Department of Transportation has recognized this. When the transportation system is unable to provide the efficiency and reliability that yield optimal transit times and low operating costs, the economic well-being suffers (A. Strauss-Wieder Inc., 1999).

"Goods movement today is a pressurized environment with little room for error" (Robins & Strauss-Wieder, 2006, p. 9). Congestion and the risk of encountering congestion force shippers to reevaluate their supply chains (i.e., routing options) to avoid disruptions in delivery, which may or may not be the most optimal alternative route. It is also imperative that shippers operate on a transportation network equipped with infrastructure that offers them flexibility to make the best decision in how to transport freight.

Infrastructure is a matter of public policy because its ownership and use are multi-jurisdictional. For example, ocean carriers and container ships are operated by private entities, the federal government regulates national highways and interstates, railroads, waterways and channels; terminals are operated by the private sector, and port authorities regulate overall port operations (Robins & Strauss-Wieder, 2006). Thus, maintaining an efficient transportation network equipped with proper infrastructure is a priority in the public and private sectors.

The development of a network flow model for an intermodal freight transportation network is a direct contribution to this policy arena in that it allows for public and private stakeholders to expand their knowledge base and make decisions that are better suited to their goals. It provides a systems approach to evaluating physical, operational, and user measures that define scenarios that can be actual or forecasted.

In particular, the network flow model developed as part of this thesis provides a framework for a policymaker or planner for a freight company to perform the following, provided that the model is outfitted with the appropriate data:

- Evaluate infrastructure investments, such as the accessibility of intermodal terminals according to route distance, which may contribute to assessments of whether additional terminals or access roads should be built.
- Evaluate economic efficiency of installing fleet-wide emissions technologies compared to utilizing emissions minimization objectives as the basis for route choice.
- Evaluate congestion pricing strategies as an alternative to infrastructure investments.
- Plan emergency alternative routes in the case of unanticipated disruptions (i.e., highway accidents, maintenance of railroad tracks).
- Assess emissions savings of using alternative fuels.

Performing these types of scenario analysis may require additional sorts of data that are particular to the entity by which it is employed. The model developed as part of this thesis has been simplified to allow for customized analysis by such entities.

Furthermore, as the literature review section indicated, there are very few models that address multiple modes used in freight, much less those concerned with emissions impacts. This project intends to pave the way for better, more environmentally integrated policy analysis on all levels—public or private. The presence of this type of model can enhance data collection practices related to emissions that may not have previously existed. Hopefully, with more widespread use and expanded applications, emissions impacts will have a greater presence in transportation decision-making. This is supported by the idea that an environmentally integrated decision tool can only enhance environmentally integrated policy analysis.

10.0. Conclusion

The core purpose of the model is quite simple: it allows a decision-maker to evaluate the tradeoffs of travel time, travel cost, and air emissions attributed to freight transportation. The model employs the Solver platform via Excel to perform nonlinear optimization and find the most optimal trip itinerary that satisfies the decision objective.

While the model in itself is relatively straightforward, the Case Studies have demonstrated that the model functions can be versatile, such as the ability to block or omit certain nodes and/or route segments. with this model, it is possible to evaluate how changes in certain operating costs (i.e., drayage cost) can impact the bottom line. The data sets listed on the *Inputs* sheet are intentionally basic for the purpose of model demonstration, but it is possible to further enhance or expand the datasets to allow for more precise decision-making.

For each decision-maker, the mission and criteria used in making a decision are as unique as the decision itself. Every model can be customized according to individual needs, and this model is no different. The model framework is intentioned at demonstrating how optimization can be a powerful tool in providing answers and constructing possible scenarios that can have great influence on decisions, such as those related to trip planning or policies regarding freight transportation. This model is a contribution to the arena of environmentally integrated transportation planning and modeling, and the fundamental idea of making air pollution a weighing factor in freight transportation is an important one. In the modern world where environmental interactions are of top priority among decision-makers, optimization models such as the one developed as part of this thesis can potentially pave the way to more frequent, and more importantly, more standard use in not just the freight transportation industry, but for environmental advocacy groups, public transportation agencies, and other relevant entities.

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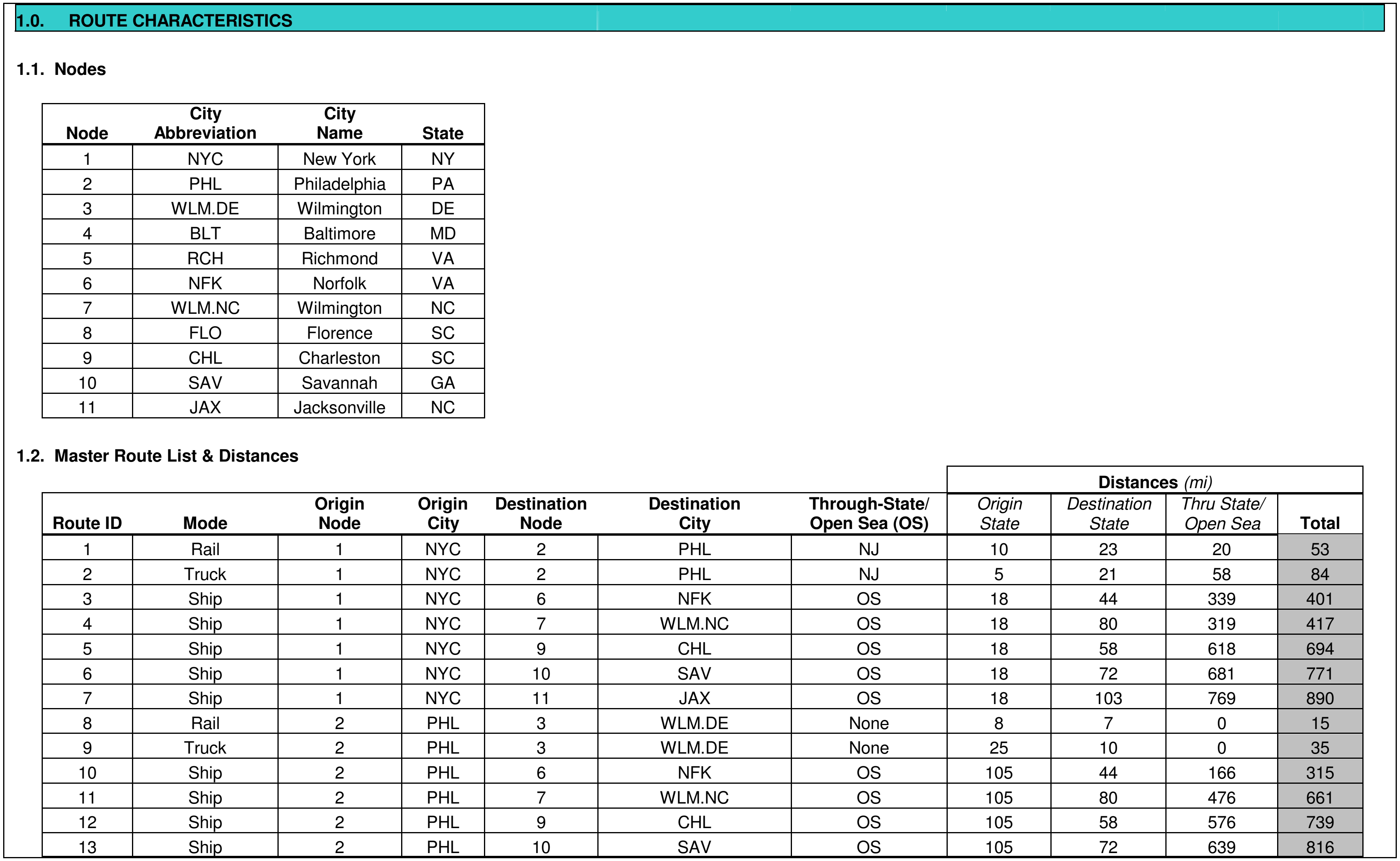
Appendix A: The *Inputs* Worksheet as Shown on Excel

A-1.0. Route Characteristics



1.0. ROUTE CHARACTERISTICS

1.1. Nodes

Node	City Abbreviation	City Name	State
1	NYC	New York	NY
2	PHL	Philadelphia	PA
3	WLM.DE	Wilmington	DE
4	BLT	Baltimore	MD
5	RCH	Richmond	VA
6	NFK	Norfolk	VA
7	WLM.NC	Wilmington	NC
8	FLO	Florence	SC
9	CHL	Charleston	SC
10	SAV	Savannah	GA
11	JAX	Jacksonville	NC

1.2. Master Route List & Distances

							Distances *(mi)*			
Route ID	**Mode**	**Origin Node**	**Origin City**	**Destination Node**	**Destination City**	**Through-State/ Open Sea (OS)**	*Origin State*	*Destination State*	*Thru State/ Open Sea*	**Total**
1	Rail	1	NYC	2	PHL	NJ	10	23	20	53
2	Truck	1	NYC	2	PHL	NJ	5	21	58	84
3	Ship	1	NYC	6	NFK	OS	18	44	339	401
4	Ship	1	NYC	7	WLM.NC	OS	18	80	319	417
5	Ship	1	NYC	9	CHL	OS	18	58	618	694
6	Ship	1	NYC	10	SAV	OS	18	72	681	771
7	Ship	1	NYC	11	JAX	OS	18	103	769	890
8	Rail	2	PHL	3	WLM.DE	None	8	7	0	15
9	Truck	2	PHL	3	WLM.DE	None	25	10	0	35
10	Ship	2	PHL	6	NFK	OS	105	44	166	315
11	Ship	2	PHL	7	WLM.NC	OS	105	80	476	661
12	Ship	2	PHL	9	CHL	OS	105	58	576	739
13	Ship	2	PHL	10	SAV	OS	105	72	639	816

	14	Ship	2	PHL	11	JAX	OS	105	103	727	935	
	15	Rail	3	WLM.DE	4	BLT	None	13	52	0	65	
	16	Truck	3	WLM.DE	4	BLT	None	15	53	0	68	
	17	Ship	3	WLM.DE	6	NFK	OS	74	44	166	284	
	18	Ship	3	WLM.DE	7	WLM.NC	OS	74	80	476	630	
	19	Ship	3	WLM.DE	9	CHL	OS	74	58	576	708	
	20	Ship	3	WLM.DE	10	SAV	OS	74	72	639	785	
	21	Ship	3	WLM.DE	11	JAX	OS	74	103	727	904	
	22	Rail	4	BLT	5	RCH	None	44	91	0	135	
	23	Truck	4	BLT	5	RCH	None	49	101	0	150	
	24	Ship	4	BLT	6	NFK	OS	163	44	0	207	
	25	Ship	4	BLT	7	WLM.NC	OS	163	80	347	590	
	26	Ship	4	BLT	9	CHL	OS	163	58	447	668	
	27	Ship	4	BLT	10	SAV	OS	163	72	510	745	
	28	Ship	4	BLT	11	JAX	OS	163	103	598	864	
	29	Rail	5	RCH	6	NFK	None	195	0	0	195	
	30	Truck	5	RCH	6	NFK	None	87	0	0	87	
	31	Rail	5	RCH	7	WLM.NC	None	72	241	0	313	
	32	Truck	5	RCH	7	WLM.NC	None	73	201	0	274	
	33	Rail	5	RCH	8	FLO	NC	72	40	178	290	
	34	Truck	5	RCH	8	FLO	NC	73	38	180	291	
	35	Ship	6	NFK	7	WLM.NC	OS	44	80	347	471	
	36	Rail	6	NFK	8	FLO	NC	64.5	40.5	193	298	
	37	Ship	6	NFK	9	CHL	OS	44	58	447	549	
	38	Ship	6	NFK	10	SAV	OS	44	72	510	626	
	39	Ship	6	NFK	11	JAX	OS	44	103	598	745	
	40	Truck	6	NFK	8	FLO	NC	105	38	180	323	
	41	Ship	7	WLM.NC	9	CHL	OS	80	58	99.8	238	
	42	Ship	7	WLM.NC	10	SAV	OS	80	72	163	315	
	43	Ship	7	WLM.NC	11	JAX	OS	80	103	251.6	435	
	44	Rail	8	FLO	9	CHL	None	100	0	0	100	
	45	Truck	8	FLO	9	CHL	None	125	0	0	125	
	46	Truck	8	FLO	10	SAV	None	158	19	0	177	
	47	Rail	9	CHL	10	SAV	None	100	22	0	122	
	48	Ship	9	CHL	10	SAV	OS	58	72	63.2	193	
	49	Ship	9	CHL	11	JAX	OS	58	103	151.8	313	
	50	Rail	10	SAV	11	JAX	OS	112	39	0	151	
	51	Ship	10	SAV	11	JAX	OS	72	103	88.6	264	
	52	Truck	10	SAV	11	JAX	OS	109	30	0	139	

A-2.0. Inputs Used in Optimization of Travel Time

2.0. INPUTS USED IN OPTIMIZATION OF TRAVEL TIME

2.1. Speeds

2.1.1. Designated Maximum Speed Limits

	Speed Limits *(mph)*		
State/Port	**Rail**	**Ship**	**Truck**
NY	70		50
NJ	70		55
PA	70		55
DE	70		55
MD	70		55
VA	70		55
NC	70		55
SC	70		60
GA	70		55
FL	70		65
NYC		25	
PHL		25	
WLM.DE		25	
BLT		25	
NFK		25	
WLM.NC		25	
CHL		25	
SAV		25	
JAX		25	
OS		50	

2.1.2. Percentage of Maximum Speed Limits

Mode	**% of Max. Speed Limit**
Rail	85%
Ship	85%
Truck	85%

2.1.3. Estimated Travel Speeds (mph)

	Estimated Travel Speed *(mph)*		
State/Port	**Rail**	**Ship**	**Truck**
NY	60		43
NJ	60		47
PA	60		47
DE	60		47
MD	60		47
VA	60		47
NC	60		47
SC	60		51
GA	60		47
FL	60		55
NYC		21	
PHL		21	
WLM.DE		21	
BLT		21	
NFK		21	
WLM.NC		21	
CHL		21	
SAV		21	
JAX		21	
OS		43	

2.2. Drayage Time

2.2.1. Total Drayage Time (Hours)

	Ending Mode		
Starting Mode	Rail	Ship	Truck
Rail	0.00	1.25	0.60
Ship	0.75	0.00	1.00
Truck	0.50	1.10	0.00

2.2.2. Drayage Time Spent Idling (%)

	Ending Mode		
Starting Mode	Rail	Ship	Truck
Rail	0%	90%	90%
Ship	90%	0%	90%
Truck	90%	90%	0%

2.2.3. Drayage Time Spent Idling (Hours)

	Ending Mode		
Starting Mode	Rail	Ship	Truck
Rail	0.00	1.13	0.54
Ship	0.68	0.00	0.90
Truck	0.45	0.99	0.00

2.3. Congestion Index (CI)

2.3.1. CI at Each Node

		Base CI *(hours)*		
Node	**City**	Rail	Ship	Truck
1	NYC	1.00	1.00	1.43
2	PHL	1.00	1.00	1.36
3	WLM.DE	1.00	1.00	1.36
4	BLT	1.00	1.00	1.37
5	RCH	1.00	1.00	1.08
6	NFK	1.00	1.00	1.22
7	WLM.NC	1.00	1.00	1.18
8	FLO	1.00	1.00	1.06
9	CHL	1.00	1.00	1.18
10	SAV	1.00	1.00	1.18
11	JAX	1.00	1.00	1.17

2.3.2. CI at Each Route Segment

Route ID	Mode	Origin	Origin	Destination	Destination	Base CI in	Base CI in	Average	User-	Use User-	Final CI
1	Rail	1	NYC	2	PHL	1.00	1.00	1.00	1.00	0	1.00
2	Truck	1	NYC	2	PHL	1.43	1.36	1.40	1.00	0	1.40
3	Ship	1	NYC	6	NFK	1.00	1.00	1.00	1.00	0	1.00
4	Ship	1	NYC	7	WLM.NC	1.00	1.00	1.00	1.00	0	1.00
5	Ship	1	NYC	9	CHL	1.00	1.00	1.00	1.00	0	1.00
6	Ship	1	NYC	10	SAV	1.00	1.00	1.00	1.00	0	1.00
7	Ship	1	NYC	11	JAX	1.00	1.00	1.00	1.00	0	1.00
8	Rail	2	PHL	3	WLM.DE	1.00	1.00	1.00	1.00	0	1.00
9	Truck	2	PHL	3	WLM.DE	1.36	1.36	1.36	1.00	0	1.36
10	Ship	2	PHL	6	NFK	1.00	1.00	1.00	1.00	0	1.00
11	Ship	2	PHL	7	WLM.NC	1.00	1.00	1.00	1.00	0	1.00
12	Ship	2	PHL	9	CHL	1.00	1.00	1.00	1.00	0	1.00
13	Ship	2	PHL	10	SAV	1.00	1.00	1.00	1.00	0	1.00
14	Ship	2	PHL	11	JAX	1.00	1.00	1.00	1.00	0	1.00
15	Rail	3	WLM.DE	4	BLT	1.00	1.00	1.00	1.00	0	1.00
16	Truck	3	WLM.DE	4	BLT	1.36	1.37	1.37	1.00	0	1.37
17	Ship	3	WLM.DE	6	NFK	1.00	1.00	1.00	1.00	0	1.00
18	Ship	3	WLM.DE	7	WLM.NC	1.00	1.00	1.00	1.00	0	1.00
19	Ship	3	WLM.DE	9	CHL	1.00	1.00	1.00	1.00	0	1.00
20	Ship	3	WLM.DE	10	SAV	1.00	1.00	1.00	1.00	0	1.00
21	Ship	3	WLM.DE	11	JAX	1.00	1.00	1.00	1.00	0	1.00
22	Rail	4	BLT	5	RCH	1.00	1.00	1.00	1.00	0	1.00
23	Truck	4	BLT	5	RCH	1.37	1.08	1.23	1.00	0	1.23
24	Ship	4	BLT	6	NFK	1.00	1.00	1.00	1.00	0	1.00
25	Ship	4	BLT	7	WLM.NC	1.00	1.00	1.00	1.00	0	1.00
26	Ship	4	BLT	9	CHL	1.00	1.00	1.00	1.00	0	1.00
27	Ship	4	BLT	10	SAV	1.00	1.00	1.00	1.00	0	1.00
28	Ship	4	BLT	11	JAX	1.00	1.00	1.00	1.00	0	1.00
29	Rail	5	RCH	6	NFK	1.00	1.00	1.00	1.00	0	1.00
30	Truck	5	RCH	6	NFK	1.08	1.22	1.15	1.00	0	1.15
31	Rail	5	RCH	7	WLM.NC	1.00	1.00	1.00	1.00	0	1.00
32	Truck	5	RCH	7	WLM.NC	1.08	1.18	1.13	1.00	0	1.13
33	Rail	5	RCH	8	FLO	1.00	1.00	1.00	1.00	0	1.00
34	Truck	5	RCH	8	FLO	1.08	1.06	1.07	1.00	0	1.07

34	Truck	5	RCH	8	FLO	1.08	1.06	1.07	1.00	0	1.07
35	Ship	6	NFK	7	WLM.NC	1.00	1.00	1.00	1.00	0	1.00
36	Rail	6	NFK	8	FLO	1.00	1.00	1.00	1.00	0	1.00
37	Ship	6	NFK	9	CHL	1.00	1.00	1.00	1.00	0	1.00
38	Ship	6	NFK	10	SAV	1.00	1.00	1.00	1.00	0	1.00
39	Ship	6	NFK	11	JAX	1.00	1.00	1.00	1.00	0	1.00
40	Truck	6	NFK	8	FLO	1.22	1.06	1.14	1.00	0	1.14
41	Ship	7	WLM.NC	9	CHL	1.00	1.00	1.00	1.00	0	1.00
42	Ship	7	WLM.NC	10	SAV	1.00	1.00	1.00	1.00	0	1.00
43	Ship	7	WLM.NC	11	JAX	1.00	1.00	1.00	1.00	0	1.00
44	Rail	8	FLO	9	CHL	1.00	1.00	1.00	1.00	0	1.00
45	Truck	8	FLO	9	CHL	1.06	1.18	1.12	1.00	0	1.12
46	Truck	8	FLO	10	SAV	1.06	1.18	1.12	1.00	0	1.12
47	Rail	9	CHL	10	SAV	1.00	1.00	1.00	1.00	0	1.00
48	Ship	9	CHL	10	SAV	1.00	1.00	1.00	1.00	0	1.00
49	Ship	9	CHL	11	JAX	1.00	1.00	1.00	1.00	0	1.00
50	Rail	10	SAV	11	JAX	1.00	1.00	1.00	1.00	0	1.00
51	Ship	10	SAV	11	JAX	1.00	1.00	1.00	1.00	0	1.00
52	Truck	10	SAV	11	JAX	1.18	1.17	1.18	1.00	0	1.18

A-3.0. Travel Cost Inputs

3.0 COST INPUTS

3.1. Rate Per Mile *($/mi)*

Mode	RPM
Truck	$1.61
Rail	$1.37
Ship	$1.12

3.2. Drayage Cost *($/transfer)*

	Ending Mode		
Starting Mode	Rail	Ship	Truck
Rail	$0	$275	$300
Ship	$275	$0	$225
Truck	$300	$225	$0

A-4.0. Emissions Inputs

4.0. EMISSIONS INPUTS

4.1. Emission Factors for Each Mode During Transport

4.1.1. Emission Factors for Rail

	Rail Emission Factors					
	VOC	CO	NO_x	PM_{10}	SO_x	CO_2
g/mBtu	73.948	213.328	1,517.110	35.940	17.259	78,363.233
Btu/ton-mi	370	370	370	370	370	370
tons/TEU	5.0	5.0	5.0	5.0	5.0	5.0
g/TEU-mi	0.14	0.39	2.81	0.07	0.03	144.97

4.1.2. Emission Factors for Ships

	Ship Emission Factors					
	VOC	CO	NO_x	PM_{10}	SO_x	CO_2
Grams/ship-mi	1,493.444	6,869.444	39,626.045	1,173.381	19,559.318	1,464,151.000
TEU/ship	5,000	5,000	5,000	5,000	5,000	5,000
g/TEU-mi	0.30	1.37	7.93	0.23	3.91	292.83

4.1.3. Emission Factors for Trucks

	Truck Emission Factors					
	VOC	CO	NO_x	PM_{10}	SO_x	CO_2
g/mBtu	0.678	3.274	13.726	0.237	0.443	2,002.000
TEU/truck	2	2	2	2	2	2
g/TEU-mi	0.34	1.64	6.86	0.12	0.22	1,001.00

4.1.4 Summary of Emission Factors for Each Mode During Transportation (g/mi)

	Summary: Emission Factors by Mode *(g/mi)*					
Mode	VOC	CO	NO_x	PM_{10}	SO_x	CO_2
Rail	0.14	0.39	2.81	0.07	0.03	144.97
Ship	0.30	1.37	7.93	0.23	3.91	292.83
Truck	0.34	1.64	6.86	0.12	0.22	1,001.00

4.2 Emission Factors for Engine Idling

4.2.1. Constants Used in Conversions for Rail

Constants (Rail)	
g/bhp-hr to g/kW-hr	1.341
hp/kw	0.746
Engine Power @ Idle (hp)	17.00
Energy Production @ Idle (kW)	12.677

4.2.2. Emission Factors for Idling Rail Engines

	Emission Factors for Idling Rail Engines					
	VOC	CO	NO$_x$	PM$_{10}$	SO$_x$	CO$_2$
g/bhp-hr	0.27	1.28	4.95	0.18	0.09	589.54
g/kW-hr	0.37	1.72	6.64	0.24	0.12	790.57
g/hr	4.66	21.76	84.15	3.06	1.58	10,022.01

4.2.3. Constants Used in Conversions for Ships

Constants (Ship)	
Energy Production @ Idle (kW)	1176.0

4.2.4. Emission Factors for Idling Ship Engines

	Emission Factors for Idling Ship Engines					
	VOC	CO	NO$_x$	PM$_{10}$	SO$_x$	CO$_2$
g/kWh	0.43	1.60	5.70	0.23	N/A	N/A
g/hr	508.03	1,881.60	6,703.20	270.48	15,507.00	1,065,151.00

4.2.5. Emission Factors for Idling Truck Engines

	Emission Factors for Idling Truck Engines					
	VOC	CO	NO$_x$	PM$_{10}$	SO$_x$	CO$_2$
g/hr	12.55	94.30	55.85	2.59	0.045	10,397.00

4.2.6 Summary of Emission Factors for Idling Engines

	Summary: Idling Emission Factors by Mode *(g/hr)*					
Mode	VOC	CO	NO_x	PM_{10}	SO_x	CO_2
Rail	4.66	21.76	84.15	3.06	1.58	10,022.01
Ship	508.03	1,881.60	6,703.20	270.48	15,507.00	1,065,151.00
Truck	12.55	94.30	55.85	2.59	0.05	10,397.00

Appendix B: Components of the Solver Worksheet as Shown on Excel

(Note: The following sections reflect the calculations and resulting objective values under a sample optimal solution as shown in B1.)

B-1.0. Solver Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	17.51	*hours*
Cost	1,894.12	*$/trip*
VOC	145.34	*g/trip*
CO	515.42	*g/trip*
NOx	2,881.67	*g/trip*
PM	67.87	*g/trip*
SOx	37.88	*g/trip*
CO2	177,919.87	*g/trip*
IM Switches	2	*switch*

B-2.0. Node Control

NODE CONTROL

Node	City	Net Flow *(O_Node)*	Net Flow *(D_Node)*	Net Flow *(Sum)*	Supply/ Demand
1	NYC	1	0	-1	-1
2	PHL	1	1	0	0
3	WLM.DE	1	1	0	0
4	BLT	1	1	0	0
5	RCH	1	1	0	0
6	NFK	0	0	0	0
7	WLM.NC	0	0	0	0
8	FLO	1	1	0	0
9	CHL	1	1	0	0
10	SAV	1	1	0	0
11	JAX	0	1	1	1

B-3.0. Route Selection and Route Segment Data

ROUTE SELECTION	**ROUTE SEGMENT DATA**									
	Route Characteristics						**Distances** *(mi)*			
Select Route? *(1=yes 0=no)*	Route #	Mode	O_Node	O_City	D_Node	D_City	O_Zone	D_Zone	Through_ Zone	Total_ Distance
0	1	Rail	1	NYC	2	PHL	10	23	20	53
0	3	Ship	1	NYC	6	NFK	18	44	339	401
0	4	Ship	1	NYC	7	WLM.NC	18	80	319	417
0	5	Ship	1	NYC	9	CHL	18	58	618	694
0	6	Ship	1	NYC	10	SAV	18	72	681	771
0	7	Ship	1	NYC	11	JAX	18	103	769	890
0	2	Truck	1	NYC	2	PHL	5	21	58	84
0	8	Rail	2	PHL	3	WLM.DE	8	7	0	15
0	10	Ship	2	PHL	6	NFK	105	44	166	315
0	11	Ship	2	PHL	7	WLM.NC	105	80	476	661
0	12	Ship	2	PHL	9	CHL	105	58	576	739
0	13	Ship	2	PHL	10	SAV	105	72	639	816
0	14	Ship	2	PHL	11	JAX	105	103	727	935
0	9	Truck	2	PHL	3	WLM.DE	25	10	0	35
0	15	Rail	3	WLM.DE	4	BLT	13	52	0	65
0	17	Ship	3	WLM.DE	6	NFK	74	44	166	284
0	18	Ship	3	WLM.DE	7	WLM.NC	74	80	476	630
0	19	Ship	3	WLM.DE	9	CHL	74	58	576	708
0	20	Ship	3	WLM.DE	10	SAV	74	72	639	785
0	21	Ship	3	WLM.DE	11	JAX	74	103	727	904
0	16	Truck	3	WLM.DE	4	BLT	15	53	0	68
0	22	Rail	4	BLT	5	RCH	44	91	0	135
0	24	Ship	4	BLT	6	NFK	163	44	0	207
0	25	Ship	4	BLT	7	WLM.NC	163	80	347	590
0	26	Ship	4	BLT	9	CHL	163	58	447	668
0	27	Ship	4	BLT	10	SAV	163	72	510	745
0	28	Ship	4	BLT	11	JAX	163	103	598	864
0	23	Truck	4	BLT	5	RCH	49	101	0	150
0	29	Rail	5	RCH	6	NFK	195	0	0	195
0	31	Rail	5	RCH	7	WLM.NC	72	241	0	313
0	33	Rail	5	RCH	8	FLO	72	40	178	290
0	30	Truck	5	RCH	6	NFK	87	0	0	87
0	32	Truck	5	RCH	7	WLM.NC	73	201	0	274
0	34	Truck	5	RCH	8	FLO	73	38	180	291

0	36	Rail	6	NFK	8	FLO	64.5	40.5	193	298
0	35	Ship	6	NFK	7	WLM.NC	44	80	347	471
0	37	Ship	6	NFK	9	CHL	44	58	447	549
0	38	Ship	6	NFK	10	SAV	44	72	510	626
0	39	Ship	6	NFK	11	JAX	44	103	598	745
0	40	Truck	6	NFK	8	FLO	105	38	180	323
0	41	Ship	7	WLM.NC	9	CHL	80	58	99.8	237.8
0	42	Ship	7	WLM.NC	10	SAV	80	72	163	315
0	43	Ship	7	WLM.NC	11	JAX	80	103	251.6	434.6
0	44	Rail	8	FLO	9	CHL	100	0	0	100
0	45	Truck	8	FLO	9	CHL	125	0	0	125
0	46	Truck	8	FLO	10	SAV	158	19	0	177
0	47	Rail	9	CHL	10	SAV	100	22	0	122
0	48	Ship	9	CHL	10	SAV	58	72	63.2	193.2
0	49	Ship	9	CHL	11	JAX	58	103	151.8	312.8
0	50	Rail	10	SAV	11	JAX	112	39	0	151
0	51	Ship	10	SAV	11	JAX	72	103	88.6	263.6
0	52	Truck	10	SAV	11	JAX	109	30	0	139

B-4.0. Optimization of Travel Time

ROUTE SELECTION	**TRAVEL TIME OPTIMIZATION**															
	State/Port Zone				**Base Travel Time (BTT)** *(hrs)*			**Base Dray Time (BDT)** *(hours)*			**Applied Dray Time (ADT)** *(hours)*			**Segment Travel Time** *(hours)*		
Select Route? *(1=yes 0=no)*	O_State/Port	D_State/Port	Through_ State/Port	**Congestion Index**	BTT_ O_Zone	BTT_ D_Zone	BTT_ Through_Zone	BDT_ Rail	BDT_ Ship	BDT_ Truck	ADT_ Rail	ADT_ Ship	ADT_ Truck	Time_ Intermodal	Time_Non_ Intermodal	Total_ Travel_Time
1	NY	PA	NJ	1.00	0.17	0.39	0.34	0.00	1.25	0.60	0.00	0.00	0.60	0.60	0.89	**1.49**
0	NYC	NFK	OS	1.00	0.85	2.07	7.98	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	NYC	WLM.NC	OS	1.00	0.85	3.76	7.51	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	NYC	CHL	OS	1.00	0.85	2.73	14.54	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	NYC	SAV	OS	1.00	0.85	3.39	16.02	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	NYC	JAX	OS	1.00	0.85	4.85	18.09	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	NY	PA	NJ	1.40	0.16	0.63	1.73	0.50	1.10	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	PA	DE	None	1.00	0.13	0.12	0.00	0.00	1.25	0.60	0.00	0.00	0.00	0.00	0.00	**0.00**
0	PHL	NFK	OS	1.00	4.94	2.07	3.91	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	PHL	WLM.NC	OS	1.00	4.94	3.76	11.20	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	PHL	CHL	OS	1.00	4.94	2.73	13.55	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	PHL	SAV	OS	1.00	4.94	3.39	15.04	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	PHL	JAX	OS	1.00	4.94	4.85	17.11	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	PA	DE	None	1.36	0.73	0.29	0.00	0.50	1.10	0.00	0.50	0.00	0.00	0.50	1.02	**1.52**
1	DE	MD	None	1.00	0.22	0.87	0.00	0.00	1.25	0.60	0.00	0.00	0.00	0.00	1.09	**1.09**
0	WLM.DE	NFK	OS	1.00	3.48	2.07	3.91	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	WLM.DE	WLM.NC	OS	1.00	3.48	3.76	11.20	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	WLM.DE	CHL	OS	1.00	3.48	2.73	13.55	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	WLM.DE	SAV	OS	1.00	3.48	3.39	15.04	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	WLM.DE	JAX	OS	1.00	3.48	4.85	17.11	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	DE	MD	None	1.37	0.44	1.55	0.00	0.50	1.10	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	MD	VA	None	1.00	0.74	1.53	0.00	0.00	1.25	0.60	0.00	0.00	0.00	0.00	2.27	**2.27**
0	BLT	NFK	OS	1.00	7.67	2.07	0.00	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	BLT	WLM.NC	OS	1.00	7.67	3.76	8.16	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	BLT	CHL	OS	1.00	7.67	2.73	10.52	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	BLT	SAV	OS	1.00	7.67	3.39	12.00	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	BLT	JAX	OS	1.00	7.67	4.85	14.07	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	MD	VA	None	1.23	1.28	2.65	0.00	0.50	1.10	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	VA	VA	None	1.00	3.28	0.00	0.00	0.00	1.25	0.60	0.00	0.00	0.00	0.00	0.00	**0.00**
0	VA	NC	None	1.00	1.21	4.05	0.00	0.00	1.25	0.60	0.00	0.00	0.00	0.00	0.00	**0.00**
1	VA	SC	NC	1.00	1.21	0.67	2.99	0.00	1.25	0.60	0.00	0.00	0.00	0.00	4.87	**4.87**

0	VA	VA	None	1.15	2.14	0.00	0.00	0.50	1.10	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	VA	NC	None	1.13	1.76	4.86	0.00	0.50	1.10	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	VA	SC	NC	1.07	1.67	0.80	4.12	0.50	1.10	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	VA	SC	NC	1.00	1.08	0.68	3.24	0.00	1.25	0.60	0.00	0.00	0.00	0.00	0.00	**0.00**
0	NFK	WLM.NC	OS	1.00	2.07	3.76	8.16	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	NFK	CHL	OS	1.00	2.07	2.73	10.52	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	NFK	SAV	OS	1.00	2.07	3.39	12.00	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	NFK	JAX	OS	1.00	2.07	4.85	14.07	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	VA	SC	NC	1.14	2.56	0.85	4.39	0.50	1.10	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	WLM.NC	CHL	OS	1.00	3.76	2.73	2.35	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	WLM.NC	SAV	OS	1.00	3.76	3.39	3.84	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	WLM.NC	JAX	OS	1.00	3.76	4.85	5.92	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	SC	SC	None	1.00	1.68	0.00	0.00	0.00	1.25	0.60	0.00	0.00	0.00	0.00	1.68	**1.68**
0	SC	SC	None	1.12	2.75	0.00	0.00	0.50	1.10	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	SC	GA	None	1.12	3.47	0.46	0.00	0.50	1.10	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	SC	GA	None	1.00	1.68	0.37	0.00	0.00	1.25	0.60	0.00	0.00	0.00	0.00	2.05	**2.05**
0	CHL	SAV	OS	1.00	2.73	3.39	1.49	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	CHL	JAX	OS	1.00	2.73	4.85	3.57	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	GA	NC	OS	1.00	1.88	0.66	0.00	0.00	1.25	0.60	0.00	0.00	0.00	0.00	2.54	**2.54**
0	SAV	JAX	OS	1.00	3.39	4.85	2.08	0.75	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	GA	NC	OS	1.18	2.74	0.75	0.00	0.50	1.10	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**

B-5.0. Optimization of Travel Cost

ROUTE SELECTION	TRAVEL COST OPTIMIZATION								
	Base Dray Cost (BDC) *($)*			**Applied Dray Cost (ADC)** *($)*			**Segment Cost** *($)*		
Select Route? *(1=yes 0=no)*	BDC_ Rail	BDC_ Ship	BDC_ Truck	ADC_ Rail	ADC_ Ship	ADC_ Truck	Cost_ Intermodal	Cost_Non_ Intermodal	**Total_ Cost**
1	0.00	275.00	300.00	0.00	0.00	300.00	300.00	72.61	372.61
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	300.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	0.00	275.00	300.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
1	300.00	225.00	0.00	300.00	0.00	0.00	300.00	39.20	339.20
1	0.00	275.00	300.00	0.00	0.00	0.00	0.00	89.05	89.05
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	300.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	275.00	300.00	0.00	0.00	0.00	0.00	184.95	184.95
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	300.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	0.00	275.00	300.00	0.00	0.00	0.00	0.00	0.00	0.00
0	0.00	275.00	300.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	275.00	300.00	0.00	0.00	0.00	0.00	397.30	397.30

0	300.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	300.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	300.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	0.00	275.00	300.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	300.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	275.00	300.00	0.00	0.00	0.00	0.00	137.00	137.00
0	300.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	300.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	275.00	300.00	0.00	0.00	0.00	0.00	167.14	167.14
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	275.00	300.00	0.00	0.00	0.00	0.00	206.87	206.87
0	275.00	0.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00
0	300.00	225.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

B-6.0. Optimization of VOC Emissions

ROUTE SELECTION	**VOC EMISSIONS OPTIMIZATION** *(gVOC/segment)*								
	Base Idling Emissions			**Applied Idling Emissions**			**VOC Emissions**		
Select Route? *(1=yes 0=no)*	Base_IE_VOC_Rail	Base_IE_VOC_Ship	Base_IE_VOC_Truck	Applied_IE_VOC_Rail	Applied_IE_VOC_Ship	Applied_IE_VOC_Truck	Intermodal_VOC_Emissions	Non_Intermodal_VOC_Emissions	**Total_VOC_Emissions**
1	0.00	5.24	2.52	0.00	0.00	2.52	2.52	7.25	**9.77**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	5.65	12.42	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	5.24	2.52	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
1	5.65	12.42	0.00	5.65	0.00	0.00	5.65	11.87	**17.51**
1	0.00	5.24	2.52	0.00	0.00	0.00	0.00	8.89	**8.89**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	5.65	12.42	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	5.24	2.52	0.00	0.00	0.00	0.00	18.47	**18.47**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	5.65	12.42	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	5.24	2.52	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	5.24	2.52	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	5.24	2.52	0.00	0.00	0.00	0.00	39.67	**39.67**

0	5.65	12.42	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	5.65	12.42	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	5.65	12.42	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	5.24	2.52	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	5.65	12.42	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	5.24	2.52	0.00	0.00	0.00	0.00	13.68	**13.68**
0	5.65	12.42	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	5.65	12.42	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	5.24	2.52	0.00	0.00	0.00	0.00	16.69	**16.69**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	5.24	2.52	0.00	0.00	0.00	0.00	20.66	**20.66**
0	342.92	0.00	457.23	0.00	0.00	0.00	0.00	0.00	**0.00**
0	5.65	12.42	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**

B-7.0. Optimization of CO Emissions

ROUTE SELECTION	**CO EMISSIONS OPTIMIZATION (gCO/segment)**								
	Base Idling Emissions			**Applied Idling Emissions**			**CO Emissions**		
Select Route? *(1=yes 0=no)*	Base_IE_ CO_Rail	Base_IE_ CO_Ship	Base_IE_ CO_Truck	Applied_IE_ CO_Rail	Applied_IE_ CO_Ship	Applied_IE_ CO_Truck	Intermodal_ CO_Emissions	Non_Intermodal_ CO_Emissions	**Total_CO_ Emissions**
1	0.00	24.48	11.75	0.00	0.00	11.75	11.75	20.92	**32.67**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	42.44	93.36	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	24.48	11.75	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
1	42.44	93.36	0.00	42.44	0.00	0.00	42.44	57.30	**142.17**
1	0.00	24.48	11.75	0.00	0.00	0.00	0.00	25.65	**25.65**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	42.44	93.36	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	24.48	11.75	0.00	0.00	0.00	0.00	53.28	**53.28**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	42.44	93.36	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	24.48	11.75	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	24.48	11.75	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	24.48	11.75	0.00	0.00	0.00	0.00	114.45	**114.45**

0	42.44	93.36	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	42.44	93.36	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	42.44	93.36	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	24.48	11.75	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	42.44	93.36	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	24.48	11.75	0.00	0.00	0.00	0.00	39.47	**39.47**
0	42.44	93.36	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	42.44	93.36	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	24.48	11.75	0.00	0.00	0.00	0.00	48.15	**48.15**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	24.48	11.75	0.00	0.00	0.00	0.00	59.59	**59.59**
0	1,270.08	0.00	1,693.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	42.44	93.36	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**

B-8.0. Optimization of NOx Emissions

ROUTE SELECTION	NOx EMISSIONS OPTIMIZATION (gNOx/segment)								
	Base Idling Emissions			Applied Idling Emissions			VOC Emissions		
Select Route? *(1=yes 0=no)*	Base_IE_ NOx_Rail	Base_IE_ NOx_Ship	Base_IE_ NOx_Truck	Applied_IE_ NOx_Rail	Applied_IE_ NOx_Ship	Applied_IE_ NOx_Truck	Intermodal_ NOx_Emissions	Non_Intermodal_ NOx_Emissions	**Total_NOx_ Emissions**
1	0.00	94.67	45.44	0.00	0.00	45.44	45.44	148.75	**194.19**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	25.13	55.29	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	94.67	45.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
1	25.13	55.29	0.00	25.13	0.00	0.00	25.13	240.21	**265.34**
1	0.00	94.67	45.44	0.00	0.00	0.00	0.00	182.43	**182.43**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	25.13	55.29	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	94.67	45.44	0.00	0.00	0.00	0.00	378.90	**378.90**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	25.13	55.29	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	94.67	45.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	94.67	45.44	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	94.67	45.44	0.00	0.00	0.00	0.00	813.93	**813.93**

0	25.13	55.29	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	25.13	55.29	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	25.13	55.29	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	94.67	45.44	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	25.13	55.29	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	94.67	45.44	0.00	0.00	0.00	0.00	280.67	**280.67**
0	25.13	55.29	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	25.13	55.29	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	94.67	45.44	0.00	0.00	0.00	0.00	342.41	**342.41**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	94.67	45.44	0.00	0.00	0.00	0.00	423.80	**423.80**
0	4,524.66	0.00	6,032.88	0.00	0.00	0.00	0.00	0.00	**0.00**
0	25.13	55.29	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**

B-9.0. Optimization of PM Emissions

ROUTE SELECTION	**PM EMISSIONS OPTIMIZATION** *(gPM/segment)*								
	Base Idling Emissions			**Applied Idling Emissions**			**VOC Emissions**		
Select Route? *(1=yes 0=no)*	Base_IE_ PM_Rail	Base_IE_ PM_Ship	Base_IE_ PM_Truck	Applied_IE_ PM_Rail	Applied_IE_ PM_Ship	Applied_IE_ PM_Truck	Intermodal_ PM_Emissions	Non_Intermodal_ PM_Emissions	**Total_PM_ Emissions**
1	0.00	3.44	1.65	0.00	0.00	1.65	1.65	3.52	**5.18**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1.17	2.56	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	3.44	1.65	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
1	1.17	2.56	0.00	1.17	0.00	0.00	1.17	4.15	**5.31**
1	0.00	3.44	1.65	0.00	0.00	0.00	0.00	4.32	**4.32**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1.17	2.56	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	3.44	1.65	0.00	0.00	0.00	0.00	8.98	**8.98**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1.17	2.56	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	3.44	1.65	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	3.44	1.65	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	3.44	1.65	0.00	0.00	0.00	0.00	19.28	**19.28**

0	1.17	2.56	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1.17	2.56	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1.17	2.56	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	3.44	1.65	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1.17	2.56	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	3.44	1.65	0.00	0.00	0.00	0.00	6.65	**6.65**
0	1.17	2.56	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1.17	2.56	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	3.44	1.65	0.00	0.00	0.00	0.00	8.11	**8.11**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	3.44	1.65	0.00	0.00	0.00	0.00	10.04	**10.04**
0	182.57	0.00	243.43	0.00	0.00	0.00	0.00	0.00	**0.00**
0	1.17	2.56	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**

B-10.0. Optimization of SO_x Emissions

ROUTE SELECTION	**SOx EMISSIONS OPTIMIZATION** *(gSOx/segment)*								
	Base Idling Emissions			**Applied Idling Emissions**			**VOC Emissions**		
Select Route? *(1=yes 0=no)*	Base_IE_ SOx_Rail	Base_IE_ SOx_Ship	Base_IE_ SOx_Truck	Applied_IE_ SOx_Rail	Applied_IE_ SOx_Ship	Applied_IE_ SOx_Truck	Intermodal_ SOx_Emissions	Non_Intermodal_ SOx_Emissions	**Total_SOx_ Emissions**
1	0.00	1.78	0.85	0.00	0.00	0.85	0.85	1.69	2.55
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	0.00	1.78	0.85	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
1	0.02	0.04	0.00	0.02	0.00	0.00	0.02	7.76	7.78
1	0.00	1.78	0.85	0.00	0.00	0.00	0.00	2.08	2.08
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	1.78	0.85	0.00	0.00	0.00	0.00	4.31	4.31
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	0.00
0	0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	0.00	1.78	0.85	0.00	0.00	0.00	0.00	0.00	0.00
0	0.00	1.78	0.85	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	1.78	0.85	0.00	0.00	0.00	0.00	9.26	9.26

0	0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	1.78	0.85	0.00	0.00	0.00	0.00	0.00	**0.00**
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	**0.00**
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	**0.00**
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	**0.00**
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	**0.00**
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	**0.00**
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	1.78	0.85	0.00	0.00	0.00	0.00	3.19	**3.19**
0	0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	1.78	0.85	0.00	0.00	0.00	0.00	3.90	**3.90**
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	**0.00**
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	1.78	0.85	0.00	0.00	0.00	0.00	4.82	**4.82**
0	10,467.23	0.00	13,956.30	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**

B-11.0. Optimization of CO_2 Emissions

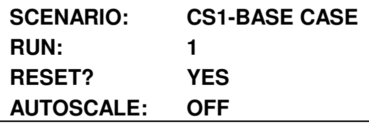
ROUTE SELECTION	**CO_2 EMISSIONS OPTIMIZATION** *(gCO_2/segment)*								
	Base Idling Emissions			**Applied Idling Emissions**			**VOC Emissions**		
Select Route? *(1=yes 0=no)*	Base_IE_ CO2_Rail	Base_IE_ CO2_Ship	Base_IE_ CO2_Truck	Applied_IE_ CO2_Rail	Applied_IE_ CO2_Ship	Applied_IE_ CO2_Truck	Intermodal_ CO2_Emissions	Non_Intermodal_ CO2_Emissions	**Total_CO2_ Emissions**
1	0.00	11,274.77	5,411.89	0.00	0.00	5,411.89	5,411.89	7,683.51	**13,095.40**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,678.65	10,293.03	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	11,274.77	5,411.89	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
1	4,678.65	10,293.03	0.00	4,678.65	0.00	0.00	4,678.65	35,035.00	**39,713.65**
1	0.00	11,274.77	5,411.89	0.00	0.00	0.00	0.00	9,423.18	**9,423.18**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,678.65	10,293.03	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	11,274.77	5,411.89	0.00	0.00	0.00	0.00	19,571.22	**19,571.22**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,678.65	10,293.03	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	11,274.77	5,411.89	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	11,274.77	5,411.89	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	11,274.77	5,411.89	0.00	0.00	0.00	0.00	42,041.87	**42,041.87**

0	4,678.65	10,293.03	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,678.65	10,293.03	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,678.65	10,293.03	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	0.00	11,274.77	5,411.89	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,678.65	10,293.03	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	11,274.77	5,411.89	0.00	0.00	0.00	0.00	14,497.20	**14,497.20**
0	4,678.65	10,293.03	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,678.65	10,293.03	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	11,274.77	5,411.89	0.00	0.00	0.00	0.00	17,686.58	**17,686.58**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
1	0.00	11,274.77	5,411.89	0.00	0.00	0.00	0.00	21,890.77	**21,890.77**
0	718,976.93	0.00	958,635.90	0.00	0.00	0.00	0.00	0.00	**0.00**
0	4,678.65	10,293.03	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**

Appendix C: Parameters and Results for Case Study 1 as Seen on Excel

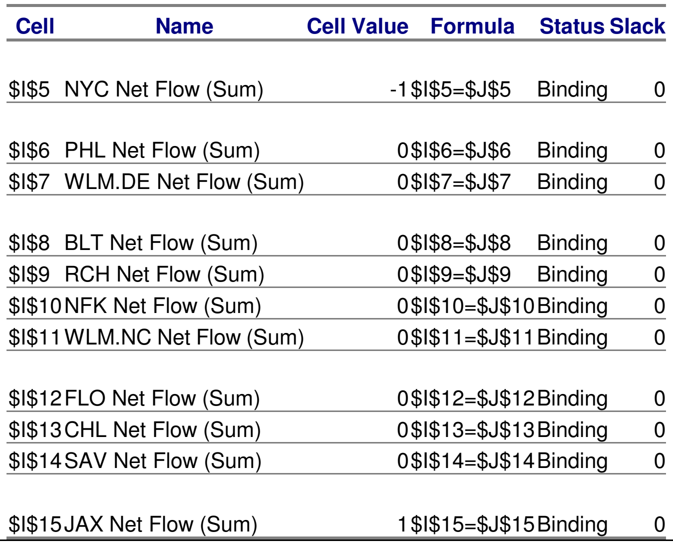
C-1.0. CS1 Base Case

Parameters



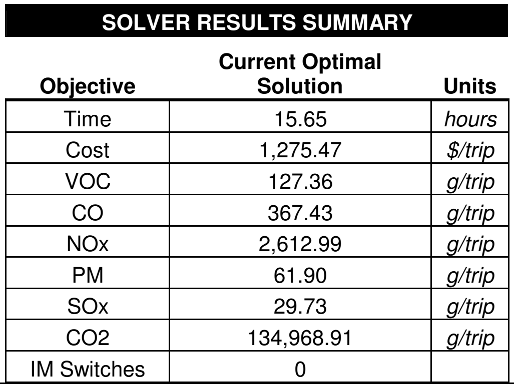
SCENARIO: **CS1-BASE CASE**
RUN: **1**
RESET? **YES**
AUTOSCALE: **OFF**

Constraints



Cell	Name	Cell Value	Formula	Status	Slack
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

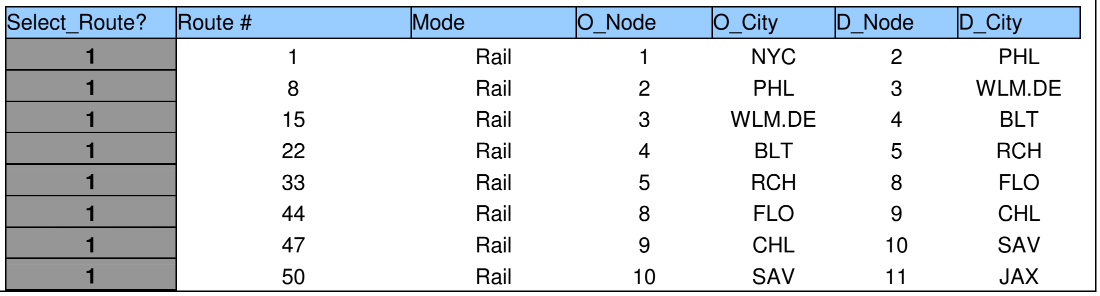
Summary Results



SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	15.65	*hours*
Cost	1,275.47	*$/trip*
VOC	127.36	*g/trip*
CO	367.43	*g/trip*
NOx	2,612.99	*g/trip*
PM	61.90	*g/trip*
SOx	29.73	*g/trip*
CO2	134,968.91	*g/trip*
IM Switches	0	

Itinerary



Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

C-2.0.a. CS1 Scenario 1A

Parameters

SCENARIO: **CS1-1A**
RUN: **1**
RESET? **YES**
AUTOSCALE: **OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$5	Time Current Optimal Solution	17.51	$B$5>=15.66	Not Binding	1.85
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	17.51	*hours*
Cost	1,894.12	*$/trip*
VOC	145.34	*g/trip*
CO	472.99	*g/trip*
NOx	2,881.67	*g/trip*
PM	67.87	*g/trip*
SOx	42.98	*g/trip*
CO2	177,919.87	*g/trip*
IM Switches	2	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	9	Truck	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

C-2.0.b. CS1 Scenario 1A (Run #2)

Parameters

SCENARIO:	**CS1-1A**
RUN:	**2**
RESET?	**NO**
AUTOSCALE:	**OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$5	Time Current Optimal Solution	16.94	$B$5>=15.66	Not Binding	1.28
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	16.94	*hours*
Cost	1,769.57	*$/trip*
VOC	165.16	*g/trip*
CO	623.75	*g/trip*
NOx	3,275.24	*g/trip*
PM	70.93	*g/trip*
SOx	62.75	*g/trip*
CO2	290,052.67	*g/trip*
IM Switches	2	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	46	Truck	8	FLO	10	SAV
1	50	Rail	10	SAV	11	JAX

C-2.0.c. CS1 Scenario 1A (Run #3)

Parameters

SCENARIO:	**CS1-1A**
RUN:	**3**
RESET?	**NO**
AUTOSCALE:	**YES**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$5	Time Current Optimal Solution	17.20	$B$5>=15.66	Not Binding	1.54
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	17.20	*hours*
Cost	1,524.28	*$/trip*
VOC	156.34	*g/trip*
CO	547.13	*g/trip*
NOx	3,188.59	*g/trip*
PM	69.99	*g/trip*
SOx	56.57	*g/trip*
CO2	257,629.03	*g/trip*
IM Switches	1	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	52	Truck	10	SAV	11	JAX

C-3.0.a. CS1 Scenario 1B

Parameters

SCENARIO:	**CS1-1B**
RUN:	**1**
RESET?	**YES**
AUTOSCALE:	**OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$5	Time Current Optimal Solution	17.51	$B$5>=16.95	Not Binding	0.56
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	17.51	*hours*
Cost	1,894.12	*$/trip*
VOC	145.34	*g/trip*
CO	472.99	*g/trip*
NOx	2,881.67	*g/trip*
PM	67.87	*g/trip*
SOx	42.98	*g/trip*
CO2	177,919.87	*g/trip*
IM Switches	2	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	9	Truck	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

C-3.0.b. CS1 Scenario 1B (Run #2)

Parameters

SCENARIO:	**CS1-1B**
RUN:	**2**
RESET?	**NO**
AUTOSCALE:	**OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$5	Time Current Optimal Solution	17.20	$B$5>=16.95	Not Binding	0.25
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	17.20	*hours*
Cost	1,524.28	*$/trip*
VOC	156.34	*g/trip*
CO	547.13	*g/trip*
NOx	3,188.59	*g/trip*
PM	69.99	*g/trip*
SOx	56.57	*g/trip*
CO2	257,629.03	*g/trip*
IM Switches	1	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	52	Truck	10	SAV	11	JAX

C-4.0.a. CS1 Scenario 1C

Parameters

SCENARIO:	**CS1-1C**
RUN:	**1**
RESET?	**YES**
AUTOSCALE:	**OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$5	Time Current Optimal Solution	17.51	$B$5>=17.21	Not Binding	0.30
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	17.51	*hours*
Cost	1,894.12	*$/trip*
VOC	145.34	*g/trip*
CO	472.99	*g/trip*
NOx	2,881.67	*g/trip*
PM	67.87	*g/trip*
SOx	42.98	*g/trip*
CO2	177,919.87	*g/trip*
IM Switches	2	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	9	Truck	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

C-4.0.b. CS1 Scenario 1C (Run #2)

Parameters

SCENARIO: **CS1-1C**
RUN: **2**
RESET? **NO**
AUTOSCALE: **OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$5	Time Current Optimal Solution	17.81	$B$5>=17.21	Not Binding	0.60
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	17.81	*hours*
Cost	1,878.47	*$/trip*
VOC	164.22	*g/trip*
CO	586.77	*g/trip*
NOx	3,260.78	*g/trip*
PM	72.88	*g/trip*
SOx	55.12	*g/trip*
CO2	255,687.25	*g/trip*
IM Switches	2	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	45	Truck	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

C-5.0.a. CS1 Scenario 1D

Parameters

SCENARIO:	**CS1-1D**
RUN:	**1**
RESET?	**NO**
AUTOSCALE:	**ON**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$5	Time Current Optimal Solution	18.81	$B$5>=17.52	Not Binding	1.29
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	18.81	*hours*
Cost	2,388.22	*$/trip*
VOC	183.14	*g/trip*
CO	729.31	*g/trip*
NOx	3,543.92	*g/trip*
PM	76.90	*g/trip*
SOx	70.90	*g/trip*
CO2	333,003.63	*g/trip*
IM Switches	4	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	9	Truck	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	46	Truck	8	FLO	10	SAV
1	50	Rail	10	SAV	11	JAX

C-5.0.b. CS1 Scenario 1D (Run #2)

Parameters

SCENARIO:	**CS1-1D**
RUN:	**2**
RESET?	**NO**
AUTOSCALE:	**ON**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$5	Time Current Optimal Solution	18.41	$B$5>=17.52	Not Binding	0.89
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	**Current Optimal Solution**	**Units**
Time	18.41	*hours*
Cost	1,858.52	*$/trip*
VOC	167.91	*g/trip*
CO	613.88	*g/trip*
NOx	3,334.12	*g/trip*
PM	73.52	*g/trip*
SOx	59.54	*g/trip*
CO2	275,638.23	*g/trip*
IM Switches	2	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	23	Truck	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

C-6.0.a. CS1 Scenario 1E

Parameters

SCENARIO:	**CS1-1E**
RUN:	**1**
RESET?	**NO**
AUTOSCALE:	**OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$5	Time Current Optimal Solution	19.07	$B$5>=18.42	Not Binding	0.65
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	19.07	*hours*
Cost	2,142.93	*$/trip*
VOC	174.32	*g/trip*
CO	652.69	*g/trip*
NOx	3,457.26	*g/trip*
PM	75.95	*g/trip*
SOx	64.73	*g/trip*
CO2	300,579.99	*g/trip*
IM Switches	3	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	9	Truck	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	52	Truck	10	SAV	11	JAX

C-6.0.b. CS1 Scenario 1E (Run #2)

Parameters

SCENARIO:	**CS1-1E**
RUN:	**2**
RESET?	**NO**
AUTOSCALE:	**OFF**

Constraints

Cell	**Name**	**Cell Value**	**Formula**	**Status**	**Slack**
$B$5	Time Current Optimal Solution	20.35	$B$5>=18.42	Not Binding	1.93
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	**Current Optimal Solution**	**Units**
Time	20.35	*hours*
Cost	2,047.68	*$/trip*
VOC	192.93	*g/trip*
CO	703.86	*g/trip*
NOx	3,844.99	*g/trip*
PM	84.43	*g/trip*
SOx	69.23	*g/trip*
CO2	319,481.98	*g/trip*
IM Switches	2	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	29	Rail	5	RCH	6	NFK
1	36	Rail	6	NFK	8	FLO
1	46	Truck	8	FLO	10	SAV
1	50	Rail	10	SAV	11	JAX

C-6.0.c. CS1 Scenario 1E (Run #3)

Parameters

SCENARIO: **CS1-1E**
RUN: **3**
RESET? **NO**
AUTOSCALE: **OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$5	Time Current Optimal Solution	19.06	$B$5>=18.42	Not Binding	0.64
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	19.06	*hours*
Cost	1,553.58	*$/trip*
VOC	155.14	*g/trip*
CO	447.54	*g/trip*
NOx	3,182.75	*g/trip*
PM	75.40	*g/trip*
SOx	36.21	*g/trip*
CO2	164,398.23	*g/trip*
IM Switches	0	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	29	Rail	5	RCH	6	NFK
1	36	Rail	6	NFK	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

C-7.0. Summary of Solution Values from All CS1 Scenarios

	SOLUTION VALUES FROM SCENARIOS IN CASE STUDY 1											
OBJECTIVE	**Base Case**	1A (Run 1)	**1A (Run 2)**	1A (Run 3)	1B (Run 1)	**1B (Run 2)**	**1C (Run 1)**	1C (Run 2)	1D (Run 1)	**1D (Run 2)**	1E (Run 1)	1E (Run 2)	**1E (Run 3)**
Time	**15.65**	17.51	**16.94**	17.20	17.51	**17.20**	**17.51**	17.81	18.81	**18.41**	19.07	20.35	**19.06**
Cost	**1,275.47**	1,894.12	**1,769.57**	1,524.28	1,894.12	**1,524.28**	**1,894.12**	1,878.47	2,388.22	**1,858.52**	2,142.93	2,047.68	**1,553.58**
VOC	**127.36**	145.34	**165.16**	156.34	145.34	**156.34**	**145.34**	164.22	183.14	**167.91**	174.32	192.93	**155.14**
CO	**367.43**	472.99	**623.75**	547.13	472.99	**547.13**	**472.99**	586.77	729.31	**613.88**	652.69	703.86	**447.54**
NOx	**2,612.99**	2,881.67	**3,275.24**	3,188.59	2,881.67	**3,188.59**	**2,881.67**	3,260.78	3,543.92	**3,334.12**	3,457.26	3,844.99	**3,182.75**
PM	**61.90**	67.87	**70.93**	69.99	67.87	**69.99**	**67.87**	72.88	76.90	**73.52**	75.95	84.43	**75.40**
SOx	**29.73**	42.98	**62.75**	56.57	42.98	**56.57**	**42.98**	55.12	70.90	**59.54**	64.73	69.23	**36.21**
CO2	**134,968.91**	177,919.87	**290,052.67**	257,629.03	177,919.87	**257,629.03**	**177,919.87**	255,687.25	333,003.63	**275,638.23**	300,579.99	319,481.98	**164,398.23**
IM Switches	**0**	2	**2**	1	2	**1**	**2**	2	4	**2**	3	2	**0**

C-8.0. Percentage Deviation from CS1 Base Case Solution Values – Data Table

	CS1 SCENARIOS				
Objective	*1A*	*1B*	*1C*	*1D*	*1E*
Time	8%	10%	12%	18%	22%
Cost	39%	20%	49%	46%	22%
CO2	115%	91%	32%	104%	22%

Appendix D: Parameters and Results for Case Study 2 as Seen on Excel

D-1.0. Original Time-Optimal Base Case

Parameters

SCENARIO: **TIME OPTIMAL BASE CASE**
RUN: **1**
RESET? **YES**
AUTOSCALE: **OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	15.65	*hours*
Cost	1,275.47	*$/trip*
VOC	127.36	*g/trip*
CO	367.43	*g/trip*
NOx	2,612.99	*g/trip*
PM	61.90	*g/trip*
SOx	29.73	*g/trip*
CO2	134,968.91	*g/trip*
IM Switches	0	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	**15**	Rail	3	WLM.DE	4	BLT
1	**22**	Rail	4	BLT	5	RCH
1	33	Rail	5	RCH	8	FLO
1	44	Rail	8	FLO	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

D-2.0. CS2 Time-Optimal Base Case

Parameters

SCENARIO: **CS2 TIME OPTIMAL**
RUN: **1**
RESET? **YES**
AUTOSCALE: **OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0
$A$51	Select_Route?	0	$A$51=0	Binding	0
$A$54	Select_Route?	0	$A$54=0	Binding	0
$A$55	Select_Route?	0	$A$55=0	Binding	0
$A$60	Select_Route?	0	$A$60=0	Binding	0
$A$64	Select_Route?	0	$A$64=0	Binding	0
$A$65	Select_Route?	0	$A$65=0	Binding	0
$A$66	Select_Route?	0	$A$66=0	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	23.46	*hours*
Cost	1,426.29	*$/trip*
VOC	587.56	*g/trip*
CO	2,331.30	*g/trip*
NOx	10,790.97	*g/trip*
PM	363.59	*g/trip*
SOx	13,190.77	*g/trip*
CO2	961,778.43	*g/trip*
IM Switches	1	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	5	Ship	1	NYC	9	CHL
1	47	Rail	9	CHL	10	SAV
1	50	Rail	10	SAV	11	JAX

D-3.0. CS2 Option A

Parameters

SCENARIO: **CS2 OPTION A**
RUN: **1**
RESET? **YES**
AUTOSCALE: **OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$5	Time Current Optimal Solution	23.55	$B$5>=23.47	Not Binding	0.08
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0
$A$51	Select_Route?	0	$A$51=0	Binding	0
$A$54	Select_Route?	0	$A$54=0	Binding	0
$A$55	Select_Route?	0	$A$55=0	Binding	0
$A$60	Select_Route?	0	$A$60=0	Binding	0
$A$64	Select_Route?	0	$A$64=0	Binding	0
$A$65	Select_Route?	0	$A$65=0	Binding	0
$A$66	Select_Route?	0	$A$66=0	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	23.55	*hours*
Cost	1,345.39	*$/trip*
VOC	593.87	*g/trip*
CO	3,659.02	*g/trip*
NOx	11,058.80	*g/trip*
PM	373.55	*g/trip*
SOx	13,488.09	*g/trip*
CO2	966,639.78	*g/trip*
IM Switches	1	*switch*

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	6	Ship	1	NYC	10	SAV
1	50	Rail	10	SAV	11	JAX

D-4.0. CS2 Option B

Parameters

SCENARIO: **CS2 OPTION B**
RUN: **1**
RESET? **YES**
AUTOSCALE: **OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$11	SOx Current Optimal Solution	1,737.37	$B$11<=6595	Not Binding	4857.625545
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0
$A$51	Select_Route?	0	$A$51=0	Binding	0
$A$54	Select_Route?	0	$A$54=0	Binding	0
$A$55	Select_Route?	0	$A$55=0	Binding	0
$A$60	Select_Route?	0	$A$60=0	Binding	0
$A$64	Select_Route?	0	$A$64=0	Binding	0
$A$65	Select_Route?	0	$A$65=0	Binding	0
$A$66	Select_Route?	0	$A$66=0	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	27.68	*hours*
Cost	1,879.19	*$/trip*
VOC	241.41	*g/trip*
CO	1,076.81	*g/trip*
NOx	5,622.50	*g/trip*
PM	151.66	*g/trip*
SOx	1,737.37	*g/trip*
CO2	303,846.63	*g/trip*
IM Switches	2	*switch*

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	2	Truck	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	31	Rail	5	RCH	7	WLM.NC
1	43	Ship	7	WLM.NC	11	JAX

D-4.1. CS2 Option B (Run #2)

Parameters

SCENARIO:	**CS2 OPTION B**
RUN:	**2**
RESET?	**NO**
AUTOSCALE:	**OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$11	SOx Current Optimal Solution	1,720.42	$B$11<=6595	Not Binding	4874.575659
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0
$A$51	Select_Route?	0	$A$51=0	Binding	0
$A$54	Select_Route?	0	$A$54=0	Binding	0
$A$55	Select_Route?	0	$A$55=0	Binding	0
$A$60	Select_Route?	0	$A$60=0	Binding	0
$A$64	Select_Route?	0	$A$64=0	Binding	0
$A$65	Select_Route?	0	$A$65=0	Binding	0
$A$66	Select_Route?	0	$A$66=0	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	25.55	*hours*
Cost	1,557.72	*$/trip*
VOC	214.53	*g/trip*
CO	875.35	*g/trip*
NOx	5,169.63	*g/trip*
PM	144.06	*g/trip*
SOx	1,720.42	*g/trip*
CO2	222,767.49	*g/trip*
IM Switches	1	*switch*

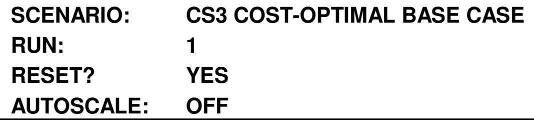
Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	8	Rail	2	PHL	3	WLM.DE
1	15	Rail	3	WLM.DE	4	BLT
1	22	Rail	4	BLT	5	RCH
1	31	Rail	5	RCH	7	WLM.NC
1	43	Ship	7	WLM.NC	11	JAX

Appendix E: Parameters and Results for Case Study 3 as Seen on Excel

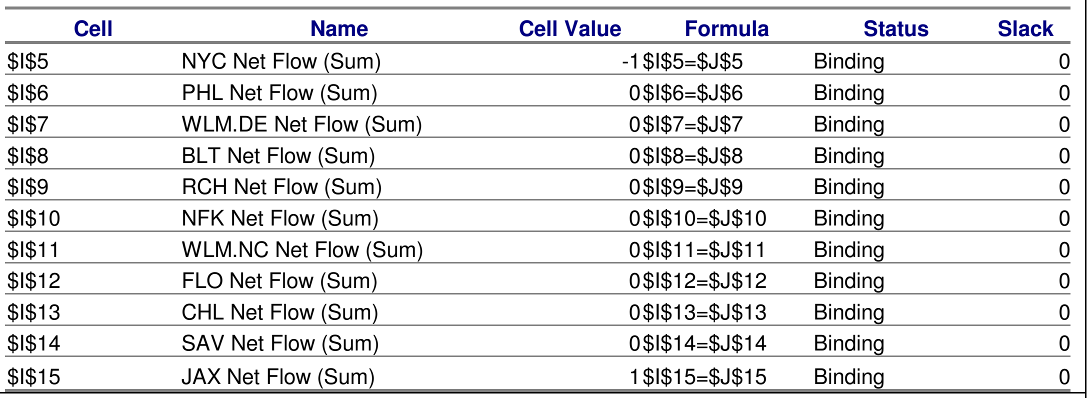
E-1.0. Time-Optimal Base Case

Parameters



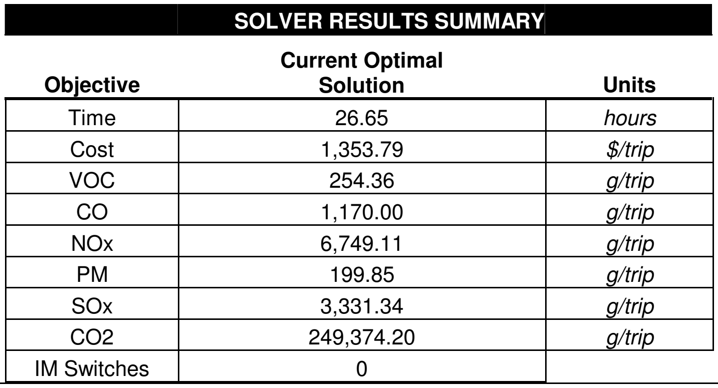
SCENARIO:	**CS3 COST-OPTIMAL BASE CASE**
RUN:	**1**
RESET?	**YES**
AUTOSCALE:	**OFF**

Constraints



Cell	Name	Cell Value	Formula	Status	Slack
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

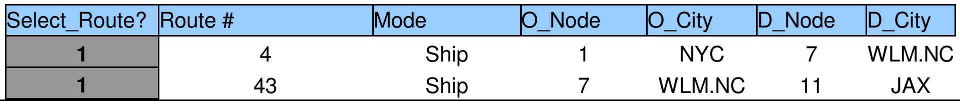
Summary Results



SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	26.65	*hours*
Cost	1,353.79	*$/trip*
VOC	254.36	*g/trip*
CO	1,170.00	*g/trip*
NOx	6,749.11	*g/trip*
PM	199.85	*g/trip*
SOx	3,331.34	*g/trip*
CO2	249,374.20	*g/trip*
IM Switches	0	

Itinerary



Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	4	Ship	1	NYC	7	WLM.NC
1	43	Ship	7	WLM.NC	11	JAX

E-2.0. CS3 Scenario 3A

Parameters

SCENARIO:	**3A**
RUN:	**1**
RESET?	**YES**
AUTOSCALE:	**OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$13	IM Switches Current Optimal Solution	1	$B$13<=1	Binding	0
$B$6	Cost Current Optimal Solution	1,366.28	$B$6>=1353.8	Not Binding	12.48
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	30.52	*hours*
Cost	1,366.28	*$/trip*
VOC	320.17	*g/trip*
CO	1,515.45	*g/trip*
NOx	8,041.85	*g/trip*
PM	231.94	*g/trip*
SOx	3,676.26	*g/trip*
CO2	368,173.27	*g/trip*
IM Switches	1	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	2	Truck	1	NYC	2	PHL
1	14	Ship	2	PHL	11	JAX

E-3.0. CS3 Scenario 3B

Parameters

SCENARIO:	**3B**
RUN:	**1**
RESET?	**YES**
AUTOSCALE:	**OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$6	Cost Current Optimal Solution	1,613.68	$B$6>=1366.3	Not Binding	247.38
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	31.48	*hours*
Cost	1,613.68	*$/trip*
VOC	788.98	*g/trip*
CO	3,272.94	*g/trip*
NOx	14,085.59	*g/trip*
PM	463.92	*g/trip*
SOx	17,197.86	*g/trip*
CO2	1,431,101.37	*g/trip*
IM Switches	2	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	2	Truck	1	NYC	2	PHL
1	13	Ship	2	PHL	10	SAV
1	52	Truck	10	SAV	11	JAX

E-4.0. CS3 Scenario 3C

Parameters

SCENARIO: **3C**
RUN: **1**
RESET? **YES**
AUTOSCALE: **OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$6	Cost Current Optimal Solution	1,649.29	$B$6>=1613.7	Not Binding	35.59
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	29.04	*hours*
Cost	1,649.29	*$/trip*
VOC	304.07	*g/trip*
CO	1,425.31	*g/trip*
NOx	7,654.08	*g/trip*
PM	224.04	*g/trip*
SOx	3,546.67	*g/trip*
CO2	323,141.93	*g/trip*
IM Switches	2	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	1	Rail	1	NYC	2	PHL
1	9	Truck	2	PHL	3	WLM.DE
1	21	Ship	3	WLM.DE	11	JAX

E-5.0. CS3 Scenario 3D

Parameters

SCENARIO:	**3D**
RUN:	**1**
RESET?	**YES**
AUTOSCALE:	**OFF**

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$13	IM Switches Current Optimal Solution	0	$B$13<=1	Not Binding	1
$B$6	Cost Current Optimal Solution	1,527.62	$B$6>=1366.3	Not Binding	161.32
$I$5	NYC Net Flow (Sum)	-1	$I$5=$J$5	Binding	0
$I$6	PHL Net Flow (Sum)	0	$I$6=$J$6	Binding	0
$I$7	WLM.DE Net Flow (Sum)	0	$I$7=$J$7	Binding	0
$I$8	BLT Net Flow (Sum)	0	$I$8=$J$8	Binding	0
$I$9	RCH Net Flow (Sum)	0	$I$9=$J$9	Binding	0
$I$10	NFK Net Flow (Sum)	0	$I$10=$J$10	Binding	0
$I$11	WLM.NC Net Flow (Sum)	0	$I$11=$J$11	Binding	0
$I$12	FLO Net Flow (Sum)	0	$I$12=$J$12	Binding	0
$I$13	CHL Net Flow (Sum)	0	$I$13=$J$13	Binding	0
$I$14	SAV Net Flow (Sum)	0	$I$14=$J$14	Binding	0
$I$15	JAX Net Flow (Sum)	1	$I$15=$J$15	Binding	0

Summary Results

SOLVER RESULTS SUMMARY

Objective	Current Optimal Solution	Units
Time	29.27	*hours*
Cost	1,527.62	*$/trip*
VOC	300.72	*g/trip*
CO	1,383.23	*g/trip*
NOx	7,979.10	*g/trip*
PM	236.27	*g/trip*
SOx	3,938.46	*g/trip*
CO2	294,821.45	*g/trip*
IM Switches	0	

Itinerary

Select_Route?	Route #	Mode	O_Node	O_City	D_Node	D_City
1	5	Ship	1	NYC	9	CHL
1	49	Ship	9	CHL	11	JAX