Regional Freight Movement and Its Impact on Air Quality: Simulation of Freight Traffic and Pavement Maintenance Operations

Abstract

Freight movement emits greenhouse gases (GHGs) and deteriorates pavement - thereby causing additional emissions from pavement maintenance and rehabilitation (M&R) treatments. This study predicts the carbon dioxide equivalent GHGs (CO_2e GHGs) emission from simulated freight movement and pavement M&R operations on regional highways connecting the Canadian provinces of New Brunswick, Prince Edward Island, Newfoundland and Labrador, Nova Scotia and Quebec. This study estimates the equivalent single axle loads (ESALs), CO_2e GHGs emissions, and vehicle-distance on every regional highway for a 30 years period. The International Roughness Index (IRI) estimates pavement deterioration curves for highways based on ESALs and observed pavement strength. Linear programming of life-cycle optimization estimates the pavement M&R operations required to maintain the pavement in good condition during the design period. The simulated freight traffic will emit 1.279 million tons of carbon dioxide gas while emissions from pavement M&R treatments will be 1.403-1.755 million tons of CO_2e GHGs.

Keywords: Carbon dioxide; Maintenance and rehabilitation; Pavements; Spatial input-output model; Simulation

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Introduction

Road infrastructure has significant impact on trade flow, its growth and development. Freight movement on roads is the major contributor to trade flow in Canada [1]. The proportion of trade flow via road is increasing because of the reduction in production and distribution costs; income, population and employment growth; and reduction in the cost of freight transport for less risk and higher reliability compared to other modes of freight transport [2]. This is the case for the interprovincial trade flow of Atlantic Canada. With the exemption of mining activities in Labrador, which are directly connected to Quebec by rail, the rest of the goods produced by New Scotia, Prince Edward Island, Newfoundland and New Brunswick are moving through Highways 1, 2, 7, 15, 16, 102 and 104 to reach their final consumption markets.

Construction and maintenance of road infrastructure cause environment burdens such as greenhouse gases (GHGs) emissions, climate change and wetland conversion etc. These impacts are sometimes seen as localized matters and treated by reducing the levels of certain pollutants, rather than as a systemic problem that needs to be addressed at policy and planning level [3]. Investment strategies require to address these issues since sustainable development of road infrastructure can only be achieved by predicting and integrating the environmental impacts into the planning system. This study estimates the carbon dioxide equivalent GHGs (CO_2eGHGs) emissions from interprovincial freight movement and pavement maintenance and rehabilitation (M&R) operations of regional highways in Atlantic Canada.

Literature Review

Transportation asset management decisions are constructed over three pillars-economic development, ecological sustainability, and social desirability. Evaluation of maintenance decisions normally focuses on economic efficiency of transportation policies and investment decisions, rather than looking at environmental impact aspects such as energy consumption and GHGs emissions at different phases of transport infrastructure life-cycle [4]. The maintenance decisions, based on only the economic measures, ignores the environmental burdens to the climate from M&R operations. The estimation of GHGs emissions from M&R operations of road infrastructure is required in support of the direct regulation or market mechanism to internalize environmental externalities of M&R operations.

Life cycle assessment (LCA) is an analytical technique for assessing potential environmental burdens to climate and is used to measure progress toward environmental sustainability [5,6]. Keoleian & Spitzley [7]. LCA of road infrastructure studies the environmental aspects and potential impacts throughout its life from raw material acquisition through production, use and disposal [5]. The LCA model includes the acquisition and processing of raw materials, construction processes, maintenance activities, transport of materials and equipment to and from the construction site, construction and maintenance related traffic congestion, overlay roughness effects on vehicular travel and fuel

consumption during normal traffic flow and end of life [5].

Different studies [5-8] performed LCA to estimate the environmental impacts and energy consumption during the life cycle of pavement. Zhang et al. [5] developed an integrated LCA and life cycle cost analysis (LCCA) model to calculate the environmental impacts and costs of overlay systems. The model identified that engineered cementitious composite (ECC) overlay system of the rigid pavement reduced GHGs emissions by 32 percent and 37 percent compared to the concrete overlay system and the HMA overlay system, respectively, over the entire 40 year life cycle of the rigid pavement [5].

Chappat & Bilal [7] reported an in-depth analysis of energy consumption and GHGs emissions over 20 different paving product types. Their comparisons revealed that Portland Cement Concrete paving materials and processes demanded the most energy, followed by hot mix asphalt paving. The report also showed that cold in-place recycling is the least energy intensive process. The report estimated that traffic consumed between 10 and 345 times the energy of road construction and maintenance over the period of 30 years depending on whether the traffic was light or heavy [7]. Similar to Chappat & Bilal [7], Terrel & Hicks [9] identified that hot in-place recycling utilized less energy than hot mix asphalt paving.

Drochies [6] examined the entire cycle of pavement construction from production to final construction (production, extraction, manufacture, transport and laying) of different types of road pavement structures over a thirty year service life with respect to energy consumption and GHGs emissions. The examination concluded that binder and mix manufactures are mainly responsible for GHGs emissions of hot mix bituminous pavements and continuous reinforced concrete pavements [6].

Chevoits & Galehouse [8,9] evaluated the energy efficiency and GHGs emissions from pavement's life extension and revealed that pavement preservation treatments significantly reduced energy use and GHGs emissions compared to traditional rehabilitation and reconstruction strategies. Miller & Bahia [10] also revealed that proactive maintenance was the least energy intensive process because minimal improvements were made to the pavement structure and surface course. The Canadian Construction Association (2005) developed a "Road Rehabilitation Energy Reduction Guide for Canadian Road Builders" to provide information on methods to reduce energy usage during road construction and maintenance operations. None of these studies considered the simulated freight traffic based on future trade flow and resulting M&R operations in the LCA models.

Methodologies

Spatial input-output modeling

Traditional forecasting of freight transport ignores different critical issues because of the stable relationship between gross domestic product and traffic forecasting. Moreover, traffic forecasting was mainly concerned with urban traffic in which freight transport has a negligible contribution [11]. The basic mechanism of predicting the freight travel demand is the prediction of potential volumes of freight traffic, which is later distributed among various types/modes of transportation according to their performance in terms of cost, time and reliability. After that, these modes are assigned to different routes based on ton-km ratio which is later translated into vehicle-km ratio.

This study estimates the inter-provincial trade flow based on a spatial input-output model and provincial capitals are considered as points of origins and destinations of trade flow. The spatial input-output model adopted in this study, includes the trade flow of goods and services for which the factors of production are private consumption, gross investment, government spending (both federal and provincial), and net exports. Gross investment includes non-residential investment (expenditure for firms for machines and tools), residential investment (expenditure by households and firms on apartments, buildings and factories), and change in inventories in a given period. Government spending consists of federal expenditure on provinces, provincial expenditure, and federal government transfers of funds to provincial governments. Net export is the summation of net international export (International export-international import) and net domestic export (domestic export-domestic import). Production of goods and services, and factors of production are included in the spatial input-output model as the sectors [12].

In principle, every sector requires input/production factors from other sectors except in the case of basic productive activities. Induced production at each province can be calculated given the amounts of final demand in one or more sectors of all other provinces, which is allocated among provinces through spatial distribution functions. The allocation of induced production among different provinces according to demand eventually causes flows of goods and services among different provinces through provincial road infrastructures [12].

The total demand for sector *n* in a particular province *i* (TD_i^n) is calculated by Equation 1.

$$TD_i^n = \sum ID_i^{mn} + ED_i^n \quad \forall ID_i^{mn} = \left(P_i^{n,t} = P_i^{n,t-1} + P_i^{n,t} * I_i^{n,t} \right) * PD_i^{mn} \quad (1)$$

$$PD_i^{mn} = PDmin^{mn} + \left(PDmax^{mn} - PDmin^{mn} \right) * \exp \exp - \delta^{mn} U_i^n$$

$P_i^{n,t-1}$ = Production of sector *n* in province *i* for time (*t*-1)

$\Delta P_i^{n,t}$ = Growth of production of sector *n* in province *i* between time (*t*-1) and *t*

$I_i^{n,t} = \frac{A_i^{n,t}}{\sum_i A_i^{n,t}}$ = Proportion of the increment of *n* allocated to province *i* for time *t*

$A_i^{n,t}$ = Attractor of sector *n* in province *i* for period *t*

ED_i^n = exogenous demand for *n* from zone other than five provinces and considered as zero

PD_i^{mn} = amount of production of sector *n* demanded by a unit of sector *m* in zone *i*

$PDmin^m{}_n$ = minimum amount of *n* required by a unit production of *m*

$PDmax^{mn}$ = maximum amount of *n* required by a unit production of *m*

U_i^n = elasticity parameter of *m* with respect to the cost of input *n*

U_i^n = disutility of *n* in *i*, where $U_i^n = \dfrac{PD_i^{mn}}{\left[\min\min\left(PD_i^{mn}\right)\right]^{\theta^m}}$

θ^m = degree of scaling. If utility function is fully scaled $\theta^m = 1$, otherwise zero.

The demand for production of good *n* in province *j* is the product of the total demand for *n* and the probability that the production of *n* in province *j*is demanded by other provinces (Equation 2)(Amador-Jimenez and Amin, 2013).

$$P_j^n = \sum_i TD_i^n * \Pr_{ij}^n \;\forall \Pr_{ij}^n = \frac{\left(A_j^n\right)^{\alpha^n} * \exp\exp - \beta^n \tilde{U}_{ij}^n}{\sum_j \left(A_j^n\right)^{\alpha^n} * \exp\exp - \beta^n \tilde{U}_{ij}^n}$$

$$\Pr_{ij}^n \qquad (2)$$

Where $\Pr_{ij}^n$ is the probability that the production of sector *n* demanded in province *i* is located in province *j*; A_j^n is the attractor term for the production of *n* in *j*; α^n is a parameter that regulates the relative importance of the attractor versus the utility function in the location of sector *n*; β^n is the dispersion parameter of the multinomial logit model; and U_i^n is the utility function of sector *n* between province *i* and *j*.

Freight demand for transporting goods and services among different provinces is estimated following Equation 3 [6].

$$F_{ij} = \sum_n \left(P_{ij}^n \frac{vol^n pc^n}{time^n} + P_{ji}^n \frac{vol^n cp^n}{time^n} \right) \qquad (3)$$

Where F_{ij} is the freight flow from province *i* to province *j*; P_{ij}^n is the production of sector *n* located at province *j* and consumed in province *i*; P_{ji}^n is the production of sector *n* located at province *i* and consumed in province *j*; vol^n is the value-to-volume factor for the economic flow of sector *n*; $time^n$ is the time factor for the economic flow of sector *n*; cp^n is the proportion of economic flow of sector *n* that moves in the direction consumption to production; pc^n is the proportion of economic flow of sector *n* that moves in the direction production to consumption [13].

Factors of transportation modeling

The peak capacities of each link of the selected highways were calculated based on the method adopted by the British Columbia Ministry of Transportation [14] in the Trans-Canada Highway 1-Malahat Corridor Study to calculate peak capacity. The peak capacity of highway 1, 2, 7, 15, 16, 102, and 104 is 3469, 3290, 3440, 3551, 3358, 3616 and 3499 vehicles per hour respectively. Since this paper is concerned with freight transport, the transportation attributes of trucks were considered for the traffic simulation. The operating cost, which includes fixed cost, distance-related cost, time-related cost, possible charges and energy cost, was calculated based on Equation 4 [12]. The waiting and travel time values of truck drivers is assumed to be zero since traveling and waiting time are within their salary. This study ignores the self-employed truckers.

$$C_{op} = C_F + C_T + C_D + C_c + C_e \qquad (4)$$

C_F = The fixed operating cost of a truck once for every trip made; usually refers to administrative costs and loading/unloading cost. The average fixed cost for a 6-axle truck at 10% profit margin is CAD 1.93 per km (CAD 2.094 per km for Quebec, CAD 1.885 per km for New Brunswick, CAD 1.838 per km for Nova Scotia, CAD 1.848 per km for Prince Edward Island, and CAD 1.985 per km for Newfoundland and Labrador) [15].

C_T = Drivers' salaries and capital payments. According to the Economic Analysis Directorate [16], the truck would either be sold or retired for use as an urban pickup and delivery unit after 500,000 to 750,000 miles (or 800,000 to 1.2 million km). The trucks operate for an average of 8 years considering 100,000 miles (160,000 km) of driving per year. The average purchasing cost of a 6-axle truck for the selected five provinces is CAD 126,000 (Quebec CAD 130,000, New Brunswick CAD 121,000, Nova Scotia CAD 121,000, Prince Edward Island CAD 133,000, and Newfoundland and Labrador CAD 121,000) [16]. The capital payment and driver's salary is CAD 21.60 per hour considering 270 working days per year and 10 hours per day for operating the truck by the drivers [12].

C_D = Operating cost CAD 1.4 per km [15], usually includes tires, spares, maintenance, lubricants, and others. This cost varies by link type.

C_c = Charges paid by driver for tolls, parking, duties, etc. The charges of tolls, parking and duties were assumed to be zero.

C_e = energy cost. The energy cost of the truck is calculated by Equation 5based on the minimum and maximum consumption of energy and optimal speed [17]. Here the price of gas is CAD 3.65 per gallon. An aerodynamic 18-wheel truck with a smooth side van trailer, 80,000 pounds gross vehicle weight, operates at 60 miles per hour. This results in a truck getting about 6 miles per gallon [18,12].

$$C_e = \left[ed_o^{\min} + (ed_o^{\max} - ed_o^{\min}) * \exp(-\delta^o V_o) \right] pe_o \quad (5)$$

$ed_o^{\min}$ = Minimum consumption of energy per mile when the truck travels at free flow speed

V_o = Maximum consumption of energy per mile when the truck travels at a speed close to zero

V_o = Speed of vehicle (*mph*)

pe_o = Price of unit of energy (*CAD per gallon*)

Minimum and maximum parameters of the elastic trip generation function in the transport model were taken as 0.21 and 0.27 [19]. The maximum trip generation rate is the maximum number of trips that a trip maker is willing to make in the time period of the simulation when the travel disutility tends to zero [12].

Different categories of straight trucks and Tractor trailers (CAT 5-13 of Federal Highway Administration, FHWA) are assumed to carry an average CAD 1 million worth of goods and services. According to the Canadian Annual Vehicle Survey 2009 [20], 54,871 registered trucks (weight 15 tons and over) of the selected five provinces made trips of 4,465.1 million vehicle-km. On the other hand, trade flow among these five provinces was CAD 97,125 million during 2009. If we consider that 57% of interprovincial trade flow was carried out by truck (Statistics Canada 2009), a truck carries tentatively CAD$ 1 million worth of goods and services [12].

Pavement performance modeling

Pavement performance modeling was based on the mechanistic modeling of roughness progression by Equation 6 [21,22]. Equation 6shows that roughness progression (International Roughness Index, *IRI*) is the function of initial as-built quality (IRI_0), *ESALs* at time *t* ($ESAL_t$), *SN*, and mean environmental exposure (Thornthwaite moisture index, *m*). However, the decision variable of predicting *IRI* is *ESALs* in this method. The *ESALs* are calculated based on the predicted *AADT* and locally observed truck distributions combined with truck factors. The Federal Highway administration (2011) defines the distribution and truck factors for truck classes of 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13 [13].

The *SN* follows the computation method developed by the 1993 AASHTO Flexible Pavement Structural Design. The actual layer thicknesses are converted to *SN* using a layer coefficient that represents the relative strength of the construction materials in that layer (AASHTO 1993). Additionally, all layers below the surface layer are assigned a drainage coefficient that represents the relative loss of strength in a layer due to its drainage characteristics and the total time it is exposed to near-saturation moisture conditions AASHTO 1993.

The Thornthwaite moisture index is identified as 0.07, 0.074 and 0.08 for the three environmental zones with a moisture index of 60, 80 and 100 within APC, respectively [23]. The IRI_0 is set between 0.7 and 1 m/km depending on the highway and coefficient *a* is set to 265 [13].

$$IRI_t = e^{mt} [IRI_0 + a(1+SNC)^{-5} \cdot NE_t] \quad (6)$$

Roughness (IRI) was rescaled to produce a 0 to 100 roughness index (PRI). Measures of rutting and linear cracking were combined to produce a surface distress index (SDI). Observed historical trends of structural strength (FWD and Dynaflect) were used to produce a structural adequacy index (SAI). These indexes were combined to produce a Pavement Condition Index [22].

Linear programming of pavement management system (PMS)

Lifecycle optimization to achieve and sustain acceptable mean network condition ($\bar{Q}$) at a minimum cost is used to find required levels of funding for Montreal road network (Equation 7 and 8). The maximization of total network condition under such a budget is then used to find optimal strategic results for pavement management (Equation 9 and 10). This formulation relied on a decision tree containing all possible paths of pavement condition across time, after hypothetically receiving available treatments [24]. This tree is based upon a transfer function used to estimate condition (Q_{ti}) as a convex combination based on the decision variable and the effectiveness or deterioration of the specific link on time *t* (Equation 11) [25].

The objective function is to minimize cost (*Z*) and maximize pavement condition of the road network

$$[\sum_{t=1}^{T} \sum_{i=1}^{a} (L_i Q_{ti})].$$

$$MINIMIZE \quad Z = \sum_{t=1}^{T} \sum_{i=1}^{a} \sum_{j=1}^{o} C_{tj} X_{tij} L_i \quad (7)$$

$$\text{Subject to:} \quad \sum_{t=1}^{T} \sum_{i=1}^{a} L_i Q_{ti} \geq (\bar{Q}) \sum_{i=1}^{a} L_i \quad (8)$$

$$MAXIMIZE \quad \sum_{t=1}^{T} \sum_{i=1}^{a} (L_i Q_{ti}) \quad (9)$$

$$\text{Subject to:} \quad Z = \sum_{t=1}^{T} \sum_{i=1}^{a} \sum_{j=1}^{k} C_{tj} X_{tij} L_i \leq B_t \quad (10)$$

$$\sum_{j \in J_{ti}} X_{tij} \leq 1 \quad 0 \leq Q_{ti} \leq 100 \text{ and } \{\text{for all times } t \text{ and for each asset } i\}$$

$$Q_{tij} = X_{tij} (Q_{(t-1)ij} + E_{ij}) + (1 - X_{tij}) (Q_{(t-1)ij} + D_{it}) \quad (11)$$

Where X_{tij} is 1 if treatment *j* is applied on road segment *i* at year *t*, zero otherwise; Q_{ti} is condition Index for road segment *i* at year *t*; Q_{tij} *is* condition Index of road segment *i* at year *t* for treatment *j*; $Q_{(t-1)ij}$ is condition Index of road segment *i* at year (*t*-1) for treatment *j*; C_{tj} is cost ($) of treatment *j* at year *t*; L_i is length of road (km) for road segment *i*; E_{ij} is improvement (+) on road segment *i* from treatment *j*, D_{it} is deterioration (-) on road segment

i at time *t*, B_t is budget at year *t*.

Pavement maintenance and rehabilitation activities, applied on the highways during the 30 years, have been presented in Table 1[12].

Table 1: Treatment and Operational Windows Used in Network-level Trade-off Analysis.

Treatment	Operational Window
Crack-sealing	IRI <= 1.13 and Crack1>= 90
Micro-surfacing (max. of 2 consecutive)	Crack>= 80 and rutting2<= 10%
Minor Rehab (e.g. thin overlay)	Arterial: IRI <= 2 and PSDI3>= 65
Major Rehabilitation	Arterial: IRI <= 2.5 and PSDI >=50
Reconstruction	IRI >= 2.0 SAI4<= 65

Note: [1]CRACK = % of surface without cracks, [2]rutting = % of surface with rutting, [3]PSDI = pavement distress index and [4]SAI = structural adequacy index

GHGs emissions from pavement maintenance and rehabilitation activities

The GHGs emissions from pavement treatments per unit area of pavement surface were calculated based on the standard developed by Chappat & Bilal [26], Chehovits & Galehouse [27] and Dorchies [28]. Dorchies [28] applied the GHGs emissions standard on highway 40 in Montreal (from the interchange at Côte de Liesse to St-Charles Boulevard), which was completely reconstructed during the period of 2003-2006. This part of the highway 40 is one of the busiest highways in Quebec with a designed value of 200 million ESALs for a 30 years life span.

These researchers [29,30] determined the pavement structure and the associated maintenance scenarios based on the French administration LCPC-SETRA design method (LCPC- SETRA 1994). The LCPC-SETRA design method used a maintenance schedule such as a new layer of HMA (hot mix asphalt concrete) every 8 to 12 years on flexible pavement, a surface overlay after 15 years, and a partial reconstruction or reinforcement overlay after 28 years on rigid pavements [23]. The elasticity modulus for the road bed and granular sub grade of the pavement structure was considered as 50 MPa and 100 MPa, respectively.

These researchers collected environmental analysis data for bitumen from Eurobitume, and for cement and steel from the Athena Sustainable Materials Institute [31,32].These studies also considered different average distances for manufacturing one metric ton of HMA. For example, they estimated an average distance of 150 km between the refinery for bitumen production and the mixing plant, 150km between the cement plant and the concrete plant, 800 km between the steel factory and the site, 5km between the aggregate quarry and the manufacturing site, and 50km between the manufacturing site and the construction site [8,23].

Interprovincial trade flow and freight traffic modeling

The total demand (Equation 1) and production (Equation 2) of the five selected provinces for the period of 2012-2041 were predicted based on the interprovincial trade flow data (1986-1996) collected from the Institut de la Statistique Quebec (Figure 1). Since the study is mainly concerned with the truck trade flow, the truck share of the interprovincial trade flow was incorporated during the calculation.

Figure 1 reveals that the predicted production and demand of goods and services in New Brunswick is the same during the period of 2012-2041. In Nova Scotia, the total demand is decreasing while total production is increasing (increasing at an increasing rate until 2030 and then increasing at a decreasing rate) and demand is far lower than production during the same period. In Newfoundland and Labrador, the total demand exceeds total production during the estimation period. Production in Newfoundland and Labrador is exponentially increasing, while demand is linearly increasing. In Quebec, the total production is far higher than total demand and increasing at a higher rate than that of demand during the design period. In Prince Edward Island, the total demand is increasing at a higher rate than that of production.

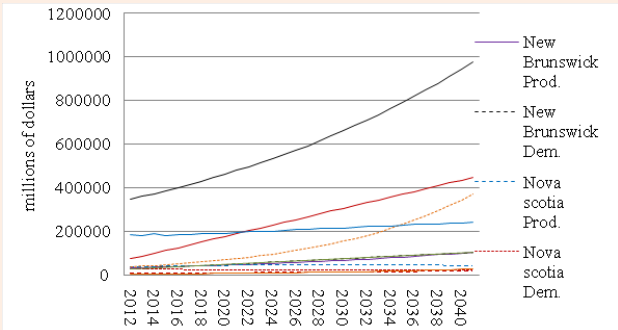

Figure 1: Total demand and production of five provinces during 2012-2041.

Data Analysis

Integration of spatial input-output and transportation modeling

Freight traffic was simulated using TRANUS, which calculated that trucks would travel 334.722 million truck-km per year. For this interprovincial trade flow, the total operating cost and energy consumption per year will be CAD 2,579.63 million and CAD 91.69 million respectively.

The Annual Average Daily Truck Traffic (AADTT) for interprovincial trade flow was estimated as 2397 for highway 1, 8008 for highway 2, 934 for highway 7, 599 for highway 15, 569 for highway 16, 226 for highway 102, and 183 for highway 104 (Figure 2). This reveals that the major impacts of the AADTT on these selected highways are contributed by truck flows for interprovincial trade among the selected five provinces (Figure 2).

Pavement performance and maintenance modeling

Accumulated traffic loading in equivalent single axle loads

(NE_c) was calculated (Table 2) based on the predicted number of trucks per year (AADTT) (Figure 3) and locally observed truck distributions combined with truck factors of (0.45, 1.18, 3.25, 0.99, 2.33, 5.91, 4.7) for truck classes 5, 6, 7, 8, 9, 10 and 13 according to the Federal Highway administration classification (FHWA 2011). Finally, cumulative equivalent single axle loads for the predicted truck traffic during the period of 2012-2041 was calculated and plotted in Figure 4.

Deterioration curves (*IRI*) (Equation 5, Figure 4), based on the predicted amount of traffic loads (*ESAL*s per year), were developed for the pavement management system following those proposed by Paterson & Attoh-Okine [31] and previously applied in New Brunswick by Amador-Jiménez & Mrawira [32]. The *IRI* of the selected highways was calculated for different environmental zones since those highways are within environmental zones for different moisture indices (Highway 1 with 100 and 80 moisture index; Highway 2 and 7 with 100, 80 and 60 moisture index; Highway 15 with 80 and 60 moisture index; Highway 16 with 60 moisture index; Highway 102 with 100 moisture index; and Highway 104 with 80 moisture index) [33].

Table 3 explains the details regarding the links of the selected routes requiring different types of pavement treatments during the design period. Treatment years represent the years of pavement maintenance carried, while control section implies the number of links of each route that required pavement treatments during different time periods. Table 3reveals that single chip sealing will be required for 7,074 km of Highway 1,1253 km for Highway 2, 2246 km for Highway 7, 2985 km for Highway 15, 1.44 km for Highway 16, 3.68 km for Highway 102, and 1698 km for Highway 104. Double chip sealing will be required for 246 km of Highway 1, 14.9 km for Highway 2, 1689 km for Highway 7, 0.56 km for Highway 15, and 1.48 km for Highway 16.

Micro-surfacing pavement treatment will be required for 18.68 km of Highway 1, 164.8 km for Highway 2, 27.28 km for Highway 7, 100.14 km for Highway 15, 2.64 km for Highway 16, 121.22 km for Highway 102, and 80.48 km for Highway 104 (Table 3). Minor rehabilitation (hot in-place recycling, *HIR*) will be required for 11.48 km of Highway 1, 100.06 km for Highway 2, 32.8 km for Highway 7, 58.24 km for Highway 15, 5.18 km for Highway 16, 126.76 km for Highway 102, and 48.78 km for Highway 104. Major rehabilitation will be required for 168 km of Highway 1, 113.8 km for Highway 2, 3.84 km for Highway 7, 4.36 km for Highway 15, 6.96 km for Highway 16, 1.8 km for Highway 102, and 5.34 km for Highway 104 (Table 3). Reconstruction will be required for 5.44 km of Highway 1, 50.26 km for Highway 2, 3.2 km for Highway 7, 5.1 km for Highway 15, 14.48 km for Highway 16, and 5.8 km for Highway 102 (Table 3).

Table 2: Predicted ESALs per year for New Brunswick regional highways [1].

Truck category (FHWA)	% Trucks	Truck Factor	Route	Route	Route	Route	Route	Route	Route
			1	2	7	15	16	102	104
5	8.2	0.45	12385	41370	4825	3092	2940	1169	943
6	5.7	1.18	22574	75409	8794	5637	5359	2132	1719
7	0.4	3.25	4363	14575	1700	1089	1036	412	332
8	2.7	0.99	8971	29968	3495	2240	2130	847	683
9	52.6	2.33	411341	1374059	160247	102710	97644	38843	31331
10	28.6	5.91	567302	1895035	221005	141653	134666	53571	43210
13	1.8	4.7	28394	94849	11062	7090	6740	2681	2163
ESALs per year			1055331	3525266	411129	263511	250514	99656	80382

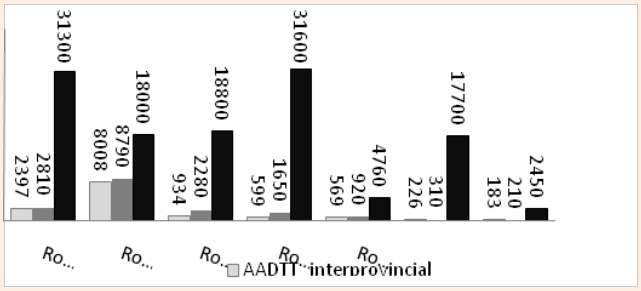

Figure 2: Annual Average Daily Traffic (AADT) of all vehicles, trucks and interprovincial trucks.

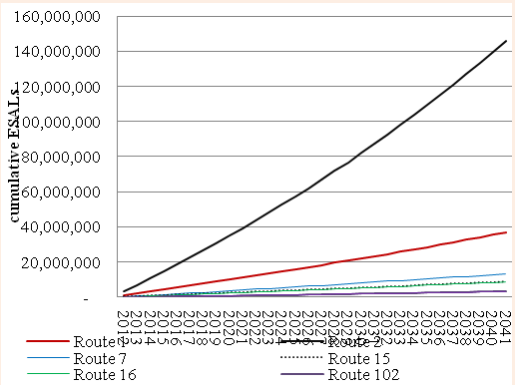

Figure 3: Cumulative Equivalent Single Axle Loads on selected routes.

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Table 3: Pavement surface treatments of links of selected routes.

Route		One Cheap Seal	Double Cheap Seal	Micro Surfacing	Minor Rehab.	Major Rehab.	Reconstruction
1	Total Length (Km)	7073.7	246	18.68	11.48	168	5.44
	Treatment year	1,2,3,4,5,	2,3	1,2,3,4,	1,2,3,	3	4,6
		6,7,8,9,10		5,8,9,10	9,10		
	Control section	12570	2116	1410	428	478	294
2	Total Length (Km)	1253.16	14.9	164.8	100.06	113.8	50.26
	Treatment year	1,2,3,4,5,	2,3	1,2,3,4,5,	1,2,3,4,5,	3,4,5,6,	4,5,
		6,7,8,9,10		6,7,8,9,10	7,8,9,10	7,8,10	6,7
	Control section	6814	1660	5908	2590	2734	1112
7	Total Length (Km)	2246.26	1689.06	27.28	32.8	3.84	3.2
	Treatment year	5,6,7,	3	1,2,4,5,	2,8,	3,5	6
		9,10		6,8	9,10		
	Control section	466	34	912	718	230	8
15	Total Length (Km)	2985.06	0.56	100.14	58.24	4.36	5.1
	Treatment year	5,7,8,	3	1,2,3,4,6,	1,2,3,	3,8	4,6
		9,10		7,8,9,10	5,9,10		
	Control section	542	10	2384	1384	22	208
16	Total Length (Km)	1.44	1.48	2.64	5.18	6.96	14.48
	Treatment year	5,7,8	3	4,6,8	3	3,5	4
	Control section	14	10	42	410	10	6
102	Total Length (Km)	3.68		121.22	126.76	1.8	5.8
	Treatment year	4,5,6		1,2,3,4,5,	1,2,7,	3,4	5
				6,7,8,9,10	8,9,10		
	Control section	46		436	392	84	28
104	Total Length (Km)	1697.8		80.48	48.78	5.34	
	Treatment year	10		2,3,4,6,	1,3,4,	7	
				7,8,9	9,10		
	Control section	20		180	114	6	

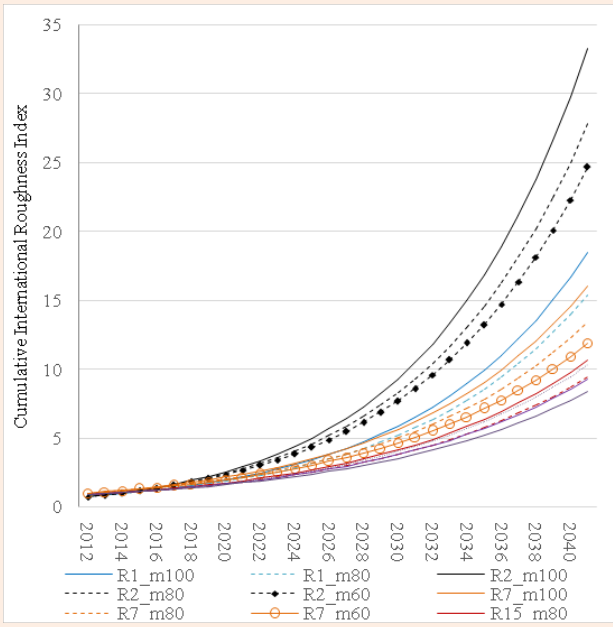

Figure 4: Cumulative International Roughness Index for moisture index of 60, 80 and 100.

The carbon footprint of forecasted freight traffic and traffic induced pavement maintenances

To calculate the 'carbon footprint', this study estimated CO_2 emissions from the fuel consumption by the anticipated truck movement and carbon dioxide equivalent (CO_2e) GHGs emissions from pavement maintenance activities due to the interprovincial trade flow during a period of 30 years. This study calculated 4.19 million gallons of fuel consumption per year due to the interprovincial truck movement on the selected highways, of which 2.6 million gallons fuel will be consumed on Highway 2, 0.78 million gallon on Highway 1, 0.3 million gallon on Highway 7, 0.19 million gallon on Highway 15, 0.18 million gallon on Highway 16, 0.07 million gallon on Highway 102 and 0.06 million gallon on Highway 104. This study estimated the total fuel consumption assuming that the average mileage of diesel-driven truck was 6 miles per gallon. During the period of 30 years (2012-2041), 125.61 million gallons of fuel will be consumed for this interprovincial truck flow among New Brunswick, Nova Scotia, Newfoundland and Labrador, Quebec, and Prince Edward Island, which will be valued at CAD 2750.96 million. In addition, per year CO_2 emissions will be 42625.28metric tons for the predicted interprovincial truck movement, which will be equal to 1.279million metric tons of CO_2emission during the projected 30 years. This study adopted that the CO_2 emission from diesel-driven freight transport was 10.18 grams per gallon [34].

This study then estimated the GHGs emissions from the pavement maintenance operations. The main GHGs in the field of pavement treatment are CO_2, nitrous oxide and methane [23]. Since the contribution of these gases is not the same, their 100-year 'Greenhouse Warming Potential (*GWP*) (1 for CO_2, 310 for nitrous oxide and 21 for methane) was expressed as a CO_2e (IPCC 2007). The CO_2e of GHGs emissions from the selected pavement treatments (chip seal, micro-surfacing, Minor rehabilitation, major rehabilitation and reconstruction) was calculated in Table 4.

Table 4: *CO_2e* GHGs emissions (metric tons) for different pavement treatments required for selected routes

Treatment	Details	Route 1	Route 2	Route 7	Route 15	Route 16	Route 02	Route 104
Chip seal	Emulsion (2.0 L/m^2), aggregate 21 kg/m^2	389054	68924	123544	164178	79	202	93379
	Emulsion (1.6 L/m^2), aggregate 15 kg/m^2	311243	55139	98835	131343	63	162	74703
Micro-surfacing	Type III (12% emulsion) (13 kg/m^2)	616	5438	900	3305	87	4000	2656
	Type II (14% emulsion) (8.7 kg/m^2)	411	3626	600	2203	58	2667	1771
Double Chip seal (two layer)	Emulsion (4.0 L/m^2), aggregate 42 kg/m^2	4928	1639	185797	62	163	0	0
	Emulsion (3.2 L/m^2), aggregate 30 kg/m^2	3942	1311	148637	49	130	0	0
Minor Rehab./ hot in-place recycling (HIR)	Thickness 3.8cm (50/50 recycle/new)	4800	41825	13710	24344	2165	52986	20390
	Thickness 5.0cm (50/50 recycle/new)	6188	53932	17679	31391	2792	68324	26292

Major Rehab. (hot mix asphalt)	100mm overlay	208824	141453	4773	5420	8651	2237	6638
	75mm overlay	157080	106403	3590	4077	6508	1683	4993
Recons-truction	100mm HMA overlay, 150mm aggregate base	7839	72425	4611	7349	20866	8358	0

The total CO_2e GHGs emissions from single chip sealing of the pavement surface will be 671,488.4 to 839,360.5 metric tons for 15,261 km of selected highways depending on the amount of emulsion (2 liter/m^2 or 1.6 liter/m^2) and aggregate (21 kg/m^2 or 15 kg/m^2) used in the chip sealing. For double chip sealing of the pavement surfaces, the total CO_2e GHGs emissions will be 154,070.4 to 192,588 metric tons since the length of pavement requiring double chip sealing treatment will be 1952 km during the period of 30 years. CO_2e GHGs emissions from micro-surfacing of pavement surface may vary based on the type of micro-surfacing. Type III (12% emulsion, 13 kg/m^2) micro-surfacing of 515.24 km pavement surface will emit 17,002.92 metric tons CO_2e GHGs in the atmosphere, which will be 11335.28 metric tons for Type II (14% emulsion, 8.7 kg/m^2) micro-surfacing of the same pavement surface (Table 4).

The total CO_2e GHGs emissions from Hot In-place Recycling (HIR) of the pavement surface will be 160,219.4 to 206,598.7 metric tons for 383.3 km pavement depending on the Thickness 3.8-5.0cm (50/50 recycle/new) of the HIR. For 100 mm or 75 mm Hot Mix Asphalt overlay of 304.1 km pavement surface, a total of 284,333.5 metric tons or 377,996.3 metric tons of CO_2e GHGs will be emitted in the atmosphere during the period of 30 years (Table 4). A total 84.28 km of pavement surface will require reconstruction (100mm Hot Mix Asphalt overlay, 150mm aggregate base) during the period of 2012-2041. For this reconstruction of the pavement surface, the total CO_2e GHGs emissions will be 121,447.48 metric tons (Table 4). Therefore, the total CO_2e GHGs emissions from different types of pavement surface treatments, due to deterioration by interprovincial truck flow, will be within the range of 1.403 million metric tons to 1.755 million metric tons depending on the type of treatments.

Conclusion

The integration of trade, transportation and environmental considerations requires a rational middle ground focusing on the environmental effects of trade and induced transportation so that trade and transportation can be part of the policy arsenal aimed at the common goal of sustainable development. The objective of this study was to integrate interprovincial trade flow induced freight movement, highway pavement maintenance, and corresponding environmental effects during the period of 2012-2041. The integration of spatial input-output and transportation modeling estimated that trucks would travel 334.722 million *truck-km* per year for trade flow among selected provinces during the design period. The predicted truck movement resulted in an AADTT of 2397 for highway 1, 8008 for highway 2, 934 for highway 7, 599 for highway 15, 569 for highway 16, 226 for highway 102, and 183 for highway 104.

The necessary pavement surface treatments of selected routes were determined based on the mechanistic modeling of roughness progression (International Roughness Index). During the projected period (2012-2041), 15,261.1 km of pavement will require chip sealing, while 515.24km, 1952km, 383.3km, 304.1km, and 84.28km of pavement will require micro-surfacing, double chip sealing, hot in-place recycling, major rehabilitation (hot mix asphalt), and reconstruction respectively. The fuel consumption for truck movement and pavement surface treatments will cause 2.682-3.034 million metric tons of CO_2e GHGs emissions depending on the type of treatments applied on the pavement surface. These predicted environmental impacts of interprovincial trade flow should encourage the incorporation of the environmental costs within the calculation of trade flows in order to ensure sustainable regional economy.

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