Fuel Consumption and Carbon Emissions of Turnpike Doubles in Manitoba

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Paper prepared for presentation

at the Responding to Climate Change: Best Practices Session

of the 2010 Annual Conference of the
Transportation Association of Canada
Halifax, Nova Scotia

ABSTRACT

This paper analyzes fuel consumption and carbon dioxide (CO_2) emissions of specially permitted Turnpike Doubles (Turnpikes) in comparison to five-axle tractor semitrailers (3-S2s) operating on a defined network within Manitoba. Turnpikes can effectively replace two 3-S2s. This study collects fuel consumption data from two Manitoba-based carriers that operate Turnpikes. These carriers comprise nearly 1400 tractors and 3600 trailers operating in North America. The fuel consumption data are normalized, integrated, and analyzed as a function of gross vehicle weight, cube, and season. The fuel consumption characteristics of Turnpikes are compared to 3-S2 (van trailers) using system-wide estimates of truck exposure.

The results in this paper indicate that Turnpikes can save 28.7 litres per 100 kilometres of travel when compared to two 3-S2s. Savings in fuel consumption from operating a Turnpike in place of two 3-S2s is about 30.7 litres per 100 kilometres in the winter and 28.8 litres per 100 kilometres in the summer. On a tonne-kilometre basis, Turnpikes use 23 percent less fuel than 3-S2s and 34 percent less fuel on a pallet-kilometre basis. A system-wide analysis of their operations in Manitoba indicates an estimated three percent reduction in fuel consumption and emissions for the four percent reduction in 3-S2 exposure in 2006. The results of this study provide input for decisions regarding Turnpikes to engineers, planners, policy makers, trucking associations, shippers, truck freight carriers, and the research community.

INTRODUCTION

This paper develops an understanding of fuel consumption and carbon dioxide (CO_2) emission characteristics of Turnpike Doubles on a regional network in Manitoba. This paper: (1) establishes current benchmarks of fuel consumption of Turnpike Doubles (Turnpikes) and five-axle tractor semitrailers (3-S2s); (2) analyzes the data as a function of gross vehicle weight, cube, and season; and (3) estimates their system-wide impacts on fuel consumption and CO_2 emissions.

Energy consumption within the freight transportation sector grew by 61 percent between 1990 and 2005, due mainly to increased use of heavy trucks and the new supply chain requirements for just-in-time delivery [1]. Greenhouse gas (GHG) emissions generated by this sector contribute to climate change. As the international community seeks ways to coordinate mitigation of GHG production, there is a need to establish emissions benchmarks which can be used to develop future emissions reduction targets for on-road vehicles. This need is evidenced by a major international research effort conducted by the Organization for Economic Cooperation and Development (OECD), which provides energy efficiency benchmarks for common truck configurations used in Australia, South Africa, Canada, the United States, Mexico, and several European nations [2]. The benchmarking process requires a high level of spatial and temporal specificity, and an understanding of the emissions characteristics of all vehicle types.

This research is conducted to improve the understanding of fuel consumption and CO_2 emissions characteristics of Turnpikes. These vehicles operate under special permits granted by provincial jurisdictions to improve the technical productivity of transporting low density commodities. In the Canadian Prairie Region, a relatively favourable regulatory environment, expansion of the network on which they are permitted to operate, and rising demand for hauling low density commodities have generated an increase in the use of these vehicles. Turnpikes comprise two 16.2-metre (53-foot) trailers, and therefore effectively replace two 3-S2s (each with a 16.2-metre trailer). These two vehicle types are shown in Figure 1. The penetration of Turnpikes into the truck fleet in this region (and increasingly elsewhere in Canada) has implications for freight productivity, safety, infrastructure design and maintenance, traffic operations, revenue generation, and energy use and emissions. This paper focuses on the potential reductions in fuel consumption and emissions generated by Turnpikes relative to the trucks in the fleet that they replace.

APPROACH

The transportation systems analysis approach is used to develop fuel consumption models for Turnpikes and 3-S2s. This approach consists of three interrelated elements: (1) the transportation system, *T*; (2) the activity system, *A*; and (3) the flow system, *F*. Figure 2 depicts a schematic of the transportation systems analysis approach. In the short term, *T* and *A* equilibrate to define *F*. Over time, characteristics of *F* stimulate changes in *T* and *A*, eventually creating a new equilibrium point for *F*. These changes can also be affected by exogenous factors, *X*, such as the physical environment. This approach recognizes the complexity and interrelated nature of the variables influencing the context of heavy truck fuel consumption and emissions, and provides a means of categorizing these variables.

Transportation system variables are:

- *Vehicles and their operating characteristics*, including vehicle type (e.g., Turnpikes or 3-S2s); axle configuration and spacing; gross vehicle weight, payload weight and tare weight; cubic capacity for freight and payload cube; engine type, year, and other specifications; idling practices; and acceleration and deceleration characteristics.

- *Technologies*, including those that reduce tractor or trailer aerodynamic drag; reduce rolling resistance; reduce tare weight; control idling; control speed; and reduce emissions.

- *Regulations*, including those pertaining to truck size and weight; truck emissions; fuel; and speed.

- *Road network and conditions*, including links (road segments) and nodes (intersections); whether the road is divided or undivided; road surface condition; the presence of traffic signals; and horizontal and vertical curvature.

The activity system represents the demand for transportation defined in the context of the social, economic, and political environment. The variables relevant within the context of truck fuel consumption and emissions are characterized by consumer interests and behaviour, the extent to which shippers and carriers respond to consumer demands, and the economic and political environments within which these demands are met. This paper does not directly analyze the effects of these variables on truck fuel consumption and emissions, but recognizes them as contributing to the quantity and quality of truck exposure and the resources this exposure consumes.

The flow system measures the quantity of people, freight, and vehicle movements, the resources they consume, and the level of service they provide [3]. As shown in Figure 2, Regehr [4] expresses F principally in terms of exposure, E, which encompasses the quantity and quality of movements. Thus, exposure, the resources, R, it consumes, and the services, S, it provides comprise F. Flow system variables that are relevant within the context of truck fuel consumption and emissions are categorized in terms of exposure variables and resource variables. There are four principal exposure dimensions: volume, weight, cube, and speed. Each of these principal dimensions can be further characterized by the following secondary dimensions: (1) time—for example, by year, month, day of week, hour, or into real-time; (2) space—for example, by region, location, road segment, lane, or direction of travel; (3) vehicle characteristics—for example, by vehicle class, body type, or configuration [5].

Resource variables comprise both the fuel consumed (i.e., the consumption of an energy resource) and the emissions generated (i.e., the consumption of natural air resources). As these resources are consumed as a function of exposure, metrics used to track and evaluate them are expressed in terms of exposure variables. For example, fuel consumption is typically expressed in terms of “litres per 100 kilometres” or “miles per gallon”. For trucks, this metric is sometimes extended to include the weight and cube dimensions. Expressing resource consumption for specific times, places, or vehicle characteristics provides further refinement.

The transportation systems analysis approach is simplified by adapting a methodology originally developed by Malzer [6]. This methodology adapts the transportation system (T) and flow system (F) interrelationship from Manheim’s model and places them into three components as shown in Figure 3.

1) Characterize Transportation System (*T*): The first component of the approach characterizes aspects of the transportation system, *T*, relevant for understanding fuel consumption qualities of Turnpikes. This is characterized by truck size and weight regulations, technologies that reduce heavy truck fuel consumption, and the defined road network where Turnpikes are permitted to operate.

2) Develop Fuel Consumption Models (*F*): The second component of the approach develops fuel consumption models using data collected from Manitoba-based carriers that operate Turnpikes and 3-S2 vans. This data characterizes the resource consumption aspect of the flow system, *F*.

3) Estimate System-Wide Impacts (*F*): The final component involves gathering exposure data of Turnpikes and 3-S2s operating on the network, developing estimates of exposure and determining the system-wide impacts of Turnpikes and 3-S2s on fuel consumption and emissions.

CHARACTERIZATION OF THE TRANSPORTATION SYSTEM

The transportation system in which heavy trucks operate is characterized by: (1) vehicle characteristics and regulations; (2) technologies; and (3) the road network.

Vehicle Characteristics and Regulations

Size and weight regulations for heavy trucks vary by jurisdiction, highway, truck configuration, axle type, axle spreads and spacing, tire size, season, age of vehicle and other factors [7]. The regulations are complex and have important effects on pavement and bridge design, road safety, geometric design, traffic operations, and energy use and emissions. For this paper, we restrict the summary of size and weight regulations to those governing the operation of 3-S2 vans and Turnpikes on the highway network in Manitoba on which Turnpikes are permitted to travel.

A five-axle tractor semitrailer is a single-trailer truck consisting of a tractor with one semitrailer. This vehicle is subject to a gross vehicle weight (GVW) limit of 39,500 kilograms and a vehicle length limit of 23.0 metres. The semitrailer length is limited to 16.2 metres. Van semitrailers are typically 16.2 metres long. The axle weight limits of a

3-S2 are: 5,500 kilograms for the steering axle and 17,000 kilograms for the drive and trailer tandem axle groups.

A Turnpike Double is a multiple-trailer truck consisting of a tractor with one 16.2-metre van semitrailer and one 16.2-metre van trailer, subject to a length limit of 41.0 metres and a GVW limit of 62,500 kilograms [4]. The axle weight limits of a Turnpike are: 5,500 kilograms for the steering axle; 9,100 kilograms for a single (non-steering) axle; 17,000 kilograms for tandem axle groups; and 24,000 kilograms for tridem axle groups.

Van body types are of principal interest for this paper as Turnpikes (which are nearly always van body types) are being used by carriers to replace two 3-S2 vans. Van body types typically haul low density general freight (such as groceries and retail goods). Trucks carrying low density freight cube-out before they weigh-out. In other words, the freight fills the trailer's volumetric capacity before the truck's GVW limit is reached. Trucks weigh-out if they carry freight of sufficient density that their GVW limit is reached before the trailer reaches its volumetric capacity. Truck configurations designed for high density freight tend to have more axles and/or larger axle groups to support higher weights, while trucks designed for low density freight tend to have larger dimensions.

Technologies

There are no current heavy truck regulations for GHG emissions in Canada; however, concerns regarding the consequences of climate change have triggered industry driven emissions reduction practices and technologies. There is speculation that future regulations for GHG emissions of heavy trucks are to come since Canada and the United States will be regulating GHG emissions for passenger and light-duty gasoline trucks starting in 2012 [8]. Since fuel consumption is directly proportional to carbon dioxide emissions production, these technologies and practices offer savings in operational costs.

The literature reveals numerous technologies that improve heavy truck fuel consumption and CO_2 emissions. Technologies fall into the following categories: those that reduce aerodynamic drag, reduce rolling resistance, reduce vehicle tare weight, reduce vehicle idling, and control speed [9].

Manitoba Turnpike Double Network

Turnpikes are specially permitted to operate on all divided, rural highways in Manitoba. This makes up a network of over 700 centreline-kilometres of primarily uncongested highways and serves a population of over 1.1 million people. The Turnpike network in Manitoba is directly connected to the Turnpike networks in Saskatchewan and Alberta. This enables operations across the Canadian Prairie Region. Regulatory prohibitions on the Trans Canada Highway in northwest Ontario and at the North Dakota border render certain sections of the Manitoba Turnpike network impractical from an operational perspective.

As a result of these regulatory issues, the system-wide fuel consumption analysis is limited to those highways on which Turnpikes actually travel, and for which exposure estimates are readily-available. This network, shown in Figure 4, consists of 430 centerline-kilometres and is referred to as the Manitoba Effective Turnpike Double Network (METD-Network). Routes in the METD-Network are:

- Highway 1 (Trans Canada Highway), from approximately 40 kilometres east of the Saskatchewan boundary to Winnipeg's Perimeter Highway[1];
- Highway 75, from the U.S. boundary to Highway 100 (the south Perimeter Highway);
- Highway 100 (the south Perimeter Highway), from Highway 1 (west junction) to Highway 59 (Lagimodiere Boulevard);
- Highway 101 (the north Perimeter Highway), from Highway 1 (west junction) to Highway 7 (Route 90); and
- Highway 221, from Highway 101 to the City of Winnipeg municipal boundary.

DEVELOPMENT OF FUEL CONSUMPTION MODELS

The development of the fuel consumption models for Turnpikes and 3-S2s involves: (1) collection, normalization, and integration of fuel consumption data obtained from two Manitoba-based carriers; and (2) identifying relationships between key variables affecting fuel consumption.

Data Normalization and Integration

Fuel consumption data was provided by two Manitoba-based trucking companies. Together, these companies operate 1390 tractors and 3550 trailers. They represented 30 million vehicle-kilometres of travel in the Canadian Prairie Region and 210 million vehicle-kilometres of travel in North America in 2009. The surveyed carriers could not provide data on cubic load, idling, or GVW measurements.

The data provided by the carriers are in different formats, contain different data elements, and therefore require normalization prior to integration. The datasets provided by the carriers have the following common data elements:

- Year
- Month
- Tractor ID
- Tractor year (relevant to emissions production)
- Fuel purchases (in litres) by month by tractor

[1] The Turnpike volume estimates by Regehr (2009) are dated 2006, which is prior to the completion of the divided Trans Canada Highway in Manitoba near the Saskatchewan border. Prior to this completion, no Turnpikes were permitted on this 40-kilometre portion of the highway.

- Kilometres travelled by month by tractor
- Vehicle type (3-S2 or Turnpike)
- Average fuel consumption

Fuel consumption (in litres per 100 kilometres of travel) was calculated from the monthly fuel purchases and kilometres travelled by vehicle. As the vehicle's kilometres of travel increase in a given month, the litres of fuel purchased approach the litres of fuel consumed. Shorter trips result in more fuel purchased than consumed for the distance travelled, thus skewing the fuel consumption value upward.

To normalize the data and remove outliers, an analysis was performed to test the sensitivity of the average fuel consumption and standard deviation to VKT level. The purpose of this analysis is to determine a VKT level above which the average fuel consumption is constant with respect to VKT and the standard deviation is acceptable. By removing data records with VKT below this level, the data skew is removed and the distribution becomes normal. From the analysis, a VKT of 1600 kilometres (1000 miles) per month was chosen as the level below which data records were removed for standardization purposes.

Identification of Relationships

The fuel consumption data for 3-S2s and Turnpikes exhibits a normal distribution. Therefore, standard statistical techniques can be used to compare fuel consumption characteristics between the two vehicle types. Table 1 shows a statistical summary of fuel consumption data for each vehicle type. On average, the fuel consumption rate for Turnpikes is 55.7 litres per 100 kilometres of travel. By comparison, 3-S2s consumed fuel at a rate of 42.2 litres per 100 kilometres of travel. The standard deviation is larger for Turnpikes than 3-S2s. This reflects the wider operational variability of Turnpikes and the smaller sample size. The standard error is almost negligible due to the large sample size. Comparing the fuel consumption rate for Turnpikes to the operation of two 3-S2s, Turnpikes potentially save 28.7 litres of fuel per 100 kilometres of travel. This equates to a 34 percent fuel savings. These results are comparable to the findings of L-P Tardif & Associates Inc. [10], which estimated a fuel savings of 28.8 litres per 100 kilometres for Turnpikes over two 3-S2s.

To analyze the effect of fuel consumption throughout the year, seasons are defined as follows:

- Winter: December, January, and February
- Spring: March, April, and May
- Summer: June, July, and August
- Fall: September, October, and November

For both vehicle types, fuel consumption is highest in winter and lowest in the summer. Savings in fuel consumption from operating a Turnpike in place of two 3-S2s is about 30.7 litres per 100 kilometres in the winter and 28.8 litres per 100 kilometres in the summer. These results are expected as the use of climate control devices in the winter months increases the energy use of the tractor during idling.

Fuel Consumption by Average Payload Weight and Cubic Capacity

A literature search revealed a variety of metrics for measuring fuel consumption and emissions performance by heavy trucks. Metrics that involve cargo weight and/or cube allow for more realistic comparisons between different truck combinations and operations [2],[11],[12]. Metrics used in this paper are fuel consumption per payload tonne-kilometre and per pallet-kilometre.

The metric of fuel consumption per payload tonne-kilometre was developed from average operating GVWs (for Turnpikes and 3-S2 vans) collected at two weigh scales located on the METD-Network. A total of 2,734 3-S2s and 330 Turnpikes were weighed at the two scales. Once the average GVWs were calculated, vehicle tare weight estimates were subtracted to determine average payload weights. The tare weight estimates are 14,500 kilograms for 3-S2s and 22,730 kilograms for Turnpikes. On average, 3-S2s carry 12,630 kilograms of payload and Turnpikes carry 21,610 kilograms of payload. The average fuel consumption rate per payload tonne-kilometre is 3.34 litres per tonne-100 kilometres and 2.58 litres per tonne-100 kilometres for 3-S2s and Turnpikes, respectively. On a tonne-kilometre basis, Turnpikes use 23 percent less fuel than 3-S2s.

Fuel consumption in terms of cubic capacity is important since Turnpikes primarily operate under cube-out rather than weigh-out conditions, based on weigh-scale and weigh-in-motion data. Since there is no data on actual cubic load, cubic capacity is used to analyze fuel consumption. A 16.2-metre (53-foot) semitrailer can hold 52 pallets: 13 along the length, two wide, and two high. A Turnpike can carry 104 pallets. The average fuel consumption rate per cubic capacity-kilometre is 0.81 litres per pallet-100 kilometres and 0.54 litres per pallet-100 kilometres for 3-S2s and Turnpikes, respectively. On a pallet-kilometre basis, Turnpikes use 34 percent less fuel than 3-S2s.

SYSTEM-WIDE IMPACTS OF TURNPIKE DOUBLES

The effect of operating Turnpikes on fuel consumption and carbon emissions on the METD-Network is compared through two scenarios. Scenario A represents the case where Turnpikes and 3-S2s operate in conjunction with one another. Scenario B represents a case where Turnpikes do not operate on the METD-Network. The comparison of these two scenarios assumes that the demand for the freight is held constant. This means for every Turnpike in Scenario A, Scenario B will operate two 3-S2s, thus increasing the 3-S2 exposure.

Vehicle Exposure

To perform the system-wide analysis, data is required for exposure of Turnpikes and 3-S2s with van body types on the METD-Network. Details about developing exposure estimates for Turnpikes are provided in Regehr [4]. Jablonski et al. [13] discuss details about developing exposure estimates for 3-S2s. Baumgartner et al. [9] provides further information about developing van body type exposure estimates for 3-S2s based on body count data sampling.

The exposure estimates for Turnpikes are composed of analyses of traffic data collected between 2003 and 2008, inclusive. The estimates are considered representative of 2006 conditions, which is approximately the midpoint of the data collection time period.

In 2006, Turnpikes travelled a total of five million kilometres on the METD-Network. This represents about four percent of the total 3-S2 and Turnpike exposure. Figure 5 shows the spatial distribution of the Turnpike exposure. Nearly 88 percent of Turnpike travel occurred on Highway 1 west of Winnipeg, nine percent occurred on the Perimeter Highway, and about three percent occurred on Highway 75.

In 2008, 3-S2s travelled a total of 115 million kilometres on the METD-Network. This represents about 96 percent of the total 3-S2 and Turnpike exposure. Figure 6 shows the spatial distribution of the 3-S2 exposure. Nearly 75 percent of 3-S2 travel occurred on Highway 1 west of Winnipeg, 10 percent occurred on the Perimeter Highway, and about 15 percent occurred on Highway 75.

System-Wide Fuel Consumption and Emissions Impacts of Turnpike Doubles

For Scenario A, total fuel consumption is calculated by multiplying the VKT by vehicle type by the fuel consumption rates (42.2 litres per 100 kilometres for 3-S2s and 55.7 litres per 100 kilometres for Turnpikes). Since one Turnpike effectively replaces two 3-S2s, the Turnpike VKT in Scenario A is doubled to determine the 3-S2 VKT for Scenario B. This assumes that the same quantity of 16.2-metre trailers will be moved. This VKT is then multiplied by the average fuel consumption rate of a 3-S2 (42.2 litres per 100 kilometres). The product yields the fuel consumption for each vehicle type. The difference is then determined by subtracting the fuel consumed in Scenario B from that of Scenario A. The emissions impact of Turnpike Doubles on the METD-Network is determined similarly to the fuel consumption impact (using the same Scenarios A and B), with an additional step to convert fuel consumption into emissions. Environment Canada [14] provides a CO_2 emission rate of 2663 grams per litre of diesel fuel for a Heavy Duty Diesel Vehicle.

Table 3 reveals that the use of Turnpike Doubles (at 2006 levels) reduced fuel consumption by an estimated 1.4 million litres per year on the METD-Network. This is a three percent reduction in fuel consumption for a four percent reduction in VKT.

CONCLUDING REMARKS

Turnpike Doubles operate under special permits granted to increase freight transport productivity. In the Canadian Prairie Region, their operations have expanded over the last decade as carriers seek opportunities to reduce costs and meet rising demand within a regulatory framework that has facilitated regional operations. This paper analyzes the fuel consumption and carbon emissions impacts of Turnpikes relative to five-axle semitrailers with van body types—the vehicles that they effectively replace within the articulated truck fleet.

The transportation systems analysis approach is used to: (1) characterize aspects of the transportation system relevant to understanding fuel consumption and carbon emissions; (2) develop fuel consumption models based on a survey of major Manitoba-based carriers, comprising nearly 1400 tractors and about 3600 trailers; and (3) estimate system-wide exposure-based impacts of Turnpikes on fuel consumption and emissions. The analysis reveals average fuel consumption rates of 42.2 and 55.7 litres per 100 kilometres of travel for 3-S2s and Turnpikes, respectively. Therefore, operating a Turnpike instead of two 3-S2s can save a carrier 28.7 litres per 100 kilometres of travel (34 percent savings). Metrics that focus on the freight transport task (rather than on the vehicle) such as fuel consumed per tonne-kilometre or per pallet-kilometre indicate the fuel consumption benefits of Turnpikes. Five-axle tractor semitrailers consume 3.34 litres per tonne-100 kilometres and Turnpikes consume 2.58 litres per tonne-100 kilometre, saving 23 percent on a tonne-kilometre basis. On a pallet-kilometre basis, 3-S2s consume 0.81 litres per pallet-100 kilometre and Turnpikes consume 0.54 litres per pallet-100 kilometre, a savings of 34 percent. Finally, on a system-wide basis, the use of Turnpikes (at 2006 exposure levels) reduced fuel consumption by an estimated 1.4 million litres per year and CO_2 emissions by an estimated 3.7 million kilograms per year on the METD-Network. This amounts to a three percent reduction in fuel consumption and CO_2 emissions for a four percent reduction in VKT.

Energy and emissions impacts increasingly drive decisions within the trucking industry. However, developing a refined understanding of these impacts is challenging given the complexity and dynamism of many influencing factors—vehicles, technologies, regulations, networks, consumer and shipper demands, and exposure-related impacts. Establishing performance benchmarks and metrics relevant to the freight transport task provides a basis for future evaluations of the energy and emissions impacts of truck transportation.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Environment Canada for providing financial support for this research.

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TABLES

Table 1: Vehicle Fuel Consumption Data

	Five-Axle Tractor Semitrailer	Turnpike Double
Average Fuel Consumption (L/100 km)	42.2	55.7
Standard Deviation (L/100 km)	6.5	9.0
Standard Error (L/100 km)	0.05	0.07
Sample Size	18,544	4,995
Total Kilometres of Sample (millions)	335	77

Table 2: Summary of Body Type Surveys

Location	Observations	Five-Axle Tractor Semitrailers (3-S2)	3-S2 With Van Body Types [a]
Headingley	4196	55.0 %	83.3 %
Emerson	1783	84.7 %	56.6 %
Inkster Blvd	4668	58.9 %	59.5 %

Note: [a] 3-S2 Dry and Refrigerated van body types as a percentage of total 3-S2 volumes

Table 3: System-Wide Effect of Turnpike Double on Energy Use and Emissions

Scenario	3-S2 VKT (million)	Turnpike VKT (million)	Total VKT (million)	Total Fuel Consumption (million litres)	Total CO_2 Emissions (million kg)
A	114.8	4.9	119.7	51.2	136.2
B	124.6	-	124.6	52.6	139.9
Difference	9.8	4.9	4.9	1.4	3.7
% Difference	7.9%	-	3.9%	2.7%	2.7%

FIGURES

Figure 1: Five-axle Tractor Semitrailer and Turnpike Double

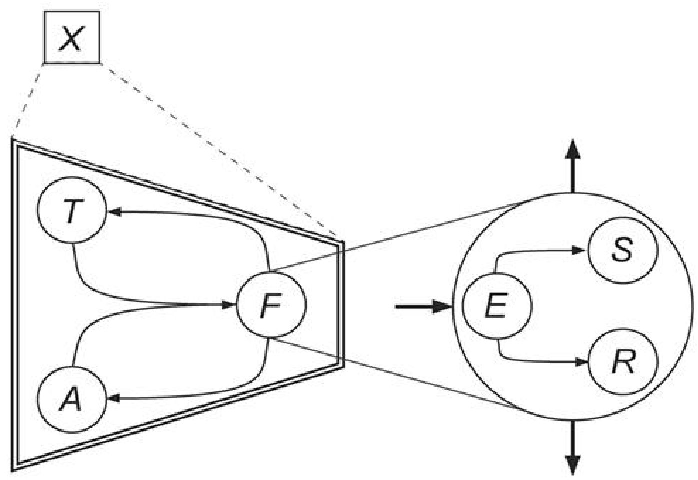

Figure 2: Transportation Systems Analysis Approach
Based on Manheim (1979), Regehr (2009)

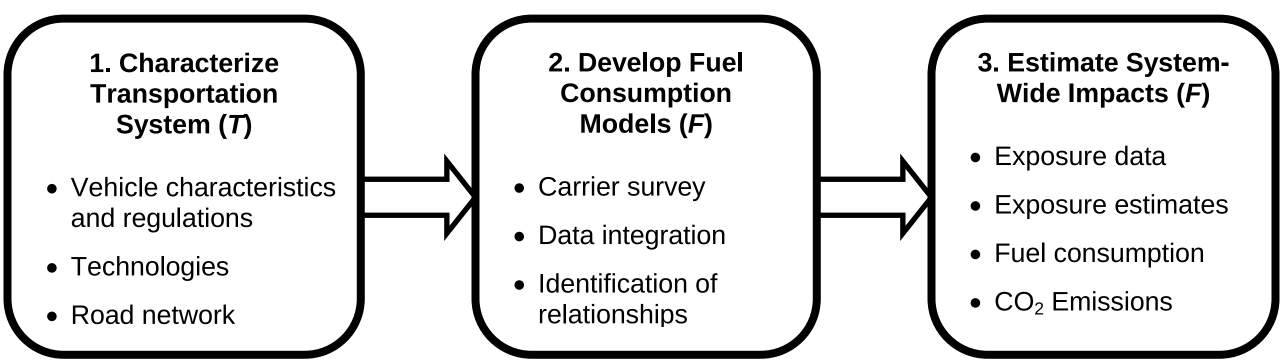

Figure 3: Approach for Development and Application of Fuel Consumption Models

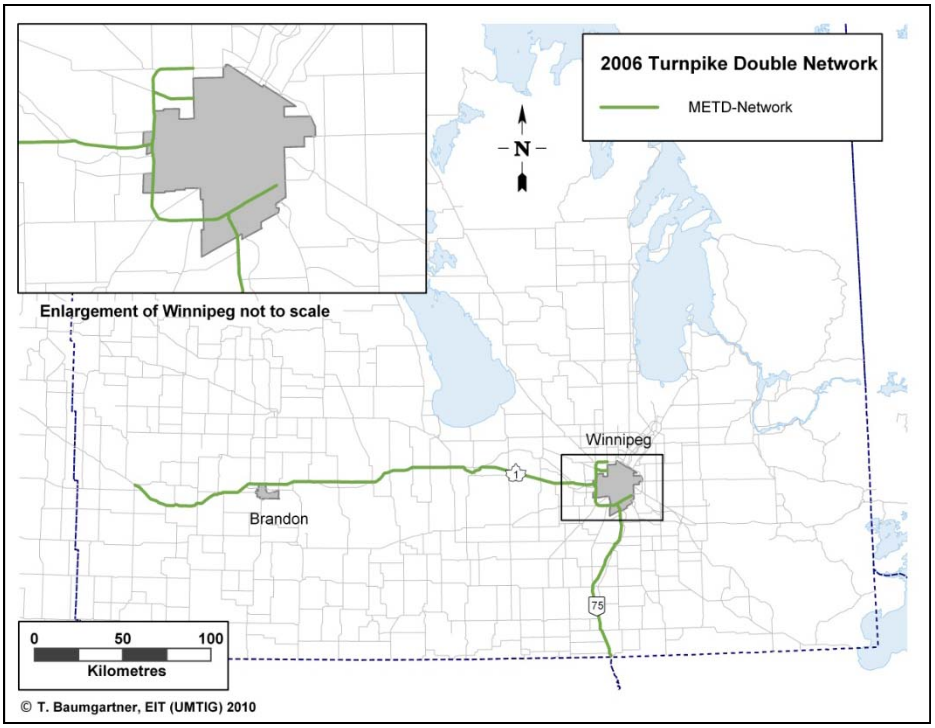

Figure 4: Manitoba Effective Turnpike Double Network

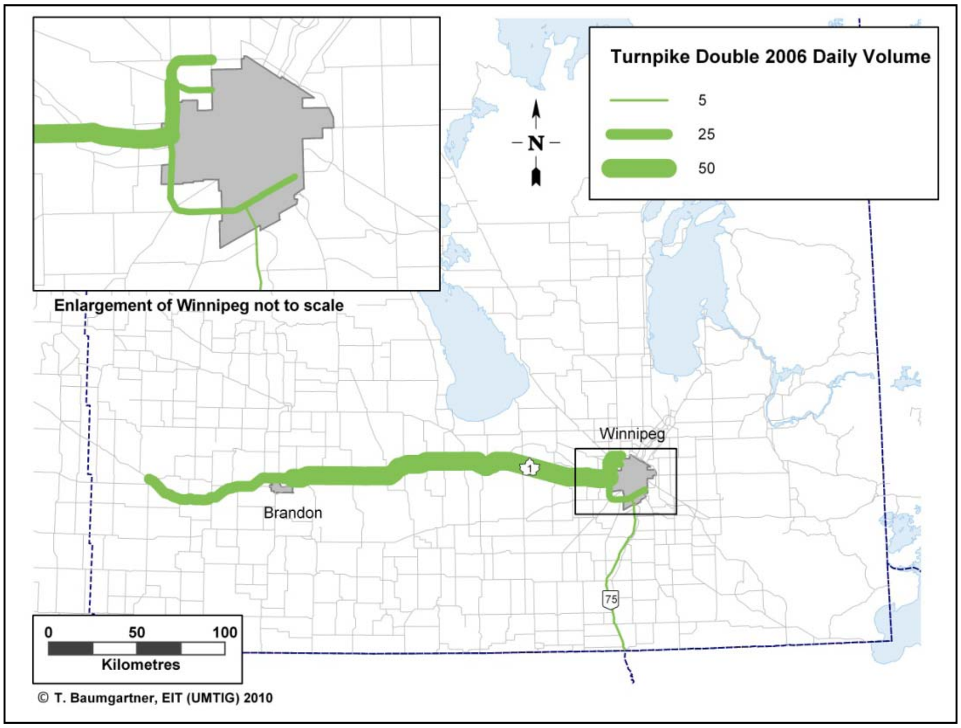

Figure 5: Turnpike Double Exposure on the METD-Network

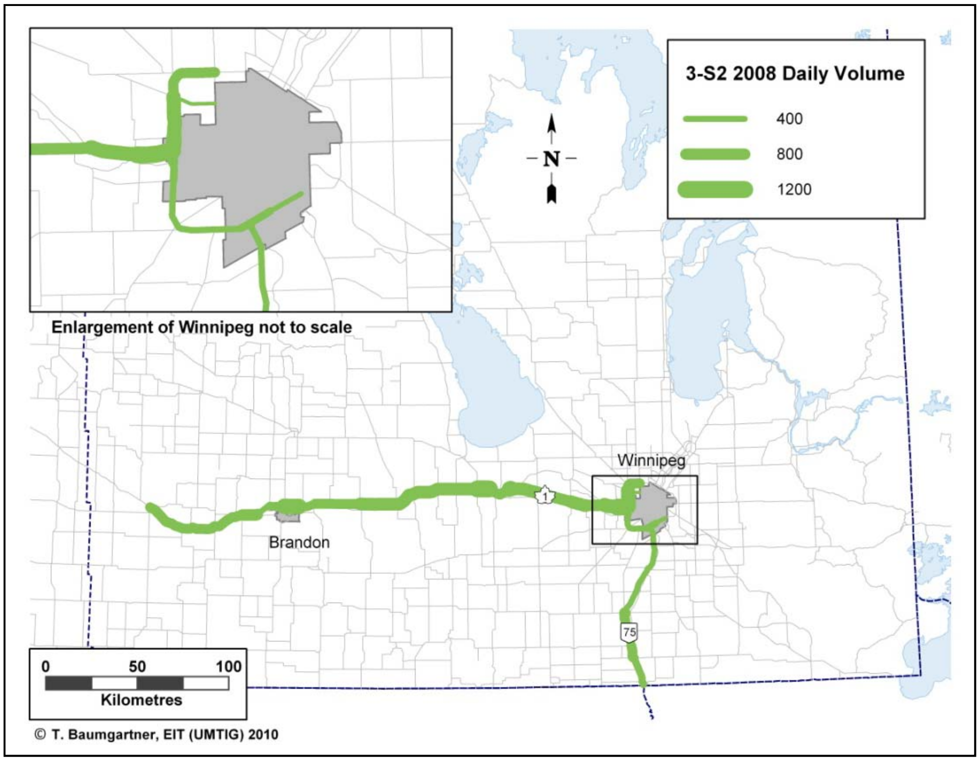

Figure 6: 3-S2 Exposure on the METD-Network