An optimization model of National Energy and Transportation Systems: Application on Assessing the Impact of High-Speed Rail on US Passenger Transportation Investment Portfolio

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Abstract — This paper deals with continuous development and application of a long-term investment planning model that co-optimizes infrastructure investments and operations across transportation and electric infrastructure systems, in meeting the national energy and transportation needs. The paper develops a national passenger transportation model and integrates it within the modeling framework of energy and transportation planning software, namely NETPLAN. NETPLAN uses a generalized multi-period network flow model with nodes and capacitated arcs to represent the transportation (multi-modal freight and passenger network), fuel (coal, natural gas, gasoline, and diesel), and electric (generation, load and transmission) sectors, and captures their planning and operational interdependencies. The developed passenger transportation model is used to investigate the impact of introducing high-speed rail in the mix of the US national transportation investment portfolio in meeting the long-term passenger transportation needs in the most cost-effective and sustainable way, as well as to assess its influence on planning decisions in the electric and fuel sectors.

Index Terms—Multi-modal transportation, Infrastructure Planning, High-speed rail, Sustainability, Energy Security

1. Introduction

Energy independence, energy security and sustainability are key factors that drive every nation's development pursuits to achieve a stable and prosperous economy. The transportation and the electric power sectors contribute significantly to the national energy consumption and the greenhouse gas emissions (GHG) (~70%) across the world due to heavy dependence on fossil sources such as petroleum, natural gas and coal [1]. Although predictions for the next 20 years suggest that the world's reliance on fossil fuels may not decline rapidly [2], especially for the transportation sector [3]; still many nations are moving towards alternative energy sources such as biomass, hydrogen, and renewable resources [4]. In the US, the development of a high-speed rail (HSR) network has been suggested as one way to reduce energy consumption and emissions from passenger transportation [5]. In addition they are seen to promote energy independence, transportation safety and efficiency, and better community inter-connectivity [6].

The work in this paper deals with two aspects of national infrastructure planning:

1. ***Development and integration of passenger transportation model:*** Recognizing the need to investigate long-term planning of energy and transportation sectors simultaneously, a multi-sector infrastructure planning tool, NETPLAN, was developed [7]. This paper develops and integrates a multi-modal passenger transportation model into the NETPLAN and presents the comprehensive formulation of the optimization framework, which co-optimizes the operations and investments within both sectors accounting for their interdependencies [8].
2. ***Investigation of impacts of HSR investments on energy and transportation portfolio:*** Electrification of transportation systems will intensify interdependencies between these two sectors. Therefore the paper also illustrates the ability of this multi-sector planning tool to investigate credible scenarios that could help achieve higher HSR penetration within the US passenger transportation system, and assess the consequent impact on long-term energy and transportation investment portfolios, as well as on energy consumption and emissions. This study will inform long-term cost and emission benefits of HSR penetration at the national scale, and identify some attractive inter-state routes for HSR investments[1].

The organization of this paper is as follows. Section 1 introduces and presents the formulation of NETPLAN, including the development and integration of multi-modal passenger transportation model within the co-optimization framework. Section 2 presents the various modeling and data assumptions in representing and co-optimizing the multi-period, national-level energy and transportation sectors. The study specifications related to national infrastructure planning with specific emphasis on HSR expansion, and the associated results of this case study are presented in Section 4. Section 5 discusses the main conclusions of this study, along with directions for future research.

2. NETPLAN – National Long Term Energy and Transportation Planning

2.1 Introduction

The National long term Energy and Transportation Planning (NETPLAN) model is a software tool that models the transportation and energy sectors, as well as their interdependencies, in order to perform national-level, long-term, and multi-sector infrastructure planning. NETPLAN accounts for electric generation and transmission, production and transportation of fuel (coal, gas, and petroleum), and freight and passenger transportation systems (highway, rail, air). This co-optimization framework identifies investment portfolio based on minimizing long term investment and operational costs.

[1] The focus of this study is not to advocate a specific design or technological features for implementing a design, and also not in developing methods to distribute the overall cost and emission benefits of HSR geographically.

NETPLAN determines optimal investment plans for the system at a national level over an extended period (e.g., 40 years), using time steps appropriate to each sector. Optimization in NETPLAN occurs at two levels: a lower-level linear programming-based cost minimization program that produces a minimum cost portfolio of energy and transportation investment, with associated resilience and sustainability metrics; and a higher level Non-dominated Sorting Genetic Algorithm-II (NSGA-II) multi-objective evolutionary algorithm that identifies Pareto optimal solutions in the space of cost, resilience, and sustainability metrics [7]. Sustainability metrics include annual CO_2, SO_2, and NO_x emissions. The resilience of long-term planning solutions [9] is evaluated in terms of the system's ability to minimize the impact and recover from extreme events at the scale of Katrina/Rita hurricanes [10], loss of petroleum supply from the Middle-east, or say, shutdown of 70% of nuclear plants. However, in this paper the emphasis is not on multiobjective features of NETPLAN, but on obtaining low-cost national portfolios from cost-minimization based linear programming module, which will be enriched with the developed passenger transportation model.

There are many existing regional- and national-level infrastructure optimization software, such as Markal-Times [11], Regional Energy Deployment System (REeDs) [12], and the Integrated Planning Model (IPM) [13]) for energy sector planning; Transportation Routing Analysis Geographic Information System (TRAGIS) [14] and Network-Centric GIS for transportation network modeling; and National Energy Modeling System (NEMS) [15], Criticality Accessibility Recoverability Vulnerability Espyability Redundancy, version 2 (CARVER2) [16], Athena, CIP/DSS, and Fort Future that can model multiple sectors. One unique feature of NETPLAN relative to other software is that it represents the transportation system (passengers and freight) and the energy system (electric, coal, natural gas, and petroleum) as a single, integrated system, making NETPLAN a multi-sector *optimization model*. Optimization in this way implies a centralized decision-maker, which of course does not exist in reality. Identified solutions are therefore idealized. Optimization offers a consistent basis for evaluating investment strategies; In addition, identification of good centralized strategies facilitates their pursuit simply by making them known. This feature also allows NETPLAN to inform societal dialogues.

2.2 Energy Sector

The energy system in NETPLAN is represented with interconnected sub-systems: coal, natural gas, petroleum and electricity. Figure 1 presents a multi-period generalized network flow [17] representation of the energy network in terms of nodes and capacitated arcs, with the shadow denoting the topology in the subsequent time period. The national level electric network is represented by dividing the nation into electric regions that are inter-connected through the bulk transmission network. The load, generation and fuel resources and infrastructures within each region are aggregated. The operational energy flows and infrastructure investments in the interconnected electric and fuel networks across multiple periods are the decision variables in the co-optimization. The demand in the energy sector is a nodal quantity denoting the energy demanded in a specific region. The unit of energy is GWh for arcs within the electric network, comprised of generation, transmission, and demand. The transmission network is represented using inter-regional power transactions. The unit is MMCF (million cubic feet) for the natural gas network; which is comprised of production (NP), transshipment (pipelines) and demand. The unit is million gallons for liquid fuels such as gasoline and diesel, and kilo-short tons for coal production (CP) and transportation (1T) network.

The various arc properties define the operational and investment attributes of each energy infrastructure system. The arc properties include cost of energy flow, efficiency, minimum and maximum flow capacity, generation capacity credit, infrastructure investment cost, infrastructure lifespan, bounds on yearly investments, and generation emission metrics. By imposing limits on energy flow, the possibility of investing in new infrastructure is explored.

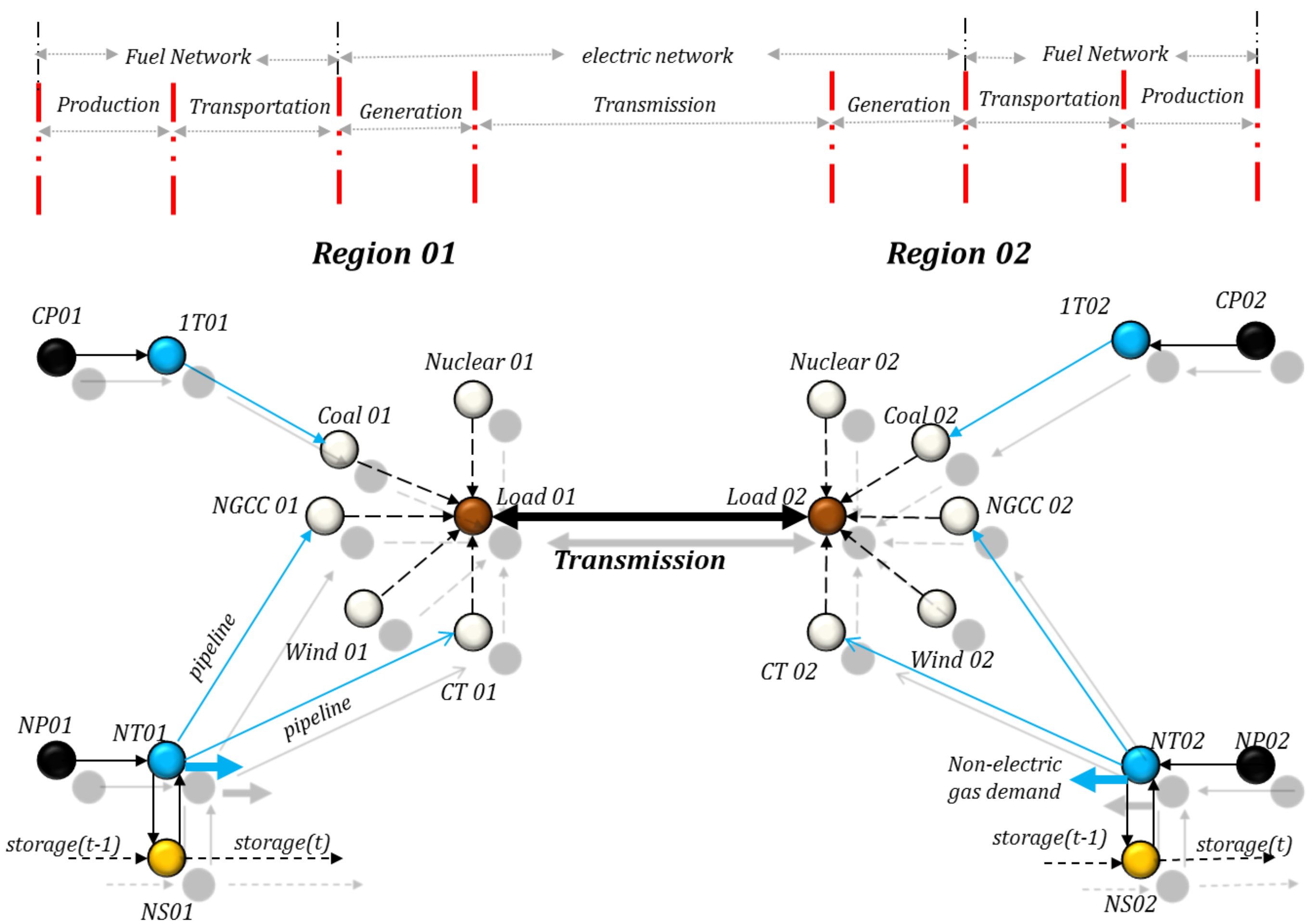


Figure 1: Multi-period energy network representation in NETPLAN

2.3 Transportation Sector

The transportation network, broadly categorized into passenger and freight networks, models multi-commodity flows of inter-regional (state) and intra-regional passengers, and freight commodities including coal, cereal grains, foodstuffs, chemicals, gravel and wood. Each region is denoted by a node in the model, and the transportation links connecting various nodes (inter-state) are modeled as arcs. The nodal demands denote intra-regional demands, while the arc-based demands represent the inter-regional transportation demands. In this paper, we focus on inter-regional transportation. The freight demand is expressed in terms of k-tons per year, whereas the passenger demand is expressed in terms of passengers per year. The freight commodities are further classified as energy (coal) and non-energy, as shown in Table 1. The demand for energy commodity transportation across various arcs is a function of electric generation from generating units fueled by that commodity. A projection of historical data is used to estimate the future demand for non-energy freight transportation and passenger transportation across various arcs. Table 1 also shows the various modes and the corresponding infrastructures that are modeled in NETPLAN.

In referring to transportation, we use the term “infrastructure” to denote the highways and railways, and use the term “fleets” or “modes” to refer to the vehicles, air planes and trains (rail). In other words, “infrastructure” will refer to “static” transportation infrastructures, and “fleet” or “mode” will refer to “mobile” transportation infrastructures.

Table 1: Transportation Commodities, Fleets and Infrastructure in NETPLAN[2]

Commodity		***Fleet (fuel)***	***Infrastructure***
Freight	1. Energy	1. Truck (diesel)	1. Highway
	2. Non-energy	2. Rail (diesel)	2. Railway
Passenger		1. Cars (Gasoline & Hybrid)	1. Highway
		2. Air planes (Jet-fuel)	2. Airport
		3. Rail (Electricity)	3. High-speed rail tracks (incl. Amtrak)

Figure 2 illustrates how freight and passenger transportation systems are modeled, where highways are shared by different fleets for freight and passengers respectively. Figure 2 also illustrates that infrastructures and their fleets must be modeled in series to ensure the capacity limitation of each are respected. The various arc properties that define the operational and investment attributes of transportation fleet and infrastructure systems are cost of commodity flow (function of fleet fuel consumption and maintenance costs), fleet occupancy factor, fleet yearly frequency over an arc, minimum and maximum fleet and infrastructure capacities, fleet and infrastructure investment cost, fleet and infrastructure lifespan, bounds on yearly investments, and emission metrics of fleet operation. Section 3 will discuss about each of these attributes and their values used for the planning study in this paper.

[2] This study does not consider waterways and the associated barges, though it can be modeled similar to other networks.

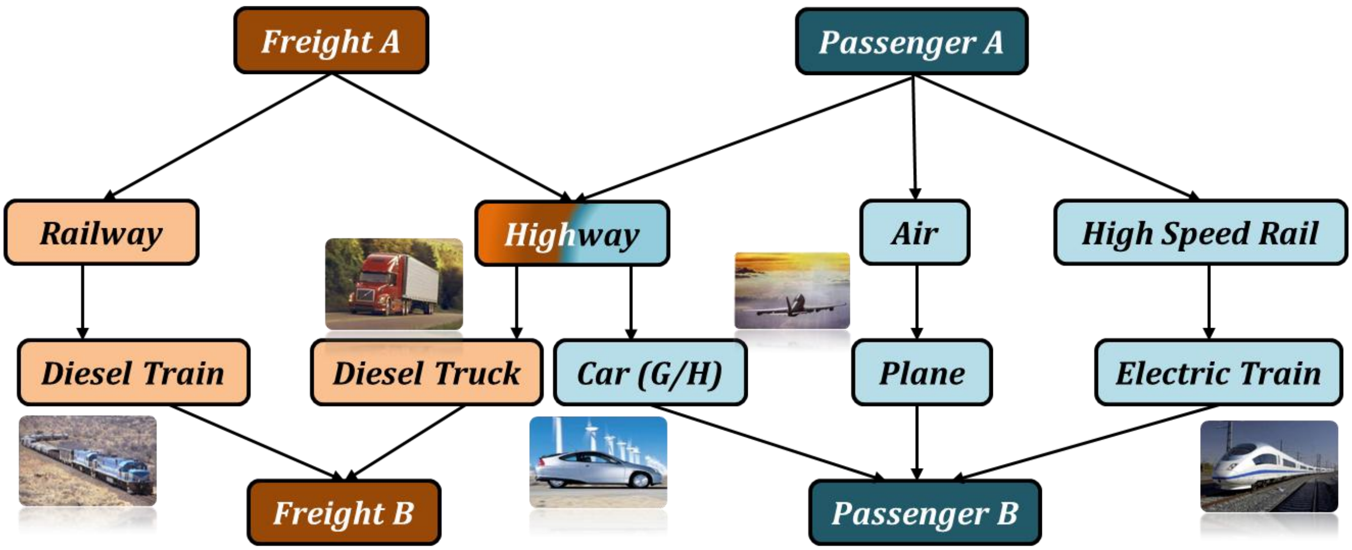


Figure 2: Multi-commodity multi-modal transportation sector

2.4 Energy and Transportation Interdependency

Figure 3 depicts the operational relationships modeled in NETPLAN between the various transportation fleets and energy sector (i.e., fuel and electric networks). The interconnections 1 and 2 show the loading of transportation network on energy network. The interconnection 3 shows the loading of electric network on fuel network, which in turn loads the transportation network, thereby effectively capturing the loading of energy sector on transportation sector.

The fleet network in Figure 3 shows the annual freight $d_{(x,y,k)}$ and passenger demands $d_{(x,y,p)}$ across a typical inter-regional transportation arc. The operational decision variables are the mode shares or assignments to transport a unit freight and passenger. The routes in both networks are fixed. The ability of a mode to carry the annual demand along an arc depends on its occupancy factor (η = units of commodity/vehicle, shown in Figure 3), their yearly frequency (λ = number of trips across the arc, also shown in Figure 3), fleet capacity[3] (number of available vehicles in a year, a function of investments), and infrastructure capacity (maximum number of trips/year). Therefore, investments in fleet and infrastructure systems serve as decision variables that are optimized in order to meet the annually increasing transportation demands.

The freight network, served by conventional rail and trucks, imposes demand for diesel fuel on the energy network, as depicted by interconnection 1. The passenger network, served by air planes, gasoline cars, hybrid cars, and HSR, imposes demand for gasoline fuel (regular and jet-fuel) and electricity on the energy network, as depicted by interconnections 1 and 2 respectively. The fuel consumption parameters

[3] Sometimes in literature the term “fleet capacity” is also used to mean occupancy factor (η). But in this paper, we use “fleet capacity” to denote the available fleet inventory, i.e., number of available vehicles at a specific time period.

in terms of *M Gallon/vehicle-mile* or *MWh/vehicle-mile* facilitate modeling these interdependencies. The electric network of the energy sector do comprise of generation technologies such as coal-fired units that require transportation services to transport fuel from source to the generating site. The interconnection 3 models the demand imposed by the electric network on the fuel network, using the heat rate parameter in terms of *k-tons/MWh*. This energy requirement consequently imposes demand on freight transportation, as shown by interconnection 4.

Therefore, two levels of operational dependencies are captured between the two sectors in NETPLAN: the demand imposed by the energy sector on the transportation sector and vice-versa. These operational dependencies affect the energy/commodity flows, infrastructure investment decisions, cost (investment and operational), and the corresponding emissions within each sector.

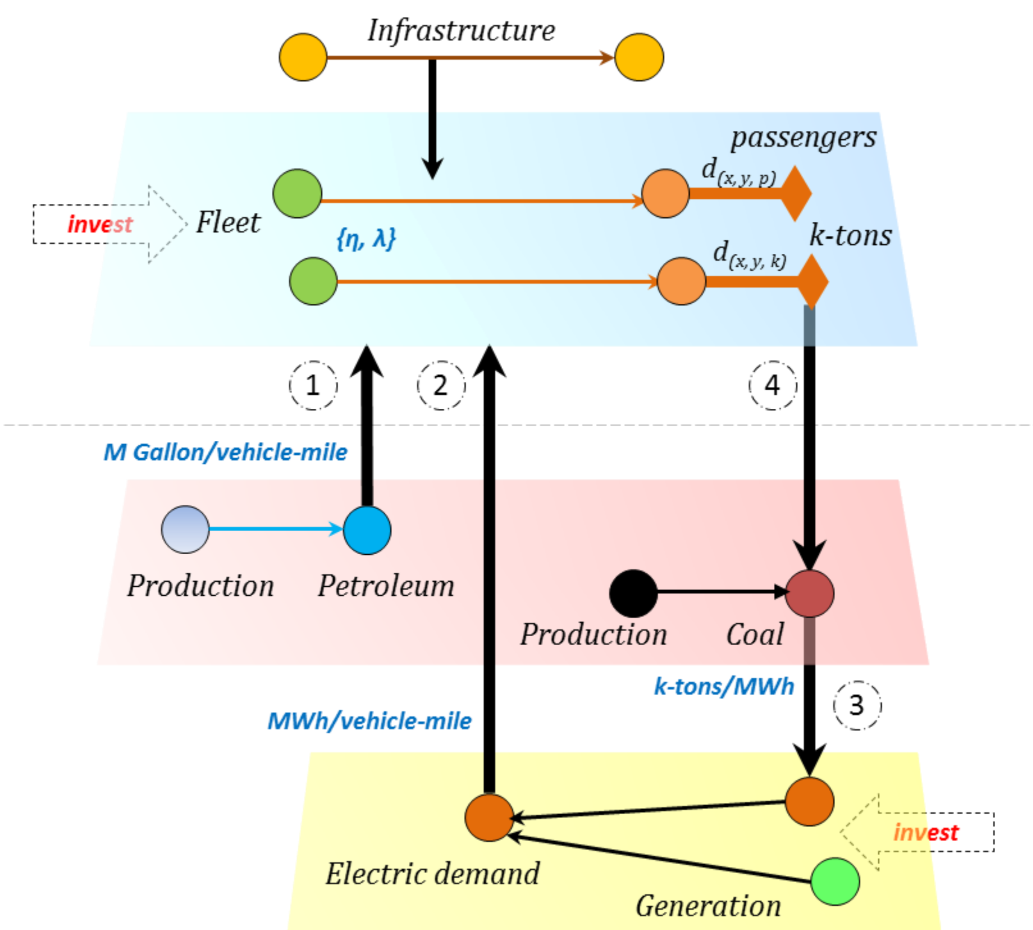


Figure 3: Energy and Transportation interdependency

2.5 Formulation of Linear Programming based Cost Co-optimization

This section presents the linear programming based cost minimization module within NETPLAN. While the network topology for both transportation and energy sectors may be different, yet they are related. For example, the electric network may consist of N regions (eg., Midwest, East, West, South), and the transportation network may consist of M regions (where M>N), such that an electric region may contain many transportation regions as sub-regions (e.g., Midwestern states). To facilitate exposition, notation for energy and transportation arcs are different, namely *(i,j) and (x,y),* for energy and transportation sectors respectively, both in equations and in the text.

2.5.1 Objective Function

The objective function of the linear program is to minimize the operational and infrastructure investment costs, as given in (1).

Minimize

$$\sum_{t}\sum_{(i,j)}(1+r)^{-t}\ CostOp^{e}{}_{(i,j)}(t)\ e_{(i,j)}(t)+\sum_{t}\sum_{(i,j)}(1+r)^{-t}\ CostInv_{(i,j)}(t)\ eInv_{(i,j)}(t)+ \quad (1)$$

$$\sum_{t}\sum_{(x,y,k,m)}(1+r)^{-t}\ CostOp^{T}{}_{(x,y,k,m)}(t)\ f_{(x,y,k,m)}(t)+\sum_{t}\sum_{(x,y,m)}(1+r)^{-t}\ CostfInv_{(x,y,m)}(t)\ fInv_{(x,y,m)}(t)$$

$$+\sum_{t}\sum_{(x,y,inf)}(1+r)^{-t}\ Costin\,fInv_{(x,y,inf)}(t)\ in\,fInv_{(x,y,inf)}(t)$$

Decision variables and parameters related to energy network are:

- $e_{(i,j)}(t)$ - energy flow in the arc *(i,j)* in respective units discussed in Section 2.2.
- $CostOp^{e}_{(i,j)}(t)$ - operational cost of energy in \$/unit-energy through arc *(i,j)* at period t
- $eInv_{(i,j)}(t)$ - yearly GW investment in generation technology *i* within region *j* (investments may also be made in energy infrastructures such as transmission and natural gas pipeline)
- $CostInv_{(i,j)}(t)$ - investment cost in \$/GW of generation technology *i* in region *j*
- *r* - discount rate

Decision variables and parameters related to transportation network are:

- $f_{(x,y,k,m)}(t)$ - number of trips made by mode *m* to transport commodity *k* across arc *(x,y)*
- $CostOp^{T}_{(x,y,k,m)}(t)$ - operational cost of transportation by mode *m* in \$/trip-mile to transport commodity *k* across arc *(x,y)*
- $fInv_{(x,y,m)}(t)$ – yearly vehicle/fleet investments in transportation mode *m* across transportation arc *(x,y)*
- $CostfInv_{(x,y,m)}(t)$ - investment cost of mode *m* in \$/vehicle across arc (*x,y)* at period *t*
- $infInv_{(x,y,inf)}(t)$ – yearly investments in infrastructure *inf* across arc *(x,y)* at period *t*
- $CostinfInv_{(x,y,inf)}(t)$ - investment cost of infrastructure *inf* in \$/unit-*inf* across arc (*x,y)*

For nodal infrastructure such as electric generators, arc *(i,j)* represents generation plant *i* in electric region *j*. For arc-based infrastructures such as transmission lines, gas pipelines, inter-regional transportation, highways, and rail tracks, arc indices represent starting and ending regions.

2.5.2 Energy Network Constraints

According to (2), at each node the energy inflow and outflow must be such that the nodal energy demand must be met.

$$\sum_{i} \eta_{(i,j)}(t)\, e_{(i,j)}(t) - \sum_{j} e_{(j,k)}(t) = d^{e}{}_{j}(t) + d^{eT}{}_{j}(t) \tag{2}$$

where,

- $\eta_{(i,j)}$ - arc efficiency parameter, which models capacity factor for generation arcs and losses for transmission and gas pipeline arcs. It also models energy conversion rate as a function of generator heat rate (i.e., unit-fuel/GWh) for arcs connecting fuel node and generation node, as shown in Figure 1 where coal and natural gas based units are connected to coal and gas network respectively.
- $d^{e}{}_{j}(t)$ – nodal energy demanded at region *j* at period *t*. The energy demanded may be electric energy, petroleum or natural gas depending upon the respective sub-system where the node *j* is situated in the energy system network. The demand for natural gas is a function of gas requirement for electric generation and non-electric (heating) purposes, as shown in Figure 1.
- $d^{eT}{}_{j}(t)$ – nodal energy demand imposed by transportation systems in region *j* at period *t*. The energy demanded may be petroleum or electric energy (i.e., interconnection 1 or 2 in Figure 3) depending upon the transportation fleet that is imposing the demand in region *j*.

The energy in the arcs are bound by the lower limit $lbe_{(i,j)}(t)$ and the total capacity $cap\_e_{(i,j)}(t)$ at time *t* as expressed in (3). The total arc capacity is the sum of the infrastructure capacity that existed at time $t=0$ minus the retirements until time *t* ($ube_{(i,j)}(t)$), and the capacity investments $eInv_{(i,j)}(t)$ from investment on the start year (*inv. start*) until time *t*, as shown in (4). The lifespan of the investment (*life*) is taken into account as indicated by the function $I(t-z \leq life_{(i,j)})$, which is equal to 0 if at time *t* the investment made at time *z* has exhausted its life, and equal to 1 otherwise. By treating limits on arc energy flows as decision variables, the possibility of investing in new infrastructure, electric generation in this case, is explored. The capacity investments are bound within limits, as given by (5).

$$0 \leq lbe_{(i,j)}(t) \leq e_{(i,j)}(t) \leq cap\_e_{(i,j)}(t) \tag{3}$$

$$cap\_e_{(i,j)}(t) = ube_{(i,j)}(t) + \sum_{z=inv.start}^{t} eInv_{(i,j)}(z)\, I(t - z \leq life_{(i,j)}) \tag{4}$$

$$lbeInv_{(i,j)}(t) \leq eInv_{(i,j)}(t) \leq ubeInv_{(i,j)}(t) \tag{5}$$

The model also accounts for renewable generation's capacity credit (*cv*) to supply peak demand (pkd_j) in region *j* during various time intervals, as represented by (6). The various generation resources available within region *j* is denoted by *ng*.

$$\sum_{i=1}^{ng} cv_{(i,j)}(t)\ cap\_e_{(i,j)}(t) \geq pkd_j(t) \tag{6}$$

There are inter-period constraints for storage entities as shown in (7), which models the operation of natural gas storage as depicted in Figure 1. The node *i* denotes the natural gas transshipment node and *j* denotes the storage node in the gas network. The stored energy (natural gas) at the end of period *t* is the sum of stored energy until previous period (*t-1)*, plus the injections and less the withdrawals at period *t*.

$$e_{(j,j)}(t) = e_{(j,j)}(t-1) + \sum_i e_{(i,j)}(t) - \sum_i e_{(j,i)}(t),\ where\ i \in NT,\ j \in NS \tag{7}$$

2.5.3 Transportation Network Constraints

Equations (8-10) ensure the arc-based transportation demand across the regions *x* and *y* for the different commodities (*k*) including energy (*k*=*ek*), non-energy freight (*k*=*fk*) commodities and passengers (*k*=*p*) respectively, are allocated appropriately among various modes within the respective network.

$$\sum_{m,k=ek,\{x,y\subset j\}} \eta_{(x,y,k,m)}(t)\ f_{(x,y,k,m)}(t) = \left(h_{ek}(t)\right)^{-1}\ e^{ek}{}_{(i,j)}(t) \tag{8}$$

$$\sum_{m,k=fk} \eta_{(i,j,k,m)}(t)\ f_{(x,y,k,m)}(t) = d^{T}{}_{(x,y,fk)}(t) \tag{9}$$

$$\sum_{m,k=p} \eta_{(x,y,k,m)}(t)\ f_{(x,y,k,m)}(t) = d^{T}{}_{(x,y,p)}(t) \tag{10}$$

where,

- $\eta_{(x,y,k,m)}$ - arc efficiency parameter, which in the transportation network models the fleet occupancy in terms of amount of freight commodity (*k*=*ek or fk*) or number of passengers (*k*=*p*) per single trip of a vehicle belonging to mode *m*
- $e^{ek}{}_{(i,j)}(t)$ – energy generated by electric generation *i* in electric region *j* in *GWh*, wherein the generation technology runs on energy commodity *ek.*
- $h_{ek}(t)$ – energy content of the energy commodity *ek* in *GWh/k-ton* at time *t.*

- $d^T_{(x,y,fk)}(t)$ – freight commodity *fk* (non-energy) transported to transportation region *y* from region *x* at period *t*. The arc-based demand is a bi-directional quantity, i.e., a separate demand is specified across each direction and the optimization satisfies the demand by appropriately allocating mode sharing in each direction
- $d^T_{(x,y,p)}(t)$ – passengers transported to transportation region *y* from region *x* at period *t*

The total trips made by mode *m* across arc *(x,y)* to carry various commodities[4] *k* is bound by the maximum capacity for yearly trips by mode *m*, $cap\_f_{(x,y,m)}(t)$, across that arc at time *t* as shown in (11). The total trip capacity for mode *m* is a function of the available fleet capacity at time *t=0* minus the retirements until time *t* ($ubf_{(x,y,m)}(t)$), and the fleet investments $fInv_{(x,y,m)}(t)$ from investment start year (*inv. start*) until time *t*, as shown in (12). The typical lifespan of the fleet (*flife*) invested is taken into account as indicated by the function $I(t\text{-}z \leq flife_{(x,y,m)})$, which is 0 if at time *t* the investment made at time *z* has exhausted its life and 1 otherwise. The fleet capacity (i.e., available plus investments) is multiplied by $\lambda_{(x,y,m)}$, which is the average number of trips the mode *m* can make across the arc (*x,y*) over a year, in order to compute the total trip capacity by mode *m* $cap\_f_{(x,y,m)}(t)$ across that arc. Equation (13) shows the limit on fleet movement imposed by capacity of infrastructure *inf,* on which various modes *m* commute. The capacity of the infrastructure is in terms of maximum allowable trips across infrastructure arc (*x,y*), $cap\_inf_{(x,y,inf)}(t)$. As mentioned in Section 2.3, only highways are shared between freight trucks and passenger cars. Hence, an appropriate factor (δ_m) such as a passenger-car-equivalent (PCE) is used to account for the different impact that different types of vehicles can have on highway capacity. The highway capacity is then expressed in terms of maximum allowable PCE-trips. Equation (14) regarding the transportation infrastructure's capacity is equivalent to (12), where the equivalent terms $infInv_{(x,y,m)}(t)$, $ubinf_{(x,y,inf)}(t)$, *inflife and* $\lambda_{(x,y,inf)}$ are used. The investments in fleet and transportation infrastructure are bound as per Equations (15) and (16) between respective limits.

$$0 \leq \sum_k f_{(x,y,k,m)}(t) \leq cap\_f_{(x,y,m)}(t) \tag{11}$$

$$cap\_f_{(x,y,m)}(t) = \lambda_{(x,y,m)}(t) \left\{ ubf_{(x,y,m)}(t) + \sum_{z=inv.start}^{t} fInv_{(x,y,m)}(z)\, I(t-z \leq flife_{(x,y,m)}) \right\} \tag{12}$$

$$\sum_m \sum_k \delta_m\, f_{(x,y,k,m)}(t) \leq cap\_inf_{(x,y,inf)}(t) \tag{13}$$

[4] Diesel and electric rails may carry multiple commodities, i.e., both passengers and freight. However in this study we assume these rails to transport specific commodities as shown in Table 1

$$cap\_inf_{(x,y,inf)}(t) = \lambda_{(x,y,inf)}(t) \left\{ ubinf_{(x,y,inf)}(t) + \sum_{z=inv.start}^{t} infInv_{(x,y,inf)}(z)\, I(t - z \le inflife_{(x,y,inf)}) \right\} \quad (14)$$

$$lbfInv_{(x,y,m)}(t) \le fInv_{(x,y,m)}(t) \le ubfInv_{(x,y,m)}(t) \quad (15)$$

$$lbinfInv_{(x,y,inf)}(t) \le infInv_{(x,y,inf)}(t) \le ubinfInv_{(x,y,inf)}(t) \quad (16)$$

By treating the limits on fleet and infrastructure arc capacities as decision variables, we explore the possibility of investing in new infrastructure in order to meet the increasing transportation needs. Given the arc parameters, such as operational cost, λ, and η for every mode, the optimization leads to appropriate investment decisions in fleet and infrastructure subject to investment cost. Given the various lifespans for the infrastructures, the salvage value of the investments at the end of the simulation is subtracted from the total cost, to indicate the remaining useful life.

Equation (13) models the infrastructure capacity constraint for arc-based transportation infrastructure, such as highways and railways. For infrastructure systems such as airports, a node-based infrastructure capacity constraint may be used, as shown in (17). This node-based capacity limits the sum of all inbound flights into an airport hub (*y*=*YY*, i.e., state code) to a maximum allowable value, which is a function of available gates that are used for domestic flights.

$$\sum_{x}\sum_{k} f_{(x,y,k,m=air)}(t) \le cap\_inf_{(x,y=YY,inf=airport/hub)}(t) \quad (17)$$

Equation (18) models the relation that governs the energy imposed on the energy sector by the transportation sector, which is accounted in (2). Assuming that a transportation sub-region *x* belongs to the electric region *j*, and a transportation sub-region *y* belongs to the electric region *i* then as per (18), a portion of energy required for transportation across the arc (*x,y*) in both directions comes from electric region *j* and the rest comes from region *i*. If both *x* and *y* belong to *j*, then all energy is supplied from *j*.

$$d^{eT}{}_{j}(t) = \alpha^{j}{}_{x,y}\; fuelC_m(t) \left\{ \sum_{k} f_{(x\subset j,y,k,m)}(t) + \sum_{k} f_{(y,x\subset j,k,m)}(t) \right\} \quad (18)$$

where,

- $\alpha^{j}{}_{(x,y)}$ – proportion that attributes energy requirements for bi-directional transportation in arc (*x,y*) to energy demand of region *j* in M gallon or GWh.

- *fuelC$_m$(t)* – fuel/energy consumption by mode *m* in fuel/vehicle-mile, i.e., M gallon/vehicle-mile for fossil fuel based modes or GWh/vehicle-mile for mode that depend on electricity.

Equations (8) and (18) model the two types of operational interdependencies between energy and transportation sectors, as mentioned in Section 2.4.

3. Network Modeling and Data Assumptions

NETPLAN is used to investigate the national transportation and energy infrastructure planning for the US. This section presents the assumptions involved in network modeling, and the associated data collection for the electric network, the fuel network, and the freight and passenger transportation networks.

3.1 Energy Sector

In this paper, the US electric system consisting of generation and consumption is modeled in terms of 13 regions, which is defined by the DOE EIA for NEMS [15]. The reference year (2009) average electric demand and generation mix within each region is provided in [18]. The annual average demand for electricity and natural gas is assumed to increase at a rate of 1.5% and 1% per year, and the annual peak electric demand is assumed to increase at 2% per year. The transmission capacity for the aggregated inter-regional transmission lines is provided in Table 2.

Table 2: Inter-regional transmission capacities [15] (NEMS region numbers shown in parenthesis)

Transmission	***Capacity (GW)***	***Transmission***	***Capacity (GW)***
ECAR_MAAC (1→3)	7.50	*MAPP_NWP (5→11)*	0.20
ECAR_MAIN (1→4)	3.69	*MAPP_RA (5→12)*	0.35
ECAR_STV (1→9)	6.89	*NY_NE (6→7)*	1.46
ERCOT_SPP (2→10)	0.97	*FL_STV (8→9)*	2.10
MAAC_NY (3→6)	3.42	*STV_SPP (9→10)*	1.26
MAAC_STV (3→9)	4.47	*SPP_RA (10→12)*	0.47
MAIN_MAPP (4→5)	1.62	*NWP_RA (11→12)*	2.59
MAIN_STV (4→9)	5.16	*NWP_CNV (11→13)*	8.64
MAIN_SPP (4→10)	2.32	*RA_CNV (12→13)*	6.88
MAPP_SPP (5→10)	1.81		

The optimization time periods for various sub-systems within the energy network are as follows: the coal sub-system (consisting of production and transportation arcs) is optimized at a yearly time step; the natural gas sub-system (consisting of production, transshipment and storage arcs) is optimized at a monthly time step; and the electric sub-system (consisting of generation, transmission and load arcs) is optimized at a monthly time step. The optimization is performed over a 40 year planning horizon (2009-2048). The cost and operational data which are related to the generation technologies and used as arc parameters within the optimization model are provided in Table 3 [19, 20, 21]. The fuel cost for generation are accounted within the fuel network, and so the operational cost in Table 3 reflects only the other cost due to operation and maintenance (O&M).

Table 3 Generation Technologies Data

Generation Technology	***Capacity Factor***	***Investment Cost (M$/GW)***	***Lifespan (years)***	***Operational Cost (M$/GWh)***	***CO_2 (Short ton/GWh)***
Nuclear	0.95	3156	60	0.006484	8.51
Coal	0.85	1788	40	0.009085	919.35
IGCC	0.85	2673	40	0.006667	865.10
IPCC	0.85	3311	30	0.028662	-
NGCC	0.61	827	30	0.004596	407.07
Oil	0.85	1655	30	0.005284	808.10
CT	0.2	551	30	0.010619	555.69
PV Solar	0.1-0.25	6865	30	0.003754	-
PV Thermal	0.15-0.32	4547	30	0.019215	-
Wind	0.1-0.5	1150	25	0.011362	-
Offshore	0-0.4	2662	25	0.015556	-
Geothermal	0.9	3149-7747	50	0.021788	123.57
OTEC	0.3	6163	50	0	-
Tidal	0.3	18286	50	0.012428	-
Hydro	0.5	-	100	0.004277	-

Oil and nuclear fuels are priced at $3/gallon and $0.002559/GWh, respectively. As far as the coal and natural gas sub-systems in the energy sector are concerned, they are modeled using production and transportation nodes in every state as indicated in Figure 1. Since the availability and quality of coal differs geographically, four varieties of coal commodities are modeled as shown in Table 4. It is assumed that enough coal and natural gas resources are available from production sites for the entire simulation period of 40 years, and hence no investments or improvements are considered for these fuel sub-systems. The fuel cost, production site capacities for coal and gas network, gas imports, gas pipeline and storage capacities; all of which are characterized based on geography, can be found in [7].

Table 4 shows the energy content (h_{ek}) of coal in terms of GWh/short ton for pulverized coal (PC) and Integrated gasification combined cycle (IGCC) generation units. These values are a function of heat rates of these generation units for respective coal type. These values are used in determining the amount of fuel required by electric system as reflected by (8), which consequently imposes demand on transportation systems (indicated by interconnection 4 in Figure 3) to move the respective energy-commodity by freight truck or train to the generation sites.

Table 4 Energy Content of Fuel

Coal Type	***PC Generation***	***IGCC Generation***

	(GWh/short ton)	*(GWh/short ton)*
Lignite	1.915	2.072
Bituminous (Appalachia)	2.616	2.829
Bituminous (Central)	2.140	2.315
Sub-bituminous	2.181	2.359

3.2 Transportation Sector

3.2.1 Network Topology and Transportation Demand

The freight network of the transportation sector is modeled using 95 bi-directional arcs that connect pairs of nodes between adjacent states, as shown in Figure 4. The historical freight demands over long-distance routes that connect non-adjacent states are disaggregated into respective shorter arcs (among these 95 arcs) that eventually connect the non-adjacent states. However this simplification is not adopted for passenger network, in order to capture the significance of travel length in choosing the appropriate mode of passenger transportation over an arc. Therefore, the passenger network includes 140 additional bi-directional arcs as shown in Figure 5 to capture long-distance passenger travel, making it a 235-arc network. The arc thickness in both figures is proportional to the 2009 non-energy freight and passenger demands respectively. Both networks in the transportation sector are optimized at yearly time steps, meaning NETPLAN finds the least-cost allocation of respective commodities demanded over each arc among the competing fleets, as pictorially shown in Figure 2.

Passenger demand estimations along various arcs are based on the 2001 National Household Travel Survey (NHTS) [22]. More particularly, the long-trip file is used to extract information such as origin and destination states, mode and total trip length (≥ 50 miles). All the mode-specific demands are aggregated to estimate the total mode-independent passenger demand over every passenger transportation arc. The direction of passenger demand is preserved. NETPLAN assigns the total passenger demand in each direction of an arc among the various modes based on cost minimization. The 2009 demand was estimated based on 2001 values, assuming an annual increase specified by mode. Specifically, 1% annual increase for the highway demand, 2.3% for the air travel demand, and 3% for the railway demand respectively. These values were estimated based on the historical overall average growth factors [23]. From 2009 onwards, the total passenger demand is assumed to increase uniformly at 3%/year throughout the planning horizon.

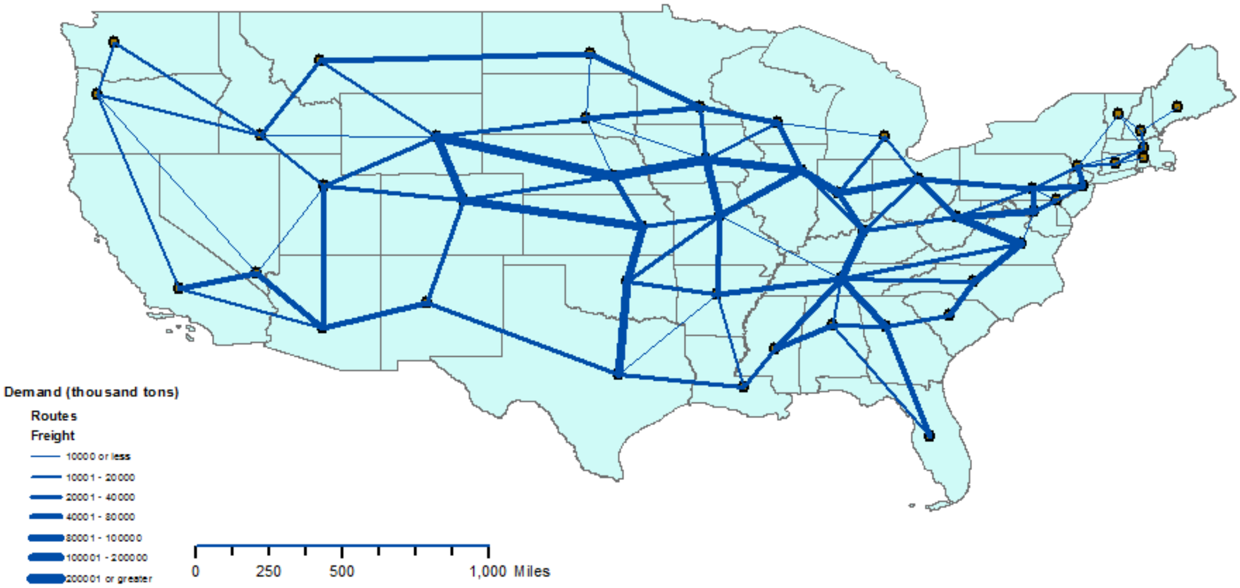


Figure 4: US freight network with NETPLAN (95 links connecting adjacent states)

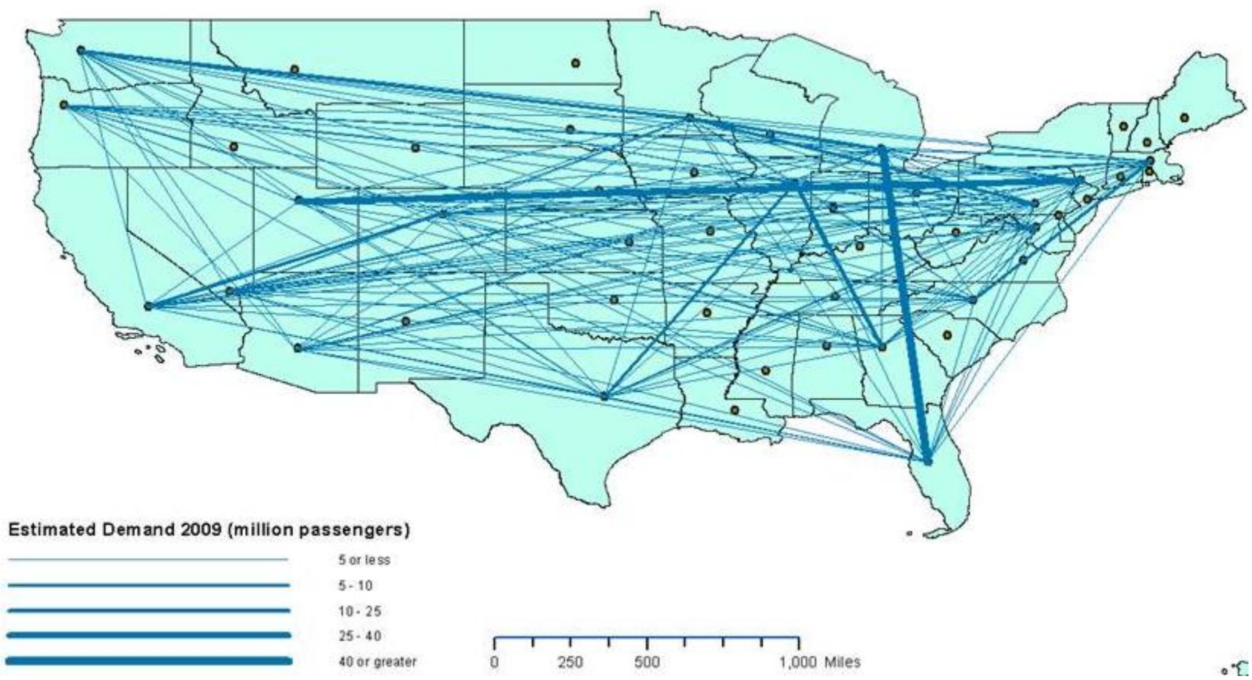


Figure 5: US passenger network within NETPLAN (must also include 95 links of Figure 4)

3.2.2 Transportation Operational Characteristics

The fuel cost related to fleet operation is accounted for within the energy network, as illustrated in Figure 3 that show the energy demand imposed on fuel arcs by the respective transportation networks. The characteristics of transportation fuels are shown in Table 5. Table 6 shows the *fuelC* parameter (fuel/vehicle-mile) that determines the fuel/energy consumed by transportation systems, and consequently imposes a load on the energy network as per (18). In these simulations, the parameter $\alpha^{j}_{(x,y)}$ is assumed to be equal to 50%, indicating that the total energy required for transportation in arc (x,y) is equally distributed to the associated electric regions across which the respective transportation arc spans.

Table 5: Fossil fuel characteristics

Fuel	*Cost ($/gallon)*	*CO2 (Short ton/gallon)*
Diesel	4.0	0.0111
Gasoline	3.8	0.0097
Jet fuel	3.3	0.01055

Table 6 further presents the occupancy factor for each mode, and the transportation O&M costs as a function of the estimated demand for each mode. For the aircraft, the average occupancy factor is assumed to be approximately 85% of the maximum capacity, based on the average historical data for 2009-2011. The same percentage of occupancy was assumed for HSR with total capacity of 304 passengers [24]. The diesel rail is assumed to have 100 rail cars each having a load carrying capacity of 115 tons, and the diesel truck is assumed to transport 25 tons of freight [25]. The O&M cost consists of fleet and infrastructure operating and maintenance cost, which include administration and management, stations, insurance, tracks/roads, equipment (e.g. tires), onboard services related costs, and labor O&M costs. The O&M cost does not include profit made by fleet operators.

Table 6: Fleet operational characteristics

Mode	*Fuel (Gallon / vehicle-mile)*	*Electricity (kWh / vehicle-mile)*	*Occupancy, η (k-tons or Passengers)*	*O&M ($/vehicle-mile)*
Diesel Truck	0.169	-	0.025	0.255
Diesel Rail	16.65	-	11.50	47.30
Gasoline Car	0.044	-	1.630	0.156
Hybrid Car	0.026	0.340	1.630	0.156
Aircraft	2.248	-	229.0	8.90
HSR TrainSet	-	14.924	260.0	46.90

The parameter $\lambda_{(x,y,m)}$ in (12) is the yearly frequency, i.e., average number of trips made by mode *m* over a year across the arc (*x,y*). It is estimated as a function of arc distance, each mode's speed and dwell time, and end-of-day service hours. It is specified by (19-23) for the five different modes considered, in terms of number of trips per day (converted to yearly values within the model).

$$\lambda_{(x,y,train)} = 1 \tag{19}$$

$$\lambda_{(x,y,truck)} = \begin{cases} 1, if \;\; length(x,y) \le 250 \; miles \\ 1/2, if \;\; 250 \; miles \le length(x,y) \le 500 \; miles \\ 1/3, if \;\; length(x,y) \ge 500 \; miles \end{cases} \tag{20}$$

$$\lambda_{(x,y,cars)} = \begin{cases} 1, if \;\; length(x,y) \le 150 \; miles \\ 1/30, if \;\; 150 \; miles \le length(x,y) \le 500 \; miles \\ 1/(30*6), if \;\; length(x,y) \ge 500 \; miles \end{cases} \tag{21}$$

$$\lambda_{(x,y,aircraft)} = \begin{cases} 3, if \;\; length(x,y) \le 500 \; miles \\ 2, if \;\; 500 \; miles \le length(x,y) \le 1000 \; miles \\ 1, if \;\; length(x,y) \ge 1000 \; miles \end{cases} \tag{22}$$

$$\lambda_{(x,y,HSR)} = \begin{cases} 3, if \;\; length(x,y) \le 100 \; miles \\ 2, if \;\; 100 \; miles \le length(x,y) \le 300 \; miles \\ 1, if \;\; length(x,y) \ge 600 \; miles \end{cases} \tag{23}$$

3.2.3 Cost of Travel Time

The study monetizes the value of travel time ($VoTT_{(x,y,m,inf)}$) in terms of \$/passenger. As shown in (24), VoTT is estimated by attributing suitable cost for the time spent by a typical passenger inside ($IVC_{(x,y,m,inf)}$) and outside the vehicle ($OVC_{(x,y,m,inf)}$) in terms of \$/passenger-h, while making a trip across arc *(x,y)* using mode *m* on infrastructure *inf*. This is consistent with what is done in references [26, 27]. These costs are estimated as a function of the average hourly wage of a typical passengers travelling for business ($H_b(t)$) and personal ($H_p(t)$) purposes respectively [28, 29, 30], as shown in (25) and (26).

$$VoTT_{(x,y,m,inf)}(t) = \tau_{(m,inf,ivc)} \, IVC_{(x,y,m,inf)}(t) + \tau_{(m,inf,ovc)} \, OVC_{(x,y,m,inf)}(t) \tag{24}$$

$$IVC_{(x,y,m,inf)}(t) = b_{(x,y,m,\text{inf})}(t) H_b(t) + p_{(x,y,m,\text{inf})}(t) H_p(t) \tag{25}$$

$$OVC_{(x,y,m,inf)}(t) = b_{(x,y,m,\text{inf})}(t) H_b(t) + p_{(x,y,m,\text{inf})}(t) H_p(t) \tag{26}$$

where,

- $\tau_{(m,inf,ivc)}$ & $\tau_{(m,inf,ovc)}$ - in-vehicle and out-of-vehicle time (in *h)* for vehicle *m* respectively. $\tau_{(m,inf,ivc)}$ is estimated based on arc distance and average speed. The average speeds of air planes, HSR, and cars are assumed to be 600 *mph*, 150 *mph*, and 65 *mph* respectively.
- $\tau_{(m,inf,ivc)}$ for air, HSR and highway travels are assumed to be 2 *h*, 1 *h*, and 0 *h* respectively.
- $p_{(x,y,m,inf)}$ & $b_{(x,y,m,inf)}$ - proportion of personal and business trips by mode *m* across arc *(x,y)* respectively. Based on the 2001 NHTS long-trips distribution by trip purpose, average values of 0.71 and 0.29 respectively were assumed for all modes and arcs.

The optimization is performed with the cost of travel time added to the operational cost of passenger transportation to reflect the effect that travel time has on a passenger's mode choice (along with other factors such as the vehicle occupancy factor, operational cost, and travel frequency). However, this cost of travel time will be subtracted from the final NETPLAN cost solution and reported separate, in order to report only the national energy-related costs.

3.2.4 Capacity and Investments

Table 7 shows the fleet investment cost, lifespan and the annual retirement rate of the existing fleet capacity at the reference year ($ubf_{(x,y,m)}(t=1)$ in Eq. (12)). We considered a 150-mph HSR service. The fleet capacity for freight and passenger transportation at the reference year is estimated from the mode-specific demand, mentioned in Section 3.2.1. Approximately 0.9% of the reported transportation demand on highway for personal vehicles is assumed to be hybrid vehicles [31] (as estimated from the reported percent of vehicles covering more than 15K miles annually, assuming this would correspond to out-of-state trips as well); and the rest corresponds to gasoline cars. The existing conventional passenger rail transportation fleet, Amtrak, is also represented, but it is not allowed to expand; this approach ensures that all passenger rail expansion will occur via HSR, allowing us to study the impacts of HSR expansion, consistent with the objective of the work. The operational parameters for Amtrak are assumed to be the same as those of HSR.

Table 7: Fleet investment related data

Mode	***Investment Cost (M$/Vehicle)***	***Lifespan (years)***	***Yearly retirement (%)***
Diesel Truck	0.128	25	0.5
Diesel Rail	1.790	50	0.5
Gasoline Car	0.0189	12	8
Hybrid Car	0.0243	12	8
Airplane	165.0	30	3
HSR Train Set	49.30	30	3

The fleet operation and expansion is also restricted by the existing transportation infrastructure capacity as captured by (13). The infrastructure capacity for HSR at the reference year is 0. Highway infrastructure capacity at the reference year is estimated based on the volume-to-capacity ratio (*v/c*) [32] and the highway transportation demand at the reference year (including both diesel trucks and personal vehicles). The *v/c* ratio describes the relationship between demand and capacity for a given level of service (LOS) and infrastructure characteristics. In this study, it is assumed that the highway infrastructure will operate under level of service C (speeds near to the free-flow speed but with reduced freedom to maneuver), with an average speed of 68mph in basic freeway segments of rural areas. Based on these characteristics, the *v/c* ratio is considered to be 0.763, denoting moderate to high congestion [33].

Therefore, (13) is transformed into (27), and the existing highway infrastructure capacity at reference year is computed as per (28).

$$\sum_{k=ek,\,fk} \delta_m \; f_{(x,y,k,m=truck)}(t) + \sum_{m=cars} f_{(x,y,k=p,m)}(t) \le cap\_inf_{(x,y,inf=highway)}(t) \quad (27)$$

$$cap\_inf_{(x,y,inf=highway)}(t=1) = (0.763)^{-1} \left\{ \sum_{m=truck,cars} \delta_m \; cap\_inf_{(x,y,m)}(t=1) \right\} \quad (28)$$

where δ_m is assumed to be equal to 2.5 for a two-way flow rate of 600 passenger cars per hour and rolling terrain [32]. The estimated highway capacity in (28) is also converted from vehicle-trips/year to a common unit of PCE-trips/year using δ_m.

Railway infrastructure capacity accounts for the number of railways that directly or indirectly connect one state to another across the border. For instance, from AL to FL, there are 3 single railways that cross the border, either directly from AL to FL or indirectly through a connecting train that navigates certain trackage within the destination state to reach the destination node. Based on the identified number of tracks per railway, which is typically 1, 2 or 3 tracks, the technologies which determine capacity (such as major communication and signaling systems) were considered [34]. The yearly railway infrastructure capacity for the reference year across all represented arcs is finally estimated using the average capacities of archetypical rail corridors (in terms of number of trains per day) for 1, 2 or 3 tracks equipped with track warrant control, automatic block signaling, and centralized traffic control, as given in [35].

In this analysis, air transportation is represented in all states, assuming one airport per state. Two or more airports in certain states are aggregated into one hub. The capacity constraint on the air fleet operation due to the infrastructure is directly imposed on every arc in (13), wherein it is assumed that there is enough hub capacity for the operation of 1.3 times the reference year aircraft fleet capacity on every arc.

4. Case Study

4.1 Study Scenarios

NETPLAN was used to study US energy and transportation infrastructure investments over a 40 year period. The objective of the case study is specifically focused towards studying the impact of investments in HSR for future passenger transportation. Table 8 shows the various case studies investigated under two possible futures, namely business as usual (BAU) and renewable friendly (RF). The BAU and RF scenarios are defined with respect to electric generation portfolio, the difference being no investments in coal and IGCC plants over the 40-year planning horizon in RF scenarios.

Under each of these futures, three scenarios are studied. For the reference scenario (Ref) under each future, all the modeling and data assumptions mentioned in Section 3 holds good with exception that the VoTT is not included in the investigation. In VoTT scenario, the value of travel time is also considered within the optimization framework. In CAP2.0 scenario apart of inclusion of VoTT, each HSR train was assumed to accommodate 520 passengers, double the number of passengers assumed for Ref scenario (Table 7). This case was performed to study the sensitivity of the results to the HSR attributes (as the assumed average occupancy of 260 passengers per train is on the conservative side compared to European trains in operation with 500-800 passengers per train). This scenario can also be understood as studying the impact of possible improvement in HSR economics in terms of investment cost per passenger. The various scenarios under each of these futures are considered in order to determine the impact of modest and high HSR growth on the energy and transportation system in terms of cost, energy consumption, future generation portfolio, and emissions.

All investments (generation, transportation fleet and HSR infrastructure) begin at year 2 (*inv. start* parameter used in Equations (4), (12), and (14)). Yearly discount and inflation rates applied to the cost information within the optimization are 7% and 2% respectively. The 40 yearlong LP cost minimization model has 748,680 constraints and 889,160 variables, and the total simulation time in an Intel dual-core 3GHz 3GB RAM computer is about 1 hour (reading input files and formulating LP problem takes about 50 minutes, and execution takes the remaining time).

4.2 Simulation Results and Discussion

4.2.1 Cost and Emissions

Table 8 shows the summary of simulation results pertaining to the minimum cost portfolios in each scenario. The results reported include, “HSR pen” which indicates the percentage of total long-distance passenger miles accommodated by HSR; the total cost that is net present value of investment plus operations costs (excluding VoTT) for the electric and transportation sectors over 40 years; and the 40 yearlong CO_2 emissions for both electric and transportation sectors given separately. Just to put these numbers in context with contemporary scenario, the power sector CO_2 emissions in year 2008 [36] were about 2.14e9 short tons (i.e., ~8.56e10 short tons over 40 years at 2008 emission rate). The resulting low-cost portfolio for Ref scenario under BAU future shows a 57% reduction in power sector emissions over 40-years. Similarly, the transportation sector CO_2 emissions in year 2008 were about 1.65e9 short tons (i.e., ~6.6e10 short tons over 40 years at 2008 emission rate). This paper models only inter-state passenger and freight transportation, which amounts to about 8.6% of 2008 emissions over 40-years under BAU_Ref scenario (read as “Ref scenario under BAU future”).

From Table 8, it is observed that including value of travel time increases HSR penetration under both the futures, and the penetration is even higher with improved HSR economics. As HSR penetration increases in CAP2.0 scenario, electric sector emissions increase by about 16e8 short tons (4.4%) and

4e8 short tons (1.9%) in BAU and RF futures respectively due to increased consumption, but passenger sector emissions decrease by about 12.5e8 short tons (34%) and 12.1e8 short tons (32.9%) in BAU and RF futures respectively due to decrease in petroleum consumption. With improved HSR economics in scenario CAP2.0, the increased HSR penetration does make a significant impact on the total system cost over 40-years. Under both the futures, compared to reference scenario in CAP2.0 scenario there is long-term cost savings of about $460B-$470B 2009 USD. The total cost of travel time over 40 years in RF_CAP2.0 scenario is $5.87T, compared to $.6.04T in RF_Ref scenario. Therefore, together with travel time cost savings of about $170B, the total long term investment and operational cost savings with 30.5% HSR penetration in CAP2.0 scenario may be about $630B.

Table 8: Case studies and summary of results

Scenarios	HSR pen. (%)	Cost (T$)	40- year CO_2 Emissions (e10 short tons)			
			Total	Freight	Passenger	Power
Business As Usual (BAU)						
Ref	0	11.31	4.21	0.199	0.367	3.65
VoTT	2.2	11.33	4.22	0.199	0.363	3.66
CAP2.0	31.1	10.84	4.26	0.2	0.242	3.81
Renewable Friendly (RF)						
Ref	0	11.61	2.59	0.193	0.367	2.03
VoTT	2.1	11.63	2.60	0.193	0.363	2.04
CAP2.0	30.5	11.15	2.51	0.193	0.246	2.07

4.2.2 Electric Generation Portfolio

Figure 6 shows the annual electric energy generated over the 40 years for the scenarios under BAU future. The total generation over 40 years increases in CAP2.0 scenarios compared to Ref scenarios under both BAU and RF futures by about 4011.83TWh and 3899TWh respectively. The increase in electric generation required to support the HSR operations, increases the CO_2 emissions in power sector as seen in Table 8. Though high penetration of HSR does decrease inter-state passenger transportation related emissions, however the trend in total cumulative national emissions depend heavily on the nature of generation portfolio.

Figure 7 compares the mix of generation for BAU and RF futures under Ref and CAP2.0 scenarios. In order to focus on other generations, the figure does not show generation from Nuclear that contributes about 70% of the energy production over 40 years. We observe the following from the figure:

1. **Lower emissions in RF future:** In the Ref scenarios, the generation from coal units in RF future is about 62% of coal generation in BAU future, and RF future do not have any generation from coal-fired IGCC units. On the other hand, the wind generation in BAU future is only about 38% of wind generation in RF future, and BAU future allows very less penetration in geothermal energy (about 0.7% of geothermal energy in RF future over 40 years). Therefore, all scenarios in RF future have lesser total CO_2 emissions than BAU futures (lesser by about 38.5%). The reduction in coal based generation in RF future also reduces the emission from freight transportation sector related to coal transportation using

diesel rails and trucks.

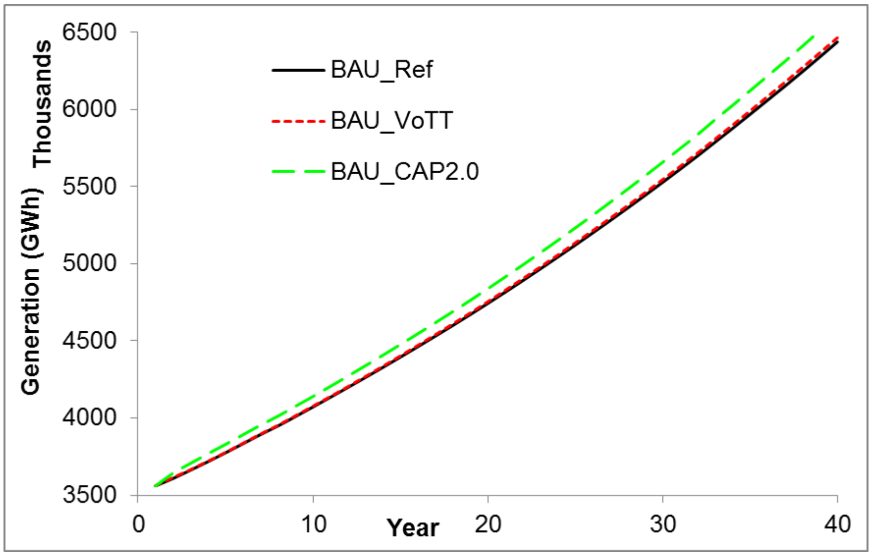


Figure 6: Yearly electric energy generation - influence of HSR penetration

2. **High HSR penetration in RF future promises sustainability:** Comparing CAP2.0 and Ref scenarios under each future, the additional generation to economically support the higher HSR penetration mainly stems from fossil-fuel based units in BAU future. Under BAU future, the coal generation over 40-years increases by about 800TWh, IGCC by about 930TWh, NGCC by about 300TWh and wind by about 176TWh. On the other hand under RF future, the increase in generation mainly stems from NGCC by about 350TWh, wind by about 475TWh and geothermal by about 1300TWh. The coal units increase by about 280TWh over 40 years. Nuclear under both the futures increases by about 1800TWh to support HSR in CAP2.0 scenario. Therefore, under RF future the higher HSR penetration promises an overall reduction in CO_2 emissions, i.e., 3.1% reduced in CAP2.0 scenario compared to Ref scenario.

However the higher investment cost of low-CO_2 emitting generation increases the total long term cost for RF future by about $300B compared to BAU future, as seen in Table 8. Assuming a carbon tax of $30/short ton, the reference scenario under RF future assures a carbon credit of about $486B due to its sustainable operation in electric generation and freight transportation. Therefore, under the assumption that the increased requirement for electric power can be provided from renewable resources, scenarios promoting higher HSR penetration promise an overall reduction in national emissions. The carbon credit with HSR in the national portfolio increases to about $525B as observed from RF_CAP2.0 scenario emissions in Table 8. In other words, electrification of passenger transportation using HSR further necessitates promoting renewable generation futures in order to ensure long term sustainability.

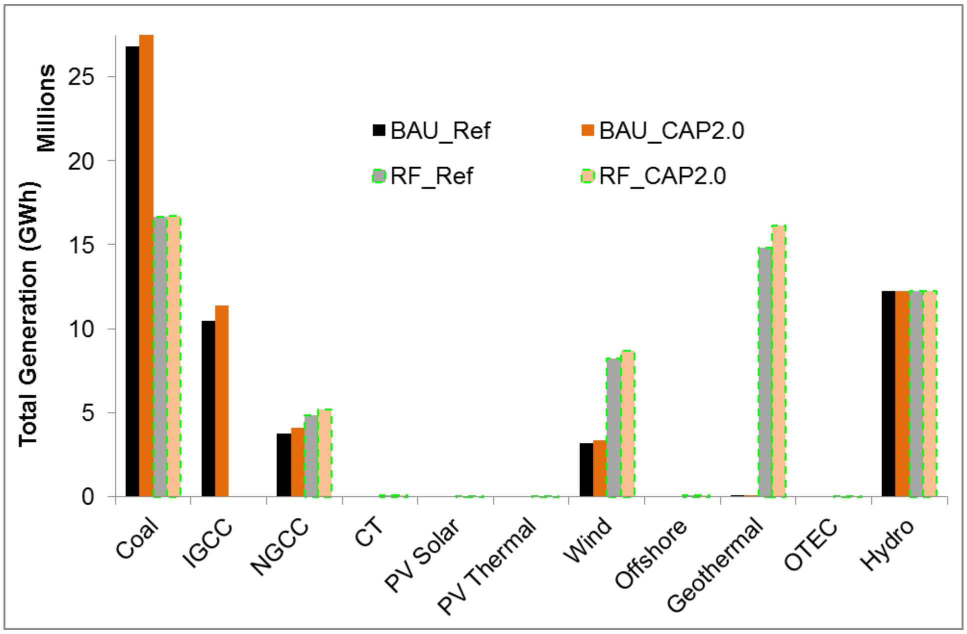
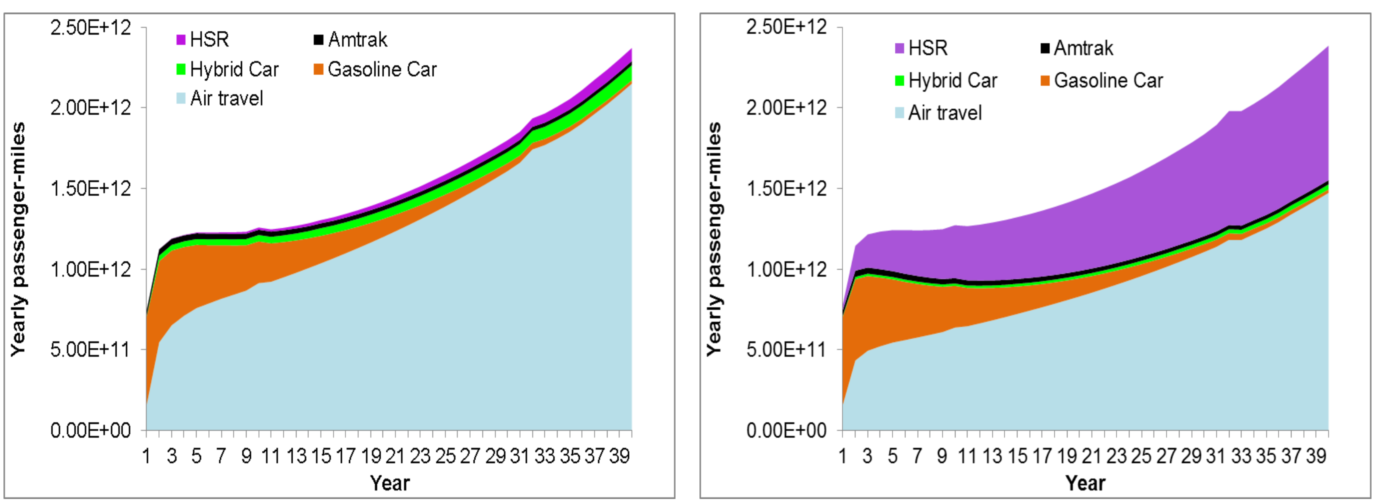


Figure 7: 40-year electric energy generation from various technologies

4.2.3 Passenger Transportation Portfolio Diversification

Figures 8 (a)-(b) illustrate the mode share in yearly long-distance passenger mileage for VoTT and CAP2.0 scenarios. It can be inferred from these figures that the primary competition for interstate passenger travel is between air and HSR. Inclusion of VoTT within optimization shifts a portion of demand from air travel to HSR across many short and medium-length transportation paths to produce a minimum cost transportation portfolio. Improvement in HSR economics in CAP2.0 scenario further enables HSR to transport a major portion of yearly passenger demand, thereby diversifying the passenger transportation portfolio. Figure 9 illustrates the set of HSR investments selected in CAP2.0 scenario resulting in 30.5% penetration, a set very similar to those which have been designated by the US Department of Transportation during the last 4 years [6].



(a) RF_VoTT (b) RF_CAP2.0

Figure 8: Yearly passenger transportation mode share

In general, the diversification of passenger transportation portfolio could provide:

1. Alternative mode choice for the passengers and means of interconnecting communities
2. Resilience or operational flexibility to the passenger transportation system in the face of extreme events causing inter-state movement by certain fleet or route very expensive or impossible

The diversification of transportation portfolio with higher penetration of HSR adds one more thing:

3. Reduction in transportation sector's over-dependence on petroleum

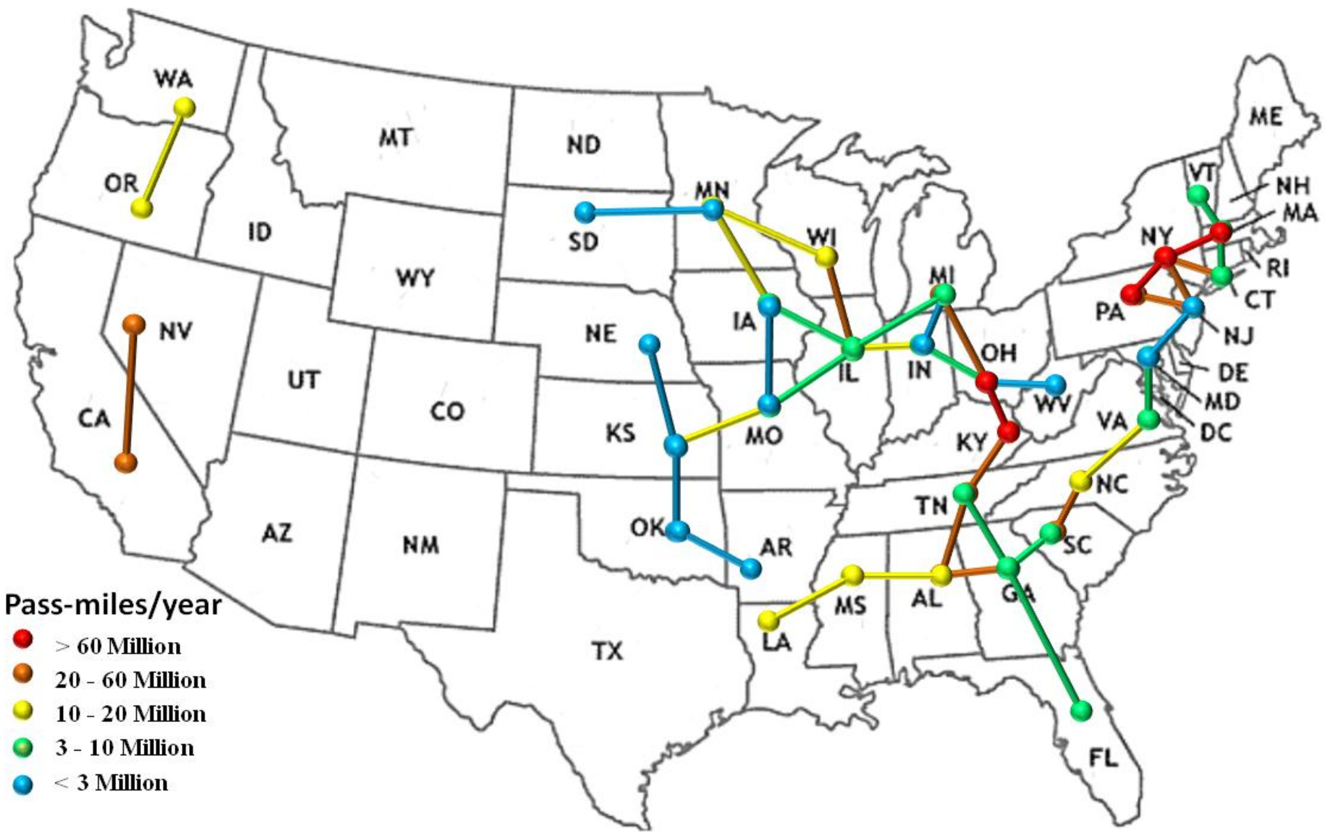


Figure 9: HSR interstate route capacities at year 40 for RF_CAP2.0 scenario

4.2.4 Dependence on Petroleum

Figure 10 shows the annual gasoline and jet fuel consumption respectively over the 40 years for the various scenarios. It is seen that inclusion of VoTT, decreased air travels and consequently the jet-fuel consumption. However VoTT shifted some demand to both HSR as well as personal vehicles (over shorter distances) and hence there is increase in gasoline consumption compared to Ref scenario. Increase in HSR economics and the cooresponding higher penetration of HSR reduced both gasoline and jet-fuel consumption, with significant impact on air travel. Compared to Ref scenario, CAP2.0 scenario sees a 34% decrease in total inter-state air passenger-miles over 40-years.

In order to evaluate the impact of decrease in petroleum dependence caused by HSR penetration from national energy security and independence point of view [37], a petroleum price increase (PP) event was devised and investigated under various scenarios in RF future. The PP event models a yearly increase in petroleum price by 3%, reflected in terms of yearly price increase in gasoline and jet fuel. Table 9 shows the results of various scenarios with PP event. NoHSR is same as reference scenario without HSR among the investment options. Cap1.5 is a scenario with 1.5 times (390 passengers) the original assumed HSR occupancy. In PP+NoHSR scenario, the significantly higher cost increase is due primarily to the PP event. Table 8 indicated Ref scenario to typically not allow investments in HSR, however the PP event induces about 6.2% of HSR penetration even in Ref scenario to ensure a low-cost national portfolio (as seen by $30B cost savings compared to NoHSR scenario). Together with PP increase, improvement in HSR economics drastically increases HSR penetration to 63.2% under CAP1.5 scenario and 83.1% in CAP2.0 scenario. Both the total long term cost and emissions significantly decreases for CAP2.0 scenario compared to PP+NoHSR scenario when there is no HSR in the portfolio.

This analysis shows the ability of high HSR in the portfolio to securely dampen the impacts of extreme events with respect to transportation sector's dependence on petroleum products. For this PP event, economic HSR (resulting in 83.1% penetration) promises to save upto $1790B 2009 USD and reduce CO_2 emissions by about 24e8 short tons (9.3%) compared to not having HSR in the national portfolio. This cost decrease can be attributed to the economies obtained from the lower long-term operational costs of HSR travel compared to those of air and highway travel under a high petroleum-priced future.

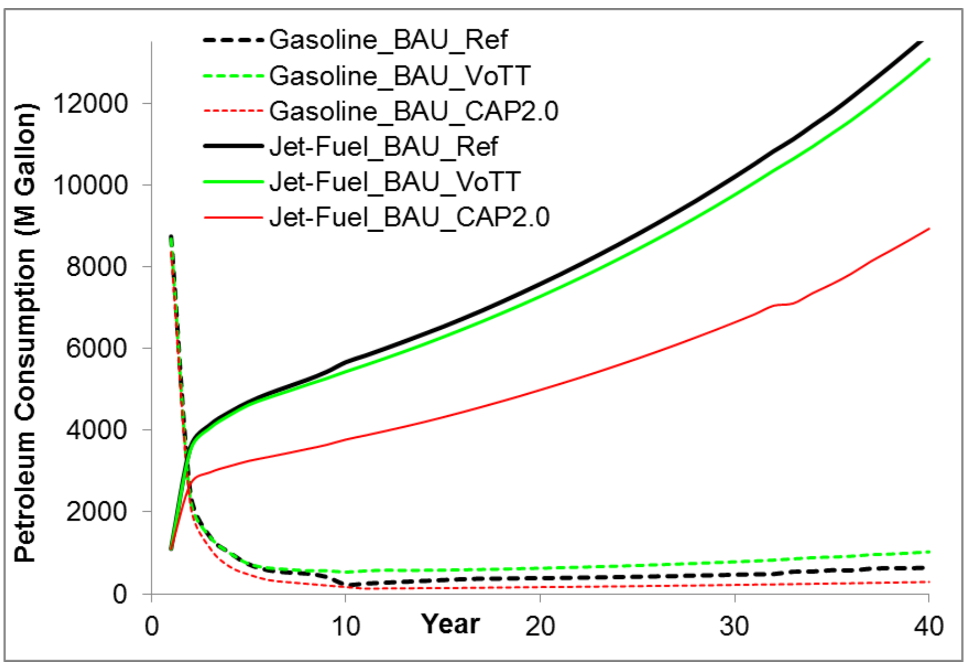


Figure 10: Annual petroleum consumption for passenger transportation

Table 9: HSR penetration vs. petroleum price increase (PP)

Scenarios	HSR pen. (%)	Cost (T$)	40- year CO_2 Emissions (e10 short tons)			
			Total	Freight	Passenger	Power
PP + NoHSR	0	12.85	2.59	0.193	0.364	2.03

PP + Ref	6.2	12.82	2.58	0.193	0.348	2.04
PP + CAP1.5	63.2	12.11	2.42	0.193	0.134	2.1
PP + CAP2.0	83.1	11.06	2.35	0.193	0.0378	2.12

4.3 Summary

Table 10 presents the summary of case studies, showing the value of HSR penetration in passenger transportation portfolio in terms of change in national energy consumption, CO_2 emissions and cost savings; given that the energy requirement for HSR is provided by renewable generation future. Higher penetration of HSR of about 30% can reduce gasoline and jet fuel consumption for inter-state[5] passenger travels upto about 34%, promising a long-term cost savings of upto $499B including carbon credits. Under a petroleum price increase scenario of about 3%/year, the national cost savings may rise upto $1829B 2009 USD (including carbon credits) with HSR in the transportation sector than not having it.

It is also seen that a moderate peneration of HSR in the portfolio under RF_CAP2.0 scenario (30.5%) does increase the travel efficiency by reducing the travel time cost, resulting in escalation of long-term cost savings to about $669B. However a very large penetration of HSR under RF_PP+CAP2.0 scenario (83.1%) results in significant demand shift from air to HSR along longer distance trips, which reduce the overall travel efficiency, quantified as increase in travel time cost by $950B. Nevertheless such a scenario still ensures economic security against shocks in petroleum prices, in this case by about $879B.

Based on the long-term passenger transportation planning model developed in this paper, future investigations will consider optimizing for the right mix of passenger transportation portfolio such that it ensures both overall transportation efficiency as well as operational resilience against such extreme events.

Table 10: HSR penetration vs. 40-year national energy consumption and cost savings

Fuel Type	***RF_Ref***	***RF_CAP2.0***	***RF_PP+Ref***	***RF_PP+CAP2.0***
HSR pen. (%)	0	30.5	6.2	83.1
Total Cost (T$)	11.61	11.15	12.82	11.06
Travel time Cost (T$)	6.04	5.87	6.04	6.99
Emissions (e10 short tons)	2.59	2.51 (-3.1%)	2.58	2.35 (-8.9%)
Gasoline (E+3 MGallon)	29.84	19.92 (-33.2%)	18.88	16.12 (-14.6%)
Jet Fuel (E+3 MGallon)	320.55	211.25 (-34.1%)	312.32	20.99 (-93.3%)
Electric Energy (E+6 TWh)	194.23	198.24 (2.06%)	195.24	200.95 (2.9%)
Cost Savings (B$)	Reference	460	Reference	1760
Cost Savings w/ CO_2 credit (B$)	Reference	499	Reference	1829
Cost Savings w/ CO_2 credit and travel time cost (B$)	Reference	669	Reference	879

[5] In this paper the intra-state passenger transportation are not modeled, and hence the impact of HSR penetration on intra-state demand sharing and the corresponding energy consumption has not been evaluated. Such an effort will be part of future investigation.

5. CONCLUSIONS

This paper presents the modeling aspects of a long-term national level energy and transportation planning framework, with primary emphasis on the developed multi-modal freight and passenger transportation systems within the co-optimization. The purpose of such a large scale multi-sector planning model is to achieve a low-cost and sustainable energy and transportation infrastructures taking into account their operational and planning interdependencies. The developed multi-modal passenger transportation model was integrated within national energy and transportation infrastructure planning software, NETPLAN, and was used to investigate the impact of high-speed rail investments on US national inter-state mode sharing, electric energy use and generation portfolio, and national energy consumption and emissions over the next 40 years.

The case studies show that there are credible scenarios under which significant HSR penetration can be achieved, leading to reasonable decrease in national long-term CO_2 emissions and costs relative to a future without HSR. A renewable electric generation future, towards which the current trend of generation expansion is leaning towards owing to global warming issues, is seen to support such high HSR penetration scenarios in a sustainable manner to ensure overall national emissions reduction. The diversification of passenger transportation portfolio with HSR, apart from promising passengers with an alternative time-efficient choice for short and medium-distance inter-state travels, will also reduce national dependence on petroleum consumption and the consequent vulnerability against shocks in oil import. With the growing penetration of renewable power generation sources within the electric sector, the penetration of HSR within the national transportation portfolio seems highly promising to achieve the goals of energy independence, security, efficiency and sustainability.

The future investigations will enhance the long-term planning model presented in this paper with the ability to account for intra-state transportation needs, and consider waterways among the options to transport freight. Studies that can assess and quantity the impact of fleet diversification on freight and passenger transportation resilience against extreme events will be also of interest in order to build a resilient infrastructure.

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