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An optimization model of energy and transportation systems: Assessing the high-speed rail impacts in the United States

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ABSTRACT

This paper presents a long-term investment planning model that co-optimizes infrastructure investments and operations across transportation and electric infrastructure systems for meeting the energy and transportation needs in the United States. The developed passenger transportation model is integrated within the modeling framework of a National Long-term Energy and Transportation Planning (NETPLAN) software, and the model is applied to investigate the impact of high-speed rail (HSR) investments on interstate passenger transportation portfolio, fuel and electricity consumption, and 40-year cost and carbon dioxide (CO_2) emissions. The results show that there are feasible scenarios under which significant HSR penetration can be achieved, leading to reasonable decrease in national long-term CO_2 emissions and costs. At higher HSR penetration of approximately 30% relative to no HSR in the portfolio promises a 40-year cost savings of up to \$0.63 T, gasoline and jet fuel consumption reduction of up to 34% for interstate passenger trips, CO_2 emissions reduction by about 0.8 billion short tons, and increased resilience against petroleum price shocks. Additionally, sensitivity studies with respect to light-duty vehicle mode share reveal that in order to realize such long-term cost and emission benefits, a change in the passenger mode choice is essential to ensure higher ridership for HSR.

1. Introduction

Energy independence, energy security, and sustainability are key factors that drive every nation's pursuits to achieve a stable and prosperous economy. In the United States (U.S.), the transportation and the electric power sectors account for about 70% of total energy consumption and about 70% of total anthropogenic greenhouse gas emissions due to heavy dependence on fossil sources such as petroleum, natural gas and coal (U.S. Energy Information Administration, 2013). Although predictions for the year 2035 suggest that the world's reliance on fossil fuels may not decline much (BP Statistical Review, 2013), especially in the transportation sector (BP Energy Outlook, 2013), still many countries are moving toward the use of energy resources with low greenhouse gas (GHG) emission, including renewable resources. In the U.S., the development of a nationwide high-speed rail (HSR) network has been suggested as a "greener" passenger transport solution.

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Nomenclature

Indices

(i, j)	energy sector nodes (regions) and arc
(x, y)	transportation sector nodes (states) and arc
t, z	time period
ng	number of generation technologies in a region
k	transportation commodities; energy freight ($k = ek$), non-energy freight ($k = fk$) and passengers ($k = p$)
m	transportation mode
inf	transportation fixed infrastructure (highway, railway)

Decision variables

$e_{(i,j)}(t)$	energy flow in the arc (i, j) at time t
$eInv_{(i,j)}(t)$	investment in generation technology i within region j or in transmission line (i, j) in GW at time t
$f_{(x,y,k,m)}(t)$	number of trips made by mode m to transport commodity k across arc (x, y) at time t
$fInv_{(x,y,m)}(t)$	yearly fleet investments in transportation mode m across transportation arc (x, y) at time t
$infInv_{(x,y,inf)}(t)$	yearly investments in infrastructure inf across arc (x, y) at time t

Constants and parameters

$CostOp^{e}_{(i,j)}(t)$	operational cost of energy in \$/unit-energy through arc (i, j) at time t
$CostInv_{(i,j)}(t)$	investment cost in \$/GW for arc (i, j) at time t
$CostOp^{T}_{(x,y,k,m)}(t)$	operational cost of transportation by mode m in \$/trip-mile to transport commodity k across arc (x, y) at time t
$CostfInv_{(x,y,m)}(t)$	investment cost of mode m in \$/vehicle across arc (x, y) at time t
$CostinfInv_{(x,y,inf)}(t)$	investment cost of infrastructure inf in \$/unit-inf across arc (x, y) at time t
r	discount rate
$\eta_{(i,j)}$	arc efficiency parameter
$d^{e}_{j}(t)$	nodal energy demanded at region j at time t
$d^{eT}_{j}(t)$	nodal energy demand imposed by transportation systems in region j at time t
$d^{T}_{(x,y,fk)}(t)$	freight commodity fk (non-energy) transported to transportation region y from region x at time t
$d^{T}_{(x,y,p)}(t)$	passengers p transported to transportation region y from region x at time t
$d^{T}_{(x,y,LDV)}(t)$	passengers transported to transportation region y from region x at time t by light-duty vehicles (LDVs)
$lbe_{(i,j)}(t)$, $ube_{(i,j)}(t)$	lower and upper (existing, subject to periodic retirements) capacity bounds on arc energy at time t
$cap\_e_{(i,j)}(t)$	total arc energy capacity at time t, subject to expansion decision
$lbeInv_{(i,j)}(t)$, $ubeInv_{(i,j)}(t)$	minimum and maximum infrastructure investments at time t
$life_{(i,j)}$	lifespan of the investment in arc (i, j)
$inv.\ start$	investment start year
$I(t - z \leqslant life)$	indicator function on available life of an infrastructure
$pkd_{j}(t)$	peak electric energy demand in region j at time t
$cv_{(i,j)}$	capacity value of generator technology i in region j
$h_{ek}(t)$	energy content of the energy commodity ek in GW h/k-ton at time t
$lbf_{(x,y,m)}(t)$, $ubf_{(x,y,m)}(t)$	lower and upper fleet capacity bounds on trips by mode m across arc (x, y) at time t
$cap\_f_{(x,y,m)}(t)$	maximum capacity for yearly trips by mode m across arc (x, y) at time t, subject to expansion decision
$lbfInv_{(x,y,m)}(t)$, $ubfInv_{(x,y,m)}(t)$	minimum and maximum mode m investments across arc (x, y) at time t
$flife_{(x,y,m)}$	lifespan of the mode m
$\lambda_{(x,y,m)}$	average trips made by mode m across arc (x, y) in a year (yearly frequency)
$lbinf_{(x,y,inf)}(t)$, $ubinf_{(x,y,inf)}(t)$	lower and upper (existing) fleet capacity bounds imposed by infrastructure inf across (x, y) at time t
$cap\_f_{(x,y,inf)}(t)$	maximum capacity for yearly fleet trips allowed by infrastructure inf across arc (x, y) at time t
$lbfInv_{(x,y,inf)}(t)$, $ubfInv_{(x,y,m)}(t)$	minimum and maximum infrastructure inf investments across arc (x, y) at time t
$inflife_{(x,y,m)}$	lifespan of the fixed infrastructure inf
δ_{m}	passenger-car-equivalent (PCE) of mode m
$\lambda_{(x,y,inf)}$	average trips allowable by infrastructure inf across arc (x, y) in a year
$\alpha^{j}_{(x,y)}$	proportion of total energy requirements for the bi-directional transportation in arc (x, y) attributed to region j energy demand in MM gallon or GW h
$fuelC_{m}(t)$	fuel/energy consumption by mode m in units of fuel/vehicle-mile
$VoTT_{(x,y,m,inf)}$	value of travel time for each mode m in \$/passenger
$IVC_{(x,y,m,inf)}$, $OVC_{(x,y,m,inf)}$	in-vehicle and out-of-vehicle passenger time cost for mode m in \$/passenger-h
$H_{b}(t)$, $H_{p}(t)$	average hourly wage of a passenger traveling for business and personal purposes respectively at time t
$\tau_{(m,inf,ivc)}$, $\tau_{(m,inf,ovc)}$	in-vehicle and out-of-vehicle time (in h) for mode m using infrastructure inf
$p_{(x,y,m,inf)}$, $b_{(x,y,m,inf)}$	proportion of passengers traveling for personal and business purposes by mode m across arc (x, y)
$m_{(x,y,LDV)}$	percentage of inter-state passenger travel over the arc (x, y) performed by light-duty vehicles