1   **A STUDY ON EFFECT ON GHG EMISSIONS BY ADDITION OF TRANSIT MODE IN**
2   **EXISTING ROAD NETWORK AND OPTIMAL EMISSION PRICING MODELS FOR**
3   **REDUCING CARBON FOOTPRINTS**

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5   By

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1 **ABSTRACT**

2 *Scientists and policymakers intend worldwide emissions reduction of up to 80 percent of carbon dioxide*
3 *(CO_2) and other greenhouse gases (GHGs) in the next four decades to stabilize atmospheric*
4 *concentrations (1). Henceforth, an immediate response from the transportation sector, one of the largest*
5 *producers of GHGs (up to 30 percent in the U.S.), is critical for GHGs reduction. Possible long-term*
6 *solutions towards cutting back on emissions from transportation are increasing supply-of/demand-for*
7 *more energy efficient/fuel efficient vehicles and to substantially improve the transit system (high-speed*
8 *rail, passenger rail, metro), to reduce reliance on private vehicles and air travel for short trips. However,*
9 *the markets are still struggling to produce supply-of/demand-for energy efficient vehicles and public*
10 *debate on potential ridership of high speed rail is ongoing in the U.S. Another feasible strategy that can*
11 *prove to be effective is emission pricing[1]. Recent advancement in Intelligent Transportation Systems (ITS)*
12 *offers a technical solution to implement emission pricing effectively in a reasonable period of time.*
13 *Further, this strategy can foster demand for efficient vehicles and high transit ridership while reducing*
14 *GHGs emission and generating revenue.*
15 *As state departments of transportation (DOTs) and metropolitan planning organizations (MPOs)*
16 *struggle to find more options to reduce GHGs emission, emission pricing offers a solution. To consider*
17 *emission pricing as an alternative, planners and policymakers will need tools to understand the*
18 *implications on private vehicle users and the environment. Therefore, in this study, we propose models*
19 *for understanding the reduction of GHGs emission and shifts of private vehicle trips to transit by*
20 *implementing ITS based optimal emission pricing to reduce GHGs emission by a certain percentage in a*
21 *composite transportation network (transit and highway network). The bi-level models presented in this*
22 *study take into account the planner's policy decision and the road user's response to such policies in a*
23 *simple and methodologically robust framework. The complex decision of choosing transit over private*
24 *vehicle and road user behavior in the study has been studied by mode split functions and the classical*
25 *user equilibrium principle. The performance of proposed models is compared to the base-case (do-*
26 *nothing); reductions in total GHGs emission by optimal emission pricing shows efficacy of the models.*
27 *The presented methodology in this paper is generalizable and can be applied to any transportation*
28 *network.*
29
30 **Keywords:** *greenhouse gases, optimal emission pricing, transit, mode choice, user equilibrium*

31 **INTRODUCTION**

32 Efficient, affordable and clean transportation is necessary for the U.S. to rebuild economic
33 strength and remain globally competitive. In regard to this, a publically debated initiative of the
34 Obama Administration is the expansion of high-speed passenger rail across the country.
35 However, a key issue that needs to be addressed in context to high-speed rail is: Will high-speed
36 rail generate enough riders and revenue thereof for the states to sustain the billions of dollars
37 required to build, maintain and operate the system? Some of the answers to the question of
38 ridership depends on the population density of a region and can be answered by travel demand
39 forecasting. Another possible solution lies in seeking private sector capital to help with the
40 substantial investment needed to achieve high-speed rail. These are already being studied at
41 various levels across the country. However, the authors view addition of high speed rail into the

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[1] Emission pricing is different from congestion pricing as the objective of emission pricing is reducing total emissions in a system as well as total delay whereas for congestion pricing the objective is reduce the total delay or total system travel time. Reducing total delay does not directly corresponds to reducing total emissions *(4)*.

1   existing network as another opportunity of marriage between two critical issues 1) sustainable
2   mode development 2) reduced reliance on private vehicles for longer trips.

3   International concern towards GHGs is at the center of all emission reduction issues with a
4   significant percentage produced by the transportation sector (*2*) of which a major portion is
5   attributed to emissions from private vehicles. A recent Transportation Research Board (TRB)
6   report suggests that scientists contend a 50% to 80% reduction in GHGs is needed by mid-
7   century in which a major response should come from transportation sector (*1*). In the next
8   decade, transportation agencies will be challenged to reduce the carbon footprint of private
9   vehicles nationwide. This will be a difficult proposition for DOTs and MPOs already struggling
10 to regulate GHGs or CO_2 vehicular emissions. A state of minimum emissions could be achieved
11 by substantially improving public transit; developing supply-of/demand-for green modes
12 (energy/fuel efficient and non-polluting); and/or changing road user behavior by imposing ITS
13 based emission pricing (i.e. similar to electronic tolls) such that it reduces dependence on private
14 vehicles. We acknowledge political and technical issues related to pricing, but given the highway
15 budget deficit and the need to curtail emissions, it is probable that emission pricing may become
16 reality in the near future. Further, recent advances in ITS offer technical solutions to problems
17 associated with implementation. While improvement of the transit system is the ideal scenario,
18 for a long-term sustainable solution, it is presumptuous to assume a natural shift to transit given
19 the reliance (preference and attitudes) on private vehicles. By imposing additional cost in terms
20 of emission pricing, many private vehicle users may shift to transit leading to reduced GHGs
21 emissions. However, it may be noted that emission pricing defined in this paper is different from
22 congestion pricing as in emission pricing the objective is to reduce emissions and congestion.
23 Johansson-Stenman (2006) has shown that negative externalities due to indirect environmental
24 costs are overlooked while performing conventional congestion pricing. Hence a new model was
25 proposed for considering environmental concern in traditional optimal steady-state road pricing
26 models. Also in the literature, it has been proven that reducing congestion does not necessarily
27 mean reducing emissions (*4*). Emission pricing has potential to achieve a reduction of GHGs
28 emission primarily in two ways. It can encourage private vehicle users to shift to an alternate
29 mode due to additional cost (in this study the alternate mode is transit). This can also prompt
30 consumer demand for green modes (fuel/energy efficient), provided these green modes do not
31 pay for emissions. Secondly, a shift of private vehicle trips to transit will reduce congestion on
32 the road network leading to reduced emissions. Moreover, the revenue earned from emission
33 pricing and selling of carbon credits gained by a reduction of GHGs emission can be used for
34 maintaining a transit system and other infrastructure.

35   In this paper we seek to understand how the addition of a new transit mode influences the
36 mode choice based on a sound behavioral model. Next, we develop various models for optimal
37 emission pricing to reduce total system emission (in terms of CO_2) to achieve a given target of
38 emission reduction for a transportation network. The models developed in this paper are at the
39 macroscopic level and can be used for any transit mode either high speed rail or a metro system
40 in a city, state or national transportation network. An agreeable assumption in this paper is that
41 the transit system is independent and is not influenced by traffic congestion on the road network.
42 It may be noted that this will not hold true if the transit system being studied is a bus transit and
43 additional research is needed to analyze all modes of transit.

The developed models simultaneously consider planner (or policymaker) and user; a planner's sole objective is to design emission pricing to minimize congestion and total GHGs emission on the road network while users (drivers) accordingly respond to policy decisions while minimizing their travel-cost/travel-time. Thus, considering a user's reaction to a given policy, an optimal decision is one that is not detrimental to other users or adversely affects the performance of the composite network (transit and road network). The methodology developed in this paper is generic and can be applied to any pollutant or transportation network. However, we show the application of proposed models in terms of reducing CO_2, a major GHG from the transportation sector, where the implementation of emission pricing can be conducted using ITS (electronic toll, EZ pass etc).

LITERATURE REVIEW

As described in the previous section we will model planner's policy decision and user's response in a single model. In optimization this can be best achieved and easily understood by using a bi-level problem approach. In general, the bi-level problem can be expressed as follows: the planner wishes to determine an optimal policy as a function of his/her control variable (x) (i.e. upper level) and the users respond (y) to these policy decisions (i.e. lower level) (*5*). An example of x can be toll, or signal setting, whereas an example of y can be route/mode choice of user. In our study, the user response generally takes the form of a network traffic flow. The planner then seeks to minimize both x and y, where some constraints may be imposed upon x as well as the fact that y should model user behavior, parameterized by the control vector, x. The network users, after and with complete knowledge of the planner's decision, make route choice decisions in an attempt to minimize their travel cost, resulting in an aggregate network flow pattern. A complete description of bi-level problem can be found in Yang and Yagar, 1994 (*6*).

Some of the initial studies in domain of emission modeling in a transportation network considered only traffic assignment while modeling and quantifying the emissions. The traffic assignment process is to reproduce the pattern of traffic flow which would be observed with a given travel demand. Yin and Lu (1999) studied the traffic equilibrium problems with environmental concerns, and proposed minimal traffic emission model (*7*). Nagurney (2000) with the help of three distinct paradoxical phenomena tested on a hypothetical highway network, and proved that the so-called improvements (like capacity expansion, toll, etc.) to the transportation network may result in increased emissions (*8*). Later, Nagurney and Dong (2002) developed a multi-criteria traffic network model with emissions in the objective function to reduce emissions (*9*). Sugawara and Niemeier (2003) explored a theoretical emissions-optimized trip assignment model to estimate the maximum carbon monoxide reduction under varying congestion levels on a hypothetical network (*10*). The experimental results indicated moderate reductions in system-level vehicle emissions under emissions-optimized trip assignment as compared to the conventional models.
Recent research related to emission minimization in the networks included imposing emission pricing as one possible solution. Yin and Lawphongpanich (2006) studied congestion and emission pricing such that it allows decision-makers to trade-off between two conflicting objectives, alleviating congestion versus reducing traffic emissions in a road network (*11*). However, no pre specified constraints for planners were considered in the model. Sharma and Mathew (2007) studied transportation network design in a bi-level problem when a user is

1 conscious about emission, in terms of emission cost (*12*). This was modeled in traffic assignment
2 stage by a generalized cost function. Sharma and Mathew (2011) studied a case when the planner
3 is environmentally conscious and plans capacity expansion of the road network while
4 minimizing total emissions as one of the objectives (*4*). A large network case study showed
5 marginal reductions in emissions while improving the road network. Later, Sharma and Mishra
6 (2011) studied emission pricing in a given road network (*13*). However, the methodology used
7 was only for a simple road network where users don't have choice between modes. An important
8 observation was emission pricing on a road network will produce moderate reduction in
9 emissions since the only choice users have is to reduce vehicle miles traveled by choosing
10 links/routes which are not congested or/and are not charged. This may not be a fair option for
11 road users as they have limited choice between routes. It was concluded emission pricing should
12 be more effective if road users have other mode choices (transit, green mode, etc.).
13   Most of these studies have tried to understand emission reduction either by formulating it
14 as objective in the traffic assignment problem or making improvement (i.e. capacity expansion
15 and toll) to the network while minimizing total emissions. However, it is critical that emission
16 pricing on the road-links/routes be decided such that it does not adversely impact the composite
17 network and the road user's travel cost. Further, there is a need to model the optimal emission
18 pricing value that reduces GHG emissions by a certain percentage while capturing the
19 perspective of planners and road users in terms of various objectives in a composite network.
20 The change in GHG emissions with the addition of a transit network also needs to be studied. In
21 this study we attempt to find the optimal emission price value for a network such that it reduces
22 the overall emissions and associated objectives for planners as well as users of the composite
23 network.

24 **MODEL PHILOSOPHY**

25 In this study, the problem is formulated as a bi-level problem with the upper level representing
26 the planner's policy decision to achieve his/her objective of minimizing congestion and total
27 emissions of CO_2 or GHG emissions (we can also say total carbon footprint). At the lower level
28 we model user (driver) response to the policy decision taken by planner.

29 **Upper Level:**

30 The upper level here implies the planner's policy decision, which is the amount of emission
31 pricing on a link/route to achieve the objective of minimal emissions in the network while
32 incurring least delay to users. The essence of the model is that some users sacrifice their travel
33 time by opting transit over private vehicles. These users can be seen as emission/carbon footprint
34 conscious since they are sensitive to emission cost (emission pricing), as they pay for using
35 private vehicles over the road network. In the model, planner's optimal emission pricing is based
36 on the objective of minimizing the carbon footprint or GHG emission on the road network while
37 maintaining the minimum amount of total delay or total system travel time (TSTT)[2]. The model
38 is capable of incorporating a constraint on desired percentage reduction in the amount of GHGs
39 by employing optimal emission pricing. However, it may be noted throughout the study that the

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[2] Total system travel time is the time spent in network by the user and minimizing total system travel time is equivalent to minimizing total delay in the system. Both these terms physically have the same meaning and are used interchangeably in the paper.

1 transit mode has been considered as a non-polluting mode. High-speed rail, Amtrak or metro
2 system may use power generated in thermal plants that produce GHGs, but for the sake of
3 simplicity in modeling and limiting the scope of the problem to only the transportation sector, we
4 have considered the transit mode as a green mode (i.e. transit mode is non-polluting).

5 **Lower Level:**

6 The traffic flow in the network is known by solving the traffic assignment problem. The
7 fundamental aim of the traffic assignment process is to reproduce on the transportation system,
8 the pattern of vehicular trips/personal trips which would be observed when the travel demand
9 (represented by the trip matrix, or matrices) is assigned to the network satisfied by employing
10 behavioral models. The lower level in this problem is either a single mode traffic assignment
11 when only the road network is considered or a combined modal split traffic assignment problem
12 for the composite network (when both modes are considered). The lower level model is based on
13 the behaviorally-sound principle of user equilibrium. This principle is based on the fact that
14 individuals choose a route so as to minimize his/her travel time or travel cost and such a behavior
15 on the individual level creates equilibrium at the system (or network) level over a long period of
16 time (*14*). In simple words, for each origin-destination (O-D) demand pair, the travel-cost/travel-
17 time on all used routes of the road network should be equal when only private vehicle mode is
18 considered.

19 Similarly, if both modes are used over the composite network then travel-cost/travel-time
20 on all used routes of the road network and equivalent value of performance function for transit
21 should be equal. This principle in addition to being behaviorally robust, is computationally
22 efficient, and possesses a unique solution (*14*) which means it can be used to model any large
23 real-life transportation network. More than 90% of the large MPOs apply the user equilibrium
24 assignment method to assign highway traffic or road network traffic (*15*). We are using the same
25 principle to model both the road and composite network.

26 During the design period of analysis in transportation networks the travel demand is
27 mostly fixed. If an alternative mode of transportation is present some of these trips may be
28 conducted on the alternative mode like transit as well as the road network. In real life the mode
29 choice decisions taken by user in a composite network are a complex mix of different factors
30 (individual preference, comfort, waiting time, travel time, etc.). This complex mode choice
31 problem can be studied by developing mode split functions. Mode split functions can account
32 for the factors that are not easy to quantify or measure, but are part of user mode choice
33 behavior. A classical mode split function is given by

$$\hat{q}_{rs} = \bar{q}_{rs} \frac{1}{1 + e^{\theta(\hat{t}_{rs} - t_{rs})}} \qquad (1)$$

34 where θ is a positive parameter (known as logit parameter), $\hat{q}_{rs}$ is the trips on transit between a
35 O-D pair r-s, $\bar{q}_{rs}$ is the total travel demand between O-D pair r-s, t_{rs} is the minimum travel time
36 by private vehicle between an O-D pair r-s on the road network and $\hat{t}_{rs}$ is minimum travel time
37 by transit mode. At equilibrium the composite network will satisfy the equation 1 and road
38 network will satisfy User Equilibrium (UE) condition, i.e. travel time on all the used routes will

1 be equal. The reader should consider this equation 1 simply as a formula for the demand of
2 vehicular trips and person trips between origin (r) and destination (s) by private vehicle or transit.
3 In the next section, we will discuss the mathematical construct of the models and base cases that
4 are used for comparison. If a reader wishes to skip the complex mathematical part of
5 formulations they can directly go to Table 1 and read an explanation of each formulation which
6 has been articulated for easy understanding of models developed and used in this paper and then
7 move to solution methodology.

8 **MODEL FORMULATION AND SOLUTION METHODOLOGY**

9 In this study, the optimal emission pricing model is formulated as a bi-level problem with a
10 number of constraints. The upper level is the planner's perspective i.e. either minimizing total
11 system GHG emissions (TSEM) or total system travel time (TSTT) or both objectives
12 simultaneously by determining a set of optimal emission pricing subjected to some constraints.
13 As discussed, in the future most planners at state DOTs and MPOs will be looking at realistic
14 percentage reduction of GHG emissions, so a constraint has been included as a minimum desired
15 percentage reduction in GHG emissions.

16 **Upper Level**

17 Here we formulate a Base-case-1 (only road network), Base-case-2 (addition of transit in an
18 existing road network) and two different models, Single Objective Constrained Emissions-
19 Emission Pricing Model (SOCE-EPM) and Multi-Objective Constrained Emissions- Emission
20 Pricing Model (MOCE-EPM) to augment a planner's decision-making procedure. Table 1
21 represents the structure of the proposed models, and their objectives and constraints at the upper
22 and lower levels. The first two rows in the table are base-case representations. The Base-case-1
23 is when there is only a road network available for users, a representation of a highway/road
24 network in a city or state. The Base-case-2 represents the addition of a transit network in an
25 existing road network i.e. creating a composite network. Since for Base-case-1 and Base-case-2
26 the planner has set no policy on emission pricing, these cases represent a do-nothing scenario for
27 comparison of emission pricing models.

28 *Single Objective Constrained Emissions- Emission Pricing Model (SOCE-EPM)*

29   Upper level in SOCE-EPM demonstrates the planner's objective to minimize total system
30 travel time while obtaining optimal emission pricing. The total system travel time '$TSTT_e$' is
31 time spent by users in a transportation network and should be a minimum to suffer least delay
32 within the network. A minimum percentage reduction constraint is used to obtain the desired
33 reduction in the carbon footprint or GHG emission. The value of this constraint is calculated as
34 the difference of total GHG emissions from the Base-case-2 model (TE_{BC2}) and total GHG
35 emissions from SOCE-EPM 'TE_{Mod1}' divided by total emission from SOCE-EPM 'TE_{Mod1}'. The
36 value '$\%_{red}GHG'$ is the minimum desired value of reduction in the carbon footprint or GHGs
37 from the transportation system. This value can be pre-determined by a planner or policymaker or
38 can be based on regulations at the state or national level.

39   The emission function ef_a (v_a) used for calculating total GHG emissions typically has a
40 polynomial form with an average link speed 'v_a' as the dependent variable and is given as

$$ef_a(v_a) = b_1 v_a^2 + b_2 v_a + b_3 \tag{2}$$

1   where: b_1, b_2, and b_3 are the coefficients to be calibrated from the observed vehicular
2 emission data. In this paper we consider the pollutant as CO_2, a major GHG, and adopt a
3 polynomial function from El-Shawarby et. al. (*16*). Another way of quantifying the emissions is
4 using MOVES software which can be easily integrated in the developed model Further, it is
5 equally important to quantify emissions also as a function of acceleration, deceleration and idling
6 of vehicles, but that is used in operational models rather than planning models which are
7 macroscopic in nature. In addition, availability of such microscopic level data is a challenge in
8 itself.
9   The emission pricing value 'e_a' for each link acts as an additional cost for a road user
10 given by $c_a(x_a, e_a)$ as shown in equation (6) and explained later. The different values of 'e_a'
11 lead to a change in travel cost for road users and hence variation in the traffic flows/passenger
12 trips throughout the composite network. The real value variable 'e_a' is chosen such that it is
13 within the value of 1 (i.e. maximum increase in travel cost is 100%) and 0 (i.e. no emission
14 pricing at all). It may be noted that emission pricing will take place on the road network only and
15 the transit users are not charged for using the transit mode as transit mode is assumed to produce
16 no emissions. Thus users that shift from private vehicle to transit mode sacrifice their travel time
17 to avoid the costs.

18 *Multi-Objective Constrained Emissions- Emission Pricing Model (MOCE-EPM)*

19   Upper level in MOCE-EPM is a multi-objective model, in which both objectives of total
20 system travel time and total system emissions are minimized simultaneously. Both of these are
21 conflicting objectives and minimizing either does not necessarily means that it reduces the value
22 of the other objective (*4*). Therefore, it is desirable to consider both objectives in minimization
23 while planning optimal emission pricing. The constraint used in this model makes sure that the
24 minimum desired value of GHG emissions is achieved is the same as in the Model- 1.

25 **Lower Level**

26 The lower level assigns the travel demand into the network using the route choice algorithm. A
27 user equilibrium assignment has been used for modelling Base-case-1. The formulation for the
28 user equilibrium assignment in the form of an optimization problem is shown in the first row and
29 third column of Table 1. The travel time function $t_a(.)$ is specific to a given link 'a' on the road
30 network and the commonly used model is Bureau of Public Roads (BPR) function given by :

$$t_a(x_a) = t_o \left(1 + \alpha_a \left(\frac{x_a}{C_a} \right) \right)^{\beta_a}$$

(3)

31   where $t_o(.)$ is free flow time on link 'a', C_a is capacity of link a, and α_a and β_a are link specific
32 constants, normally calibrated using the observed field data. Constraints shown for Base-case-1
33 last column in Table 1 are the standard constraints for such problems.

34   The equilibrium problem in which both modes of transportation are involved is referred
35 to as the combined modal split/traffic assignment problem. Since we assume addition of transit
36 mode in the network, Base-case-2 is modeled at the lower level using combined modal split
37 traffic assignment. To analyze the combined modal split problem we assume that transit
38 performance is independent of the private vehicle flow on the road network. In this model the

1   transit travel time, including waiting time and transfer time, is represented by $\hat{t}_{rs}$, in time units.
2   The performance function for transit is given by:

$$W_{rs}(\hat{q}_{rs}) = \left(\frac{1}{\theta} \ln \frac{\hat{q}_{rs}}{\bar{q}_{rs} - \hat{q}_{rs}} + \hat{t}_{rs} \right) \tag{4}$$

3   The trips on transit $(\hat{q}_{rs})$ are equal to the difference between total travel demand and
4   trips/traffic flow on road network (private vehicle trips) i.e. $\hat{q}_{rs} = \bar{q}_{rs} - q^{rs}$. By definition of
5   equilibrium the value of performance function for transit and travel-time/travel-cost on the road
6   network should be equal if both modes are used, and if only one mode is used then the travel-
7   time/travel-cost or equivalent performance function value on it should be lower than the unused
8   mode. The mathematical program to compute such equilibrium state is shown in column 3 and 4
9   of Base-case-2, SOCE-EPM and MOCE-EPM. The lower level (i.e. road user response) of all
10   these models will be computed based on these formulations.

$$W_{rs}(\hat{q}_{rs}) = t_{rs}(q^{rs}) \tag{5}$$

11   Equation 6 shows how emission price variable e_a and value of time constant (φ) that is in
12   monetary terms (\$/hr) changes travel time into travel cost.

$$c_a(x_a, e_a) = \varphi \, (1 + e_a) \, t_a(x_a) \tag{6}$$

13

14   The value of time is the opportunity cost of the time that a traveler spends on his/her trip or
15   commute. Multiplying travel time with value of time to obtain the travel cost is common
16   modeling practice in transportation planning. In equation 6 the travel time on a road link has
17   been converted into travel cost by multiplying it by the value of time constant (φ) and emission
18   pricing variable (e_a).

19   Next we will illustrate the complete formulation of the model presented in Table 1.The notations
20   used in these proposed models are given below:

21    $t_a(\omega)$: travel time as a function of traffic flow "ω" on road network or transit network
22   x_a : is the equilibrium link flows for road network on link "a".
23   f_k^{rs} : is the flow on path "k" between OD pair r-s.
24    $\delta_{a,k}^{rs}$: is 1 if route "k" between OD pair r-s uses link "a" and 0 otherwise.
25   θ : is the logit parameter used in mode split function.
26    $\hat{q}_{rs}$: are the passenger trips on transit between O-D pair r-s.
27   q^{rs} : are the trips on private vehicle between O-D pair r-s
28    $\bar{q}_{rs}$: is the total travel demand between O- D pair r-s
29   t_{rs} : is the minimum travel time by private vehicle between an O-D pair r-s
30    $\hat{t}_{rs}$: is minimum travel time by transit mode between O-D pair r-s.
31    $TSTT_e$: is the total system travel time with emission pricing vector "e"
32    $TSEM_e$: is the total system GHG emission with emission pricing vector "e"
33   e : is the vector of emission pricing, e = [e$_a$].
34   TE_{BC2} : are the total system GHG emissions from Base-case-2.
35   TE_{Mod1} : are the total system GHG emissions from SOCE-EPM.

1   TE_{Mod2} : are the total system GHG emissions from MOCE-EPM.

2     $\%_{red}GHG$: % desired reduction in GHGs emissions.

3     $ef_a(v_a)$: is the speed dependent emission factor for link "a" (gm/miles) "v_a" is link

4   speed.

5   l_a : is the length of link "a" (miles).

6     $c_a(x_a, e_a)$: travel cost as a function of flow "x_a" and emission pricing "e_a".

1   **TABLE 1 Models For Emission Reduction**

Scenario*	UPPER LEVEL		LOWER LEVEL		SIMPLE EXPLANATION
(1)	(2)		(3)		(4)
	PLANNER DECISION		USER RESPONSE		
	OBJECTIVE (Minimize)	*CONSTRAINT*	*OBJECTIVE (Minimize)*	*CONSTRAINT*	
Base-Case-1 (No Transit)	-	-	$$\sum_a \int_0^{x_a} t_a(\omega)\,d\omega$$	$\sum_{\forall k} f_k^{rs} = q^{rs}$ $x_a = \sum_r \sum_s \sum_k \delta_{a,k}^{rs} f_k^{rs}$ $f_k^{rs} \geq 0; \forall\, k, r, s$ $x_a \geq 0; \forall\, a$	These equations represent User Equilibrium principle i.e. based on the fact that individuals choose a route so as to minimize his/her travel time or travel cost. Such a behavior at individual level creates equilibrium at the network level over time. It is commonly used for modeling road network traffic.
Base-Case-2 (Addition of Green Transit Mode)	-	-	$$\sum_a \int_0^{x_a} t_a(\omega)\,d\omega$$ $$+ \sum_{rs} \int_0^{\hat{q}_{rs}} \left(\frac{1}{\theta}\ln\frac{\omega}{\bar{q}_{rs}-\omega}\right.$$ $$\left. + \hat{t}_{rs}\right) d\omega$$	$\sum_{\forall k} f_k^{rs} + \hat{q}_{rs} = \bar{q}_{rs}\,;\forall\, r, s$ $f_k^{rs} \geq 0; \forall\, r, s$ $0 < \hat{q}_{rs} < \bar{q}_{rs}; \forall\, r, s$	These equations represent that when a transit mode is added to an existing road network, by definition of equilibrium if all modes are used the performance function of transit will be equal to travel-times on used road network.
Model-1	$$TSTT_e = \sum_a (x_a t_a(x_a))$$	$\frac{TE_{BC2}-TE_{Mod1}}{TE_{Mod1}} \geq \%_{red}GHG$ $0 \leq e_a \leq 1$	$$\sum_a \int_0^{x_a} c_a(\omega, e_a)\,d\omega$$ $$+ \sum_{rs} \int_0^{\hat{q}_{rs}} \left(\frac{1}{\theta}\ln\frac{\omega}{\bar{q}_{rs}-\omega}\right.$$ $$\left. + \hat{t}_{rs}\right) d\omega$$		The planner tries to minimize delay in the network while reducing GHGs emissions by certain percentage through emission pricing and user response (as in BaseCase-2) is based on the increased travel cost on current routes from emission pricing.
Model-2	$$TSTT_e = \sum_a (x_a t_a(x_a))$$ $$TSEM_e$$ $$= \sum_a (x_a ef_a(v_a)l_a)$$	$\frac{TE_{BC2}-TE_{Mod2}}{TE_{Mod2}} \geq \%_{red}GHG$ $0 \leq e_a \leq 1$	$$c_a(x_a, e_a)$$ $$= \varphi\,(1 + e_a)\,t_a(x_a)$$		Planner minimizes both objectives simultaneously; total system travel time and total emissions; reducing emissions by certain percentage through emission pricing.

2   Note: * The "Base-Case" scenario is solved as a UE assignment method or Combined Mode Traffic Assignment (Lower Level only)

Solution Algorithm

The overall solution algorithm is presented in Figure 1. The complexity of the problem lies in simultaneously minimizing planner's objective and to define the value of emission pricing (policy decision) for the least value of the objective function and then model road user's response to this emission pricing value until no other best possible solution is reached. This complete mechanism being an iterative process and a bi-level model is not possible using simple transportation modeling software that mostly solves traffic assignment. In addition, the initial solution for solving the lower level needs to be obtained each time an emission price is fixed.

The upper level of the problem is solved using a genetic algorithm (GA) since its efficacy in solving bi-level problems of a large real-sized network has been proved in the literature (*5;17*), which is our final objective to make the model realistic and applicable in the real world. The lower level has been solved by using the traditional Frank-Wolfe algorithm; the detail algorithm is available in literature (*14*). The initialization of the algorithm to solve the combined traffic assignment model in the case of composite networks needs to be conducted differently than for traffic assignment for the road network. In the case of road network traffic assignment, the lower level of solution algorithm starts with an empty network (i.e. the flows on all links is assumed to be 0). However, in the case of a composite network, the initial solution is found by application of logit modal split function (equation 1) to travel time over an empty network.

The algorithm starts with the upper level by reading all the inputs including network details, travel demand, constraints, travel time function, and emission functions. A population of link emission pricing vector is created and randomly initialized. These trial links emission pricing vectors are then translated into the current travel cost. The lower level algorithm is then invoked with the current link emission pricing vector where the demand is assigned into the network using the formulation presented in Table 1. The lower level is solved using the Frank-Wolfe Algorithm. The output of the lower level is the link traffic flow/passenger flow vector which is used to compute link travel time using the BPR function for road network, performance function for transit, and travel cost for both modes and further TSTT. The average speed on each link and emission factor is calculated based on equation 2. After calculating speed dependent emission factors, total emissions generated for each pollutant are computed. Thus, the TSTT and total GHG emissions computed will form the objective function values of the current generation. Once the values of objective functions are obtained, solutions are checked for constraint violation and the fitness function is computed. The process is repeated until no better solution can be generated, or the current generation is greater than the pre-specified maximum generations. Solutions are reported in the form of total system travel time, total emissions, emissions on each link, optimal emission pricing vector, and link travel times.

INPUT
Network Data
Travel time function
OD Matrix
Emission function
Desired Percentage
Reduction

Start

Upper Level

Generate population of
emission pricing vector

Randomly initialize emission
pricing vector

e''

For Composite Network
Get Initial Solution

e'

Get travel cost from emission
pricing vector

Next Generation
gen = gen + 1

GA Operations

Lower Level

Traffic Assignment Using
Frank Wolfe Algorithm

x'

Yes

Is gen <
max.gen

No

Compute:
Link travel time
Link emissions
Link Travel Cost
Link traffic flow/passenger trips

OBJ 1 = Total System Travel Time
and/or
OBJ 2 = Total System Emission

OUTPUT
Objective function values
Optimal emission pricing values
Total GHGs emission

Pareto optimal solutions
Network performance measures

FIGURE 1 Flowchart demonstrating solution methodology for proposed model

TEST NETWORK

To explore the applicability and proof of concept of the model, a test network consisting of four nodes and five links is considered (Figure 2). The length (*l in miles*), capacity (*C in veh/hr*), Free Flow Speed (FFS in *miles/hr*, or *mph*), α and β of each road link is also presented in Figure 2. An additional transit link is also shown in the figure joining node 1 and 4 along with speed and length. The travel time for the transit link is constant and is equal to 36 minutes as it is assumed that transit moves on dedicated lanes with high capacity and no interaction with road traffic. The speed assumed for the transit link is 30 mph, it is just an assumption and while performing a case study for a large network, high-speed rail speed can be assumed as realistic speed of 130-150 mph or for metro between 30-75 mph. The peak hour trip demand from node 1 to node 4 is 6,000 trips/hour. The occupancy of vehicles is assumed as 1 person per vehicle. For example on a road network a value of 10 trips/hour represents 10 vehicles/hour and on the transit network the value of 10 represents 10 passengers/hr. The value of logit parameter (θ) is assumed as 0.1.
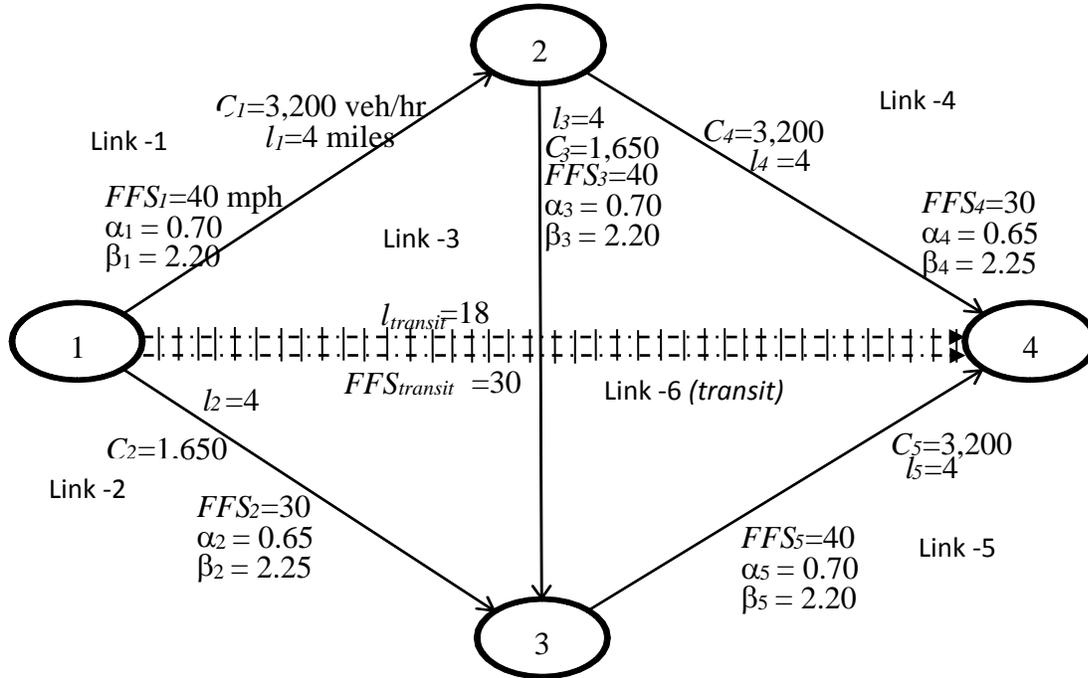
FIGURE 2 Small Test network

The link level solutions are presented in Table 2, showing link emissions, link traffic flow/passenger flow, link speed, available routes, route travel cost, and optimal emission pricing for each link. The Base-case-1 in the Table 2 represents the traffic on a given road network in the absence of transit. The Base-case-2 represents the trip distribution in the composite network (i.e. addition of transit link in the road network or a road network with existing transit link). SOCE-EPM and MOCE-EPM are the proposed models for estimating emission pricing with different objectives and constraints of the planner. SOCE-EPM is when the planner tries to minimize delay in the system (total system travel time) while reducing GHG emissions to a given percentage; this is done by proposing emission pricing on various links. In MOCE-EPM, the planner simultaneously tries to minimize total emissions and total system travel time i.e. total delay thus reducing GHG emissions by choosing the optimal value of emission pricing.

All links are subjected to emission pricing thereby increasing the user travel cost on the road network such that the traffic flow/passenger trips are dispersed so as to minimize total system emissions. For example, for link-1 (in SOCE-EPM), the optimal emission pricing (Column 6, Table 2) from the solution algorithm is $e_a = 0.157$, which translates as 0.157 times the Base-Case-2 travel cost (travel cost on link-1= Base-case-2 travel cost * 0.157). If travel time on link-1 for Base-case-2 is 10 minutes then travel cost is 10 minutes * value of time (VOT) =$10. The value of time is the opportunity cost of the time that a traveler spends on his/her commute. The commonly assumed value of time is $60/hr or $1/minute. Assuming the same income user class using the private vehicles on the road network, the travel cost on link-1 for Base-Case-2 is $10, (10 minutes *$1/minute) and the optimal emission pricing value is $1.57 ($10 * 0.157) on link-1 (also see equation 6). In practical application the emission pricing value can be rounded to the nearest dollar amount.The results presented in Table 2 show reduction in emissions from SOCE-EPM and MOCE-EPM by optimal emission pricing compared to both

base-cases. MOCE-EPM being a multi-objective problem gives multiple solutions. The solutions for MOCE-EPM in table 2 are two randomly-selected solutions from a pool of 48 solutions. It can be seen in table 2 that passenger trips in the transit link increase with emission pricing compared to Base-case-2 and hence reduces the emissions in two ways 1) the reduced traffic flow in the road network improves the average speeds of the links which further reduces the emission factor a function of speed that can lead to lower emissions, 2) the reduced number of vehicles or traffic on the road network creates less vehicle miles traveled while increasing transit patronage. Moreover with the increased average speed, the link travel time improves on the road network.

TABLE 2 Link level results for the test network

Model (1)		Link # (2)	GHGs Emission (gm) (3)	Flow (veh/hr for road network and passenger/hr for transit) (4)	Speed (mi/hr) (5)	Pricing ($) (6)	Route (Node-node) (7)	Route Travel cost ($) (8)
Base-Case-1 (Road Network Only)		1	4554271.01	4090	18.2	-*		
		2	2742018.32	1910	15.8	-		
		3	1558256.96	2177	30.8	-		
		4	2745844.01	1913	15.8	-		
		5	4551153.25	4087	18.2	-		
Base-Case-2 (Composite Network)		1	3149458.42	3059	24.5	-*		
		2	1993991.05	1466	20	-		
		3	1088633.68	1593	34.8	-	1-2-4	24.8
		4	1994634.45	1467	20	-	1-2-3-4	24.8
		5	3148943.25	3059	24.5	-	1-3-4	24.8
		6 (Transit)	-	1475	30	-	1-4	24.8†
Model-1		1	2648307.63	2661	27.3	1.57		
		2	1645284.95	1245	22.3	2.76		
		3	956795.99	1417	35.8	3.86	1-2-4	29.8
		4	1645232.99	1245	22.3	4.57	1-2-3-4	29.8
		5	2648349.09	2662	27.3	4.33	1-3-4	29.8
		6 (Transit)	-	2094	27.3	0	1-4	29.8†
Model-2‡	Solution -1	1	2338583.54	2403	29.1	0.94		
		2	1544153.01	1178	23.0	4.32		
		3	868212.22	1295	36.5	9.59	1-2-4	32.1
		4	1439298.86	1108	23.7	8.23	1-2-3-4	32.1
		5	2421622.43	2474	28.6	5.99	1-3-4	32.1
		6 (Transit)	-	2418	30	0	1-4	32.1†
	Solution -2	1	1638523.16	1774	33.6	9.99		
		2	1198665.54	941	25.3	9.92		
		3	550315.55	840	38.6	9.93	1-2-4	37.9
		4	1188110.30	934	25.4	10	1-2-3-4	37.9
		5	1646386.81	1781	33.5	10	1-3-4	37.9
		6 (Transit)	-	3285	30	0	1-4	37.9†

Note: *No emission pricing for Base-Case. † Equivalent travel time for transit given by equation 4 (performance function) ‡ Since Model-2 is Multi-objective Model there are multiple solutions, presented here are two randomly selected solutions.

Columns 7 and 8 represent the routes/paths for the OD pair 1-4 and travel cost on different routes. According to the user equilibrium principle, travel-cost on all used routes should be equal. We can see that the travel costs on all used routes/paths between OD pair 1-4 are equal. Moreover, the travel cost in SOCE-EPM and MOCE-EPM is higher compared to Base-case-2 due to emission pricing even if the travel time is lower on the road network because of shift of some private vehicle users to transit. For transit the travel cost is in equivalent terms of travel cost for road links using equation 4.

The system/network level results are presented in Table 3. In the second, third and fourth column values of TSEM, TSTT and vehicle miles traveled (VMT) for each model is presented. Emission pricing for individual links may not seem practical to most practitioners since one cannot collect a toll on multiple links lying in the same route. Therefore, we present case for each model in which emission pricing is done on the three links lying on three different routes in the network for O-D pair 1-4.

TABLE 3 Network level results for the small test network

Case (1)		Total GHG Emissions (TSEM) (tonnes) (2)	Total System Travel Time (TSTT) (hours) (3)	VMT (miles) (4)	Constraint Minimum Desired % reduction in GHGs (5)	% reduction** GHG Emissions (6)	TSTT (7)	VMT (8)
Base-Case-1		16.15	3225.1	58354	-	-	-	-
Base-Case-2		11.4	2754.3	43914	-	-	-	-
Model- 1		9.54	2713.5	37989	15%	19.19%	1.50%	15.59%
Model- 1 $^{\psi}$		10.06	2716.9	39715	10%	13.12%	1.38%	10.57%
Model- 2	Solution -1‡	8.61	2722.9	34825	-	32.09%	1.15%	26.10%
	Solution -2‡	6.22	2829.5	26117	-	82.83%	-2.66%	68.14%
Model- 2 $^{\psi}$	Solution -1‡	8.08	2735.7	39727	40%	40.74%	0.68%	33.39%
	Solution -2‡	7.56	2755.1	38125	40%	50.30%	-0.03%	37.04%

Note: **: % reduction = ((Subject model - Base-Case-2) / Base-Case-2)*100, ψ: Emission Pricing on only 3 routes/links,
‡ Since Model-2 is Multi-objective model there are multiple solutions, presented here are two randomly selected solutions.

We can see for SOCE-EPM in Table 3, pricing on all links with a minimum desired reduction in GHG emissions of 15% produces a reduction of 19.19 % of GHG emissions and 1.5% reduction in total system travel time or delay (Column 5) compared to Base-case-2. SOCE-EPM with pricing on only three links on the possible three routes/paths from OD pair 1-4 shows a reduction of 13.12% in total GHG emissions and reduction in total delay to be 1.38% compared to Base-case-2. The two randomly selected solutions in MOCE-EPM for pricing in all links shows a substantial reduction even without constraint of desired reductions in GHG. This is because solution from MOCE-EPM is better compared to SOCE-EPM as it simultaneously minimizes both objectives. The reduction in GHG emissions from MOCE-EPM solutions is 32% and 80%, but it does not necessarily mean that increasing emission pricing on all the links leads to significant reduction in GHG emissions as it may make road users worse off in terms of travel cost and travel time (-2.66%). The two solutions from MOCE-EPM in the last row of Table 3 are when emission pricing is only on the three routes. These solutions show the model's ability to

provide optimal emission pricing while confirming to constraint of reducing the GHG emissions from minimal desired value (40%).

CASE STUDY

The second test network studied to check the performance of the models is the Sioux Falls network, which is probably the most extensively used in similar studies. The original Sioux-Falls network has 24 nodes and 76 road links. Various traffic flow and network parameters such as OD matrix, mode split, α_a, β_a, free flow speed, and capacity are taken Nagurney et al. (2010) (*18*). However for this study, we have modified the original network and added four transit links into the network (1-10,10-1,10-20,20-10) making it a total of 80 links as shown in figure 3. The node 10 has been assumed as the Central Business District (CBD) of the Sioux Falls network and the travel demand has also been also modified accordingly to represent demand from the CBD. The assumed OD pairs and their demand are as following: from node 10 to node 1 demand is 40,000 trips/hour, similarly equal demand has been assumed in the reverse OD pair 1-10. For OD pair 1-20 and 20-1 the demand is assumed to be 80,000 trips/hour. This modified Sioux-Falls network is congested during the peak hours. The highlighted links in the Figure 3 are the links chosen for emission pricing and are selected based on the congestion and emissions being produced on those routes. Table 4 shows the network level results from the models for the modified Sioux-Falls network. The Base-case-2 results (i.e. do-nothing scenario for composite network) are shown in the second row of the table. The average travel time in the network is shown in the second row of each case. The desired percentage reduction of GHG emissions is 15% for both the models. Because of space constraint and for brevity we are not showing the value of emission pricing on all 17 links, but the effectiveness of pricing can be seen on the network level results in Table 4. The emission pricing ranges from $0 to $10 for the 17 links that are priced.

TABLE 4 Network level results for Modified Composite Sioux Falls Network

| Case (1) | | Total GHG Emissions (TSEM) (tonnes) (2) | Total System Travel Time (TSTT) (hours) (3) | VMT (miles) (4) | Constraint | % reduction** | | |
					Minimum Desired % reduction in GHGs (5)	GHG Emissions (6)	TSTT (7)	VMT (8)
Base-Case-2		751.06	162438.70	3179116	-	-	-	-
		Average Travel Time=40.6 minutes						
Model- 1 $^\psi$		644.92	146676.75	2897853	15%	16.46%	10.8%	9.7%
		Average Travel Time=36.6 minutes						
Model- 2 $^\psi$	Solution -1 ‡	626.41	146106.02	2821977	15%	19.90%	11.2%	12.7%
		Average Travel Time= 36.5 minutes						
	Solution -2 ‡	620.73	146245.26	2798950	15%	21%	11%	13.6%
		Average Travel Time=36.5 minutes						

Note: **: % reduction = ((Subject model - Base-Case-2) / Base-Case-2)*100, ψ: Emission Pricing on only 3 routes/links,
$\ddagger$ Since Model-2 is Multi-objective model there are multiple solutions, presented here are two randomly selected solutions.

As can be seen in Table 4, columns 6, 7 and 8 show reduction in GHG emissions, total system travel time (total delay) and vehicle miles traveled in the road network from emission pricing. SOCE-EPM shows a reduction of 16.46 % in GHG emissions, 10.75% reduction in total delay and 9.71% reduction in vehicle miles traveled in the road network. We can see the constraint of a desired 15% emission reduction for the network has been complied. It should also be noted that this reduction in GHG emissions is only for the peak hour of the day since loaded demand is for the peak hour. The overall reduction in CO_2 emissions for a complete day, and over the entire life of the network, will be substantial.
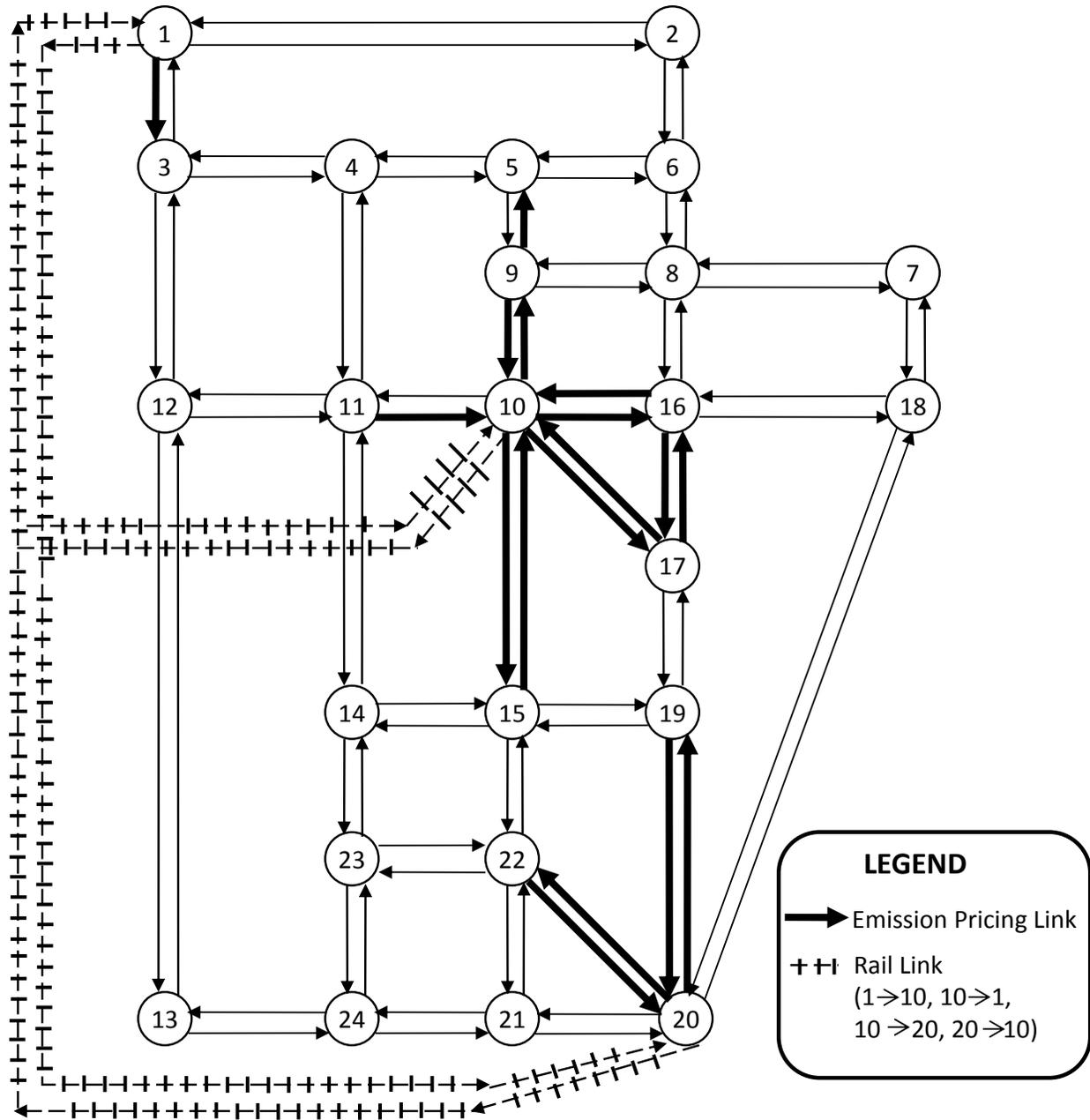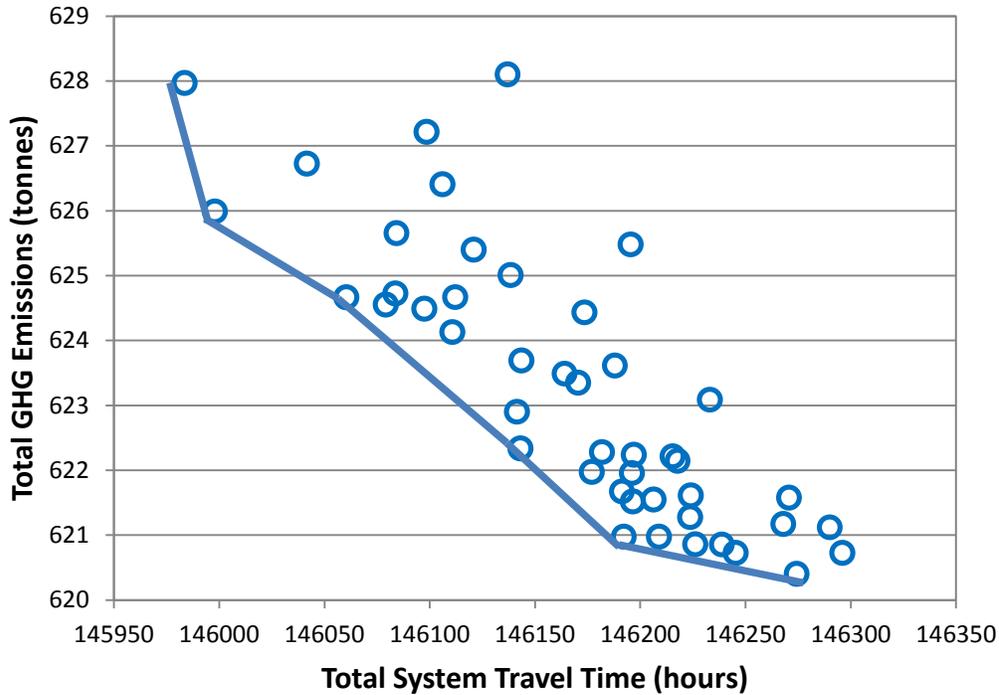

FIGURE 3 Modified Sioux Falls Network

Similarly we can see a reduction in total delay in the system which is a representation of reduced congestion and reduced vehicles miles traveled due to emission pricing. Row 4 shows results from minimizing both objectives total GHG emissions and total system travel time in the network, while maintaining the desired reduction in emissions. Two randomly selected solutions are presented out of pool of 48 solutions. Both solutions show the efficacy of the model to give optimal emission pricing values that reduce GHG emissions, total delay and vehicle miles traveled by a larger percentage. These solutions are much better than solutions from SOCE-EPM in terms of performance with approximately 20% reduction in GHG emission, 11% reduction in total delay and 13% reduction in vehicle miles traveled.

FIGURE 4 Pareto optimal solutions for Modified Composite Sioux Falls network with minimum desired GHGs emission reduction of 15 percent.

Since MOCE-EPM is multi-objective problem, it normally does not have a single best solution for both objectives, rather multiple solutions known as pareto optimal solutions. Each solution set has different values of policy variable (i.e. different values of emission pricing for each solution) and each value leads to different values of traffic flows/passenger trips, total system travel time and total emissions.

Figure 4 illustrates a series of pareto optimal solutions and a line joining frontier solutions known as pareto front, from results of MOCE-EPM with both objective functions values. Each point on Figure 4 represents a unique value of TSTT and Total GHG emissions and contains a solution vector of optimal emission pricing strategies for the network.

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DISCUSSION

Two novel models with distinct characteristics are presented and evaluated by testing on a small-sized and a medium-sized network. In SOCE-EPM a planner plans to minimize total system travel time or time spent in road network by user while reducing GHG emissions by a certain percentage through optimal emission pricing. The results of SOCE-EPM show its efficacy to reduce GHG emissions and decide an optimal emission pricing value for various links/routes. The results from SOCE-EPM also shows the need to consider both objectives of total GHG emissions and total system travel time in the modeling to further achieve the target of minimal emissions which lead to the development of MOCE-EPM. MOCE-EPM is a multi-objective model where total system GHG emissions and total system travel time (or total delay) in the system are simultaneously minimized while defining optimal value of emission pricing. The multiple solutions from MOCE-EPM represent a trade-off between value of total GHG emissions and total system delay for different values of emission pricing in each case, giving a number of options to the planner or policymaker to choose from.

It is evident from the presented models that substantial reduction in emission levels and a potential mode shift can be achieved by emission pricing. The presented model and results are only for peak hour demand. However, emission pricing must vary with respect to demand; therefore, multiple run of models is required to obtain emission charges based on time of day, day of the week or seasonal demand. This is where ITS can act as a facilitator for implementation, where users are charged dynamically on different routes/links based on travel demand, emission targets and response to charging. This seamless integration of emission pricing with ITS can aid in achieving a reduction in GHGs emission and subsequently carbon footprint.

CONCLUSION

The goal of this study is to devise an optimal emission pricing mechanism that can be implemented using ITS and can reduce GHG emissions by a certain percentage in a given composite transportation network. A methodology is presented to model the complex mix of factors (individual preference, comfort, waiting time, travel time, etc.) involved in choosing a transit mode over an existing private vehicle mode using a well established and classic mode split function. Later, the same methodology is applied to achieve user response to proposed optimal emission pricing models. The presented models are better than simple traffic assignment models that study the behavior of users under emission pricing, as in this case a planner is able to anticipate a user's reaction to a given policy and make a better implementation strategy such that it does not leave any user in the composite network worse off.

Results from the test network and case study show a need for "optimal emission pricing" as proposed in this paper. Not considering a user's perspective may result in high total system travel time and emissions in a composite network and/or make road users worse off in terms of travel-cost/travel-time. The presented models are able to suggest the optimal emission pricing for a given composite network for peak hour demand such that the final solution has minimum GHG emissions and total system travel time. In real-life the demand varies with time and emission pricing needs to be computed dynamically by using the proposed models based on changing traffic. The dynamic emission charges can only be implemented by using ITS technologies, like electronic toll collection, that can lead to seamless integration of the proposed models while reducing GHG emissions. The savings in total GHGs emission by employing emission pricing

can be sold or retired as carbon credits and funds collected from emission savings or emission pricing can be further used to improve the transit system or associated infrastructure.

This study did not consider emissions produced in generating power for running the transit system. Future studies can examine the inter-linkage between different sectors (power sector, transportation sector) and quantify emissions thereof. Also, the study did not consider bus transit or air into modeling emissions and the transportation system which the authors believe will be a natural research topic to improve the current study. Next, authors plan to solve and present a large real network of Montgomery County in Maryland that has 1683 nodes, 4490 links (both road and transit) and 55225 O-D pairs.

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