Environmental Impact Assessment of Transportation Networks with Degradable Links in an Era of Climate Change

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The U.S. Ailing Infrastructure

- Over one-quarter of the nation's 590,750 bridges were rated structurally deficient or functionally obsolete. The degradation of transportation networks due to poor maintenance, natural disasters, deterioration over time, as well as unforeseen attacks now lead to estimates of $94 billion in the U.S. in terms of needed repairs for roads alone. Poor road conditions in the U.S. cost motorists $54 billion in repairs and operating costs annually (ASCE Survey (2005)).
- Due to the constant breakdowns of the U.S. transportation networks and the increasing number of vehicles, American commuters now spend 3.5 billion hours a year stuck in traffic, which translates to a cost of $63.2 billion a year to the economy (ASCE (2005)).

The U.S. Ailing Infrastructure

- The U.S. is experiencing a freight capacity crisis that threatens the strength and productivity of the U.S. economy. According to the American Road & Transportation Builders Association (see Jeanneret (2006)), nearly 75% of U.S. freight is carried in the U.S. on highways, and bottlenecks are causing truckers 243 million hours of delay annually with an estimated associated cost of $8 billion.
- The number of motor vehicles in the U.S. has risen by 157 million (or 212.16%) since 1960 while the population of licensed drivers grew by 109 million (or 125.28%) (U.S. Department of Transportation (2004)).

Transportation Network Capacity and Its Environmental Impact

- According to a U.S. EPA (2006) report, the transportation sector in 2003 accounted for 27% of the total greenhouse gas emissions in the U.S. and the increase in this sector was the largest of any in the period 1990 – 2003.
- The energy use due to transportation is expected to increase by 48% between 2003 and 2025, even with modest improvements in the efficiency of vehicular engines.
- A study claims that infrastructure capacity increases are directly linked to decreases in polluting emissions from motor vehicles. Using a traffic micro-simulation, it showed, for example, that upgrading narrow, winding roads or adding a lane to a congested motorway can yield decreases of up to 38% in CO_2 emissions, 67% in CO emissions and 75% in NO_x emissions, without generating substantially more car trips (Knudsen and Bang (2007)).

Figure: Melting Ground and Sea Ice Destroying Villages in Alaska, Source: globalwarming.house.gov

Figure: Examples from Alaska, Source: Smith and Levasseur

Figure: Roads are Damaged by Floods, Source: The Oregonian

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Related Literature

- Network Vulnerability and Robustness
  - Berdica (2002), Sakakibara, Kajitani, and Okada (2004), Scott et al. (2006), Taylor, Sekhar, and D'Este (2006), Murray and Grubesic (2007), Jenelius (2007)
- Transportation Networks and Emissions Under Different User Behaviors
  - Wigan (1975)
  - Taylor and Anderson (1984)
  - Yin and Lawphongpanich (2006)

Our Research on Network Efficiency, Vulnerability, and Robustness

- Nagurney, A., Qiang, Q., 2007a. A network efficiency measure for congested networks. *Europhysics Letters* 79, 38005, pp 1-5.
- Nagurney, A., Qiang, Q., 2007b. Robustness of transportation networks subject to degradable links. *Europhysics Letters* 80, 68001, pp 1-6.
- Nagurney, A., Qiang, Q., 2007c. A transportation network efficiency measure that captures flows, behavior, and costs with applications to network component importance identification and vulnerability, in *Proceedings of the POMS 18th Annual Conference*, Dallas, Texas.
- Nagurney, A., Qiang, Q., 2008. A relative total cost index for the evaluation of transportation network robustness in the presence of degradable links and alternative travel behavior, to appear in *International Transactions Operational Research*.

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Notation for the Transportation Network Models

- Network $\mathcal{G}$ with the set of links L with n_L elements, the set of paths P with n_P elements, and the set of O/D pairs W with n_W elements.
- The set of (acyclic) paths connecting O/D pair w are denoted by P_w, the links by a, b, etc, the paths by p, q, etc., and the O/D pairs by w_1, w_2, etc.
- The flow on path p is denoted by x_p and the flow on link a by f_a. x is the column vector of all path flows and f is the column vector of all link flows.
- Travel cost on a path p is denoted by C_p and the travel cost on a link a by c_a. C is the column vector of all path costs and c is the column vector of all link costs. Assume that the user link cost functions are continuous.
- Denote the travel demand between O/D pair w by d_w and the travel disutility by λ_w, where d_w is fixed and known for all w.

Conservation of Flow Between Demands and Path Flows

$$d_w = \sum_{p \in P_w} x_p, \quad \forall w \in W, \tag{1}$$

Conservation of Flow Between Link Flows and Path Flows

$$f_a = \sum_{p \in P} x_p \delta_{ap}, \quad \forall a \in L, \tag{2}$$

where $\delta_{ap} = 1$, if path p contains link a, and $\delta_{ap} = 0$, otherwise.

Link Costs and Path Costs

$$C_p = \sum_{a \in L} c_a \delta_{ap}, \quad \forall p \in P, \tag{3}$$

The user cost on link a is denoted by c_a where

$$c_a = c_a(f_a), \quad \forall a \in L. \tag{4}$$

Bureau of Public Roads (BPR) (1964) Link Cost Function

$$c_a(f_a) = t_a^0[1 + k(\frac{f_a}{u_a})^\beta], \quad \forall a \in L, \tag{5}$$

u_a is the "practical" capacity on link a, which also has the interpretation of the level-of-service flow rate; t_a^0 is the free-flow travel time or cost on link a; k and β are the model parameters and both take on positive values. Typically, in applications, $k = .15$ and $\beta = 4$.

The Total Cost on Link a, denoted by $\hat{c}_a$

$$\hat{c}_a = \hat{c}_a(f_a) = c_a(f_a) \times f_a = t_a^0[1 + k(\frac{f_a}{u_a})^{\beta}] \times f_a, \quad \forall a \in L. \tag{6}$$

The Total Cost on a Network, denoted by TC

$$TC = \sum_{a \in L} \hat{c}_a(f_a), \tag{7}$$

where the link flows f must lie in the feasible set $\mathcal{K}$:
$\mathcal{K} \equiv \{f \in R_+^{n_L} | \exists x \in R_+^{n_P} \text{ satisfying } (1), (2)\}$.

The User-Optimal (U-O) Traffic Flow Pattern (Beckmann, McGuire and Winsten (1956), Dafermos and Sparrow (1969))

Definition: Network Equilibrium

A path flow pattern $x^* \in \mathcal{K}^1$, where $\mathcal{K}^1 \equiv \{x | x \in R_+^{n_P} \text{ and } d_w = \sum_{p \in P_w} x_p, \forall w \in W \text{ holds}\}$, is said to be a transportation network equilibrium, in the case of fixed demands, if the following condition holds for each O/D pair $w \in W$ and every path $p \in P_w$:

$$C_p(x^*) - \lambda_w^* \begin{cases} = 0, & \text{if} \quad x_p^* > 0, \\ \geq 0, & \text{if} \quad x_p^* = 0. \end{cases} \tag{8}$$

Equivalent Optimization Problem (cf. Beckmann, McGuire, and Winsten (1956))

The equilibrium link flow (and path flow pattern) can be obtained via the solution of the following optimization problem:

$$\text{Minimize}_{f \in \mathcal{K}} \quad \sum_{a \in L} \int_0^{f_a} c_a(y)dy. \tag{9}$$

The System-Optimal (S-O) Traffic Flow Pattern

Assume that there is a central controller of the traffic who routes the traffic in an optimal manner so as to minimize the total cost in the network. That is,

$$\text{Minimize}_{f \in \mathcal{K}} \quad \sum_{a \in L} \hat{c}_a(f_a) \tag{10}$$

The total cost on a path, denoted by $\hat{C}_p$, is the user cost on a path times the flow on a path, that is,

$$\hat{C}_p = C_p x_p, \ \forall p \in P, \tag{11}$$

where the user cost on a path, C_p, is given by (3).
In view of (2), (3), and (4), one may express the cost on a path p as a function of the path flow variables and, hence, an alternative version of the above S-O problem with objective function (10) can be stated in path flow variables only, where one has now the problem:

$$\text{Minimize}_{x \in \mathcal{K}^1} \quad \sum_{p \in P} C_p(x) x_p \tag{12}$$

System-Optimality Conditions

Under the assumption of increasing user link cost functions, the objective function (10) in the S-O problem is convex, and the feasible set $\mathcal{K}^1$ is also convex. Therefore, the optimality conditions, that is, the Kuhn-Tucker conditions are: for each O/D pair $w \in W$ and each path $p \in P_w$, the flow pattern $x \in \mathcal{K}^1$, must satisfy:

$$\hat{C}'_p(x) \begin{cases} = \mu_w, & \text{if} \quad x_p > 0, \\ \geq \mu_w, & \text{if} \quad x_p = 0, \end{cases} \tag{13}$$

where $\hat{C}'_p(x)$ denotes the marginal of the total cost on path p, given by:

$$\hat{C}'_p(x) = \sum_{a \in L} \frac{\partial \hat{c}_a(f_a)}{\partial f_a} \delta_{ap} \tag{14}$$

evaluated in (13) at the solution and μ_w is the Lagrange multiplier associated with constraint (1) for that O/D pair w.

Emission Functions

- Alexopoulos and Assimacopoulos (1993) have argued that carbon monoxide (CO), since it is emitted exclusively by vehicular traffic, is important as an indicator for the level of atmospheric pollution generated by such traffic.
- It has been shown that CO is the most significant pollutant among all other types of vehicle emissions (cf. US Department of Transportation Federal Highway Administration (2006b)).
- It is noted that other pollutants that are related to congestion exhibit similar behavior (cf. Hizir (2006) and the California Air Resources Board (2005)).

Emission Functions

Yin and Lawphongpanich (2006) utilized the following function to estimate vehicular CO emissions:

$$e_a(f_a) = 0.2038 \times c_a(f_a) \times e^{0.7962 \times (\frac{l_a}{c_a(f_a)})} \tag{15}$$

where l_a denotes the length of link a and c_a (cf. (4)) corresponds to the travel time (in minutes) to traverse link a. The length l_a is measured in kilometers for each link $a \in L$ and the emissions are in grams per hour.

The expression for total CO emissions on a link a, denoted by $\hat{e}_a(f_a)$, is then given by:

$$\hat{e}_a(f_a) = e_a(f_a) \times f_a. \tag{16}$$

The total emissions of CO generated on a network is denoted by TE and is, hence:

$$\mathrm{TE} = \sum_{a \in L} \hat{e}_a(f_a). \tag{17}$$

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The Environmental Impact Assessment Indices for Transportation Networks

The environmental impact assessment indices for a transportation network G with the vector of demands d, the vector of user link cost functions c, and the vector of link capacities u are defined as the relative total emission increase under a given uniform capacity retention ratio γ ($\gamma \in (0,1]$) so that the new capacities (cf. (5)) are given by γu. Let c denote the vector of BPR user link cost functions and let d denote the vector of O/D pair travel demands.

The Environmental Impact Assessment Index Under U-O Flow Pattern

$$\mathrm{EI}^{\gamma}_{U-O} = \mathrm{EI}_{U-O}(G, c, d, \gamma, u) = \frac{\mathrm{TE}^{\gamma}_{U-O} - \mathrm{TE}_{U-O}}{\mathrm{TE}_{U-O}} \tag{18}$$

where TE_{U-O} and $\mathrm{TE}^{\gamma}_{U-O}$ are the total emissions generated under the user-optimizing flow pattern with the original capacities and the remaining capacities (i.e., γu), respectively.

The Environmental Impact Assessment Indices for Transportation Networks

The Environmental Impact Assessment Index Under S-O Flow Pattern

$$\mathrm{EI}^{\gamma}_{S-O} = \mathrm{EI}_{S-O}(G, c, d, \gamma, u) = \frac{\mathrm{TE}^{\gamma}_{S-O} - \mathrm{TE}_{S-O}}{\mathrm{TE}_{S-O}} \tag{19}$$

where TE_{S-O} and $\mathrm{TE}^{\gamma}_{S-O}$ are the total emissions generated at the system-optimizing flow pattern with the original capacities and the remaining capacities (i.e., γu), respectively.

A transportation network, under a given capacity retention/deterioration ratio γ (and under either S-O or U-O travel behavior), is considered to be *environmentally* robust if the index EI^{γ} is low. This means that the relative total emissions do not change much and, hence, the transportation network may be viewed as being more robust, from an environmental perspective.

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Link Importance Identification and Ranking

Link importance indicators from the point of view of environmental impact assessment:

$$\mathrm{I}^{l}_{U-O} = \frac{\mathrm{TE}_{U-O}(G-l) - \mathrm{TE}_{U-O}}{\mathrm{TE}_{U-O}} \tag{20}$$

$$\mathrm{I}^{l}_{S-O} = \frac{\mathrm{TE}_{S-O}(G-l) - \mathrm{TE}_{S-O}}{\mathrm{TE}_{S-O}} \tag{21}$$

where I^{l}_{U-O} denotes the importance indicator for link l assuming U-O behavior and I^{l}_{S-O} denotes the analogue under S-O behavior; $\mathrm{TE}_{U-O}(G-l)$ denotes the total emissions generated under U-O behavior if link l is removed from the network and $\mathrm{TE}_{S-O}(G-l)$ denotes the same but under S-O behavior. Based on the specific values of (20) and (21) the links for a given transportation network can then be ranked.

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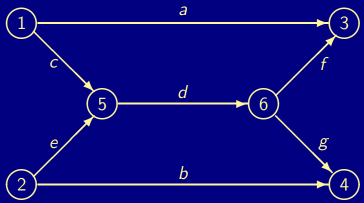
The Yin and Lawphongpanich (2006) Network

The topology of the first transportation network that we studied is depicted on the right. There are two O/D pairs in the network: $w_1 = (1,3)$ and $w_2 = (2,4)$ with demands of $d_{w_1} = 3000$ vehicles per hour and $d_{w_2} = 3000$ vehicles per hour. The user link cost functions, which here correspond to travel time in minutes, are of the BPR form given by (5) and are as follows:



$$c_a(f_a) = 8(1+.15(f_a/2000)^4), \; c_b(f_b) = 9(1+.15(f_b/2000)^4),$$

$$c_c(f_c) = 2(1+.15(f_c/2000)^4), \; c_d(f_d) = 6(1+.15(f_d/4000)^4)$$

$$c_e(f_e) = 3(1+.15(f_e/2000)^4), \; c_f(f_f) = 3(1+.15(f_f/2500)^4),$$

$$c_g(f_g) = 4(1+.15(f_g/2500)^4).$$

The Yin and Lawphongpanich (2006) Network

The lengths of the links, in kilometers, in turn, which are needed to compute the environmental emissions are given by:

$$l_a = 8.0,\ l_b = 9.0,\ l_c = 2.0,\ l_d = 6.0,\ l_e = 3.0,\ l_f = 3.0,\ l_g = 4.0.$$

Table: Total Emissions Generated (grams/hour) and Environmental Impact Indicators for Varying Degradable Capacities for the Yin and Lawphongpanich (2006) Network

γ	TE^{γ}_{U-O}	EI^{γ}_{U-O}	$TE^{\gamma}{}_{S-O}$	EI^{γ}_{S-O}
1.	26,744.62	.0000	27,140.19	.0000
.9	27,336.24	.0221	27,565.00	.0157
.8	27,982.55	.0463	28,045.61	.0334
.7	28,820.11	.0776	28,753.98	.0595
.6	30,291.05	.1326	30,162.84	.1114
.5	33,874.37	.2666	33,758.30	.2438
.4	45,033.94	.6839	44,970.11	.6570
.3	88,964.12	2.3364	88,943.63	2.2772
.2	355,639.84	12.2976	355,636.28	12.1037
.1	5,351,015.00	199.0782	5,351,016.50	196.1621

Figure: Ratio of TE^{γ}_{U-O} to $TE^{\gamma}{}_{S-O}$ for the Yin and Lawphongpanich (2006) Network

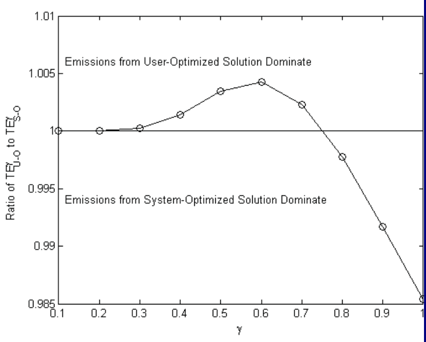
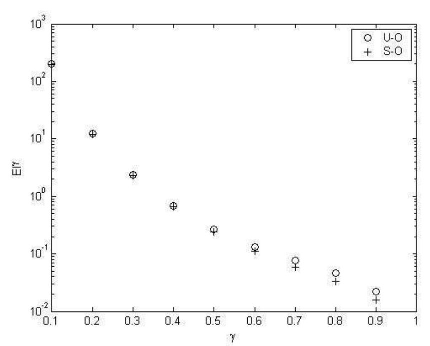
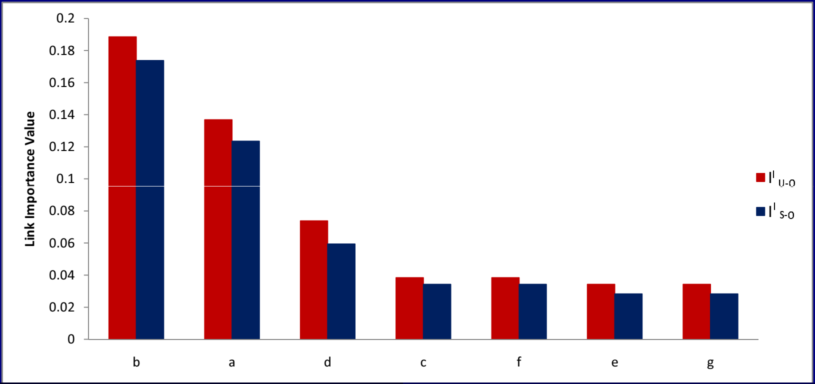


Figure: Plot of EI^{γ}_{U-O} and EI^{γ}_{S-O} for the Yin and Lawphongpanich (2006) Network

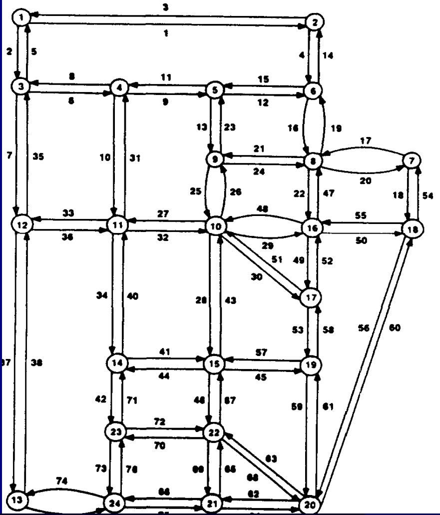


Link Importance

Figure: Link Importance Values and Rankings Under U-O and S-O Behavior for the Yin and Lawphongpanich (2006) Network



The Sioux Falls Network (Friesz et al. (1994))



There are 528 O/D pairs, 24 nodes, and 76 links in the Sioux Falls network.

Algorithms

- The projection method (cf. Dafermos (1980) and Nagurney (1999)) with the embedded Dafermos and Sparrow (1969) equilibration algorithm (see also, e.g., Nagurney (1984)) and the column generation algorithm (cf. Leventhal, Nemhauser, and Trotter (1973)) were utilized to compute the equilibrium solutions.
- Based on the equilibrium solutions, the total emissions under U-O and S-O flow patterns were determined and the environmental impact assessment indices were computed.

Table: Total Emissions Generated (grams/hour) and Environmental Impact Indicators for Varying Degradable Capacities for the Sioux Falls Network

γ	TE^{γ}_{U-O} ($\times 10^6$)	EI^{γ}_{U-O}	$TE^{\gamma}{}_{S-O}$($\times 10^6$)	EI^{γ}_{S-O}
1.	2.2323	.0000	5.2578	.0000
.9	2.5964	.1636	7.2030	.3700
.8	3.2447	.4542	10.6592	1.0273
.7	4.4820	1.0087	17.2023	2.2717
.6	7.0677	2.1675	30.7401	4.8466
.5	13.1320	4.8854	62.3732	10.8631
.4	30.0623	12.4720	150.5202	27.6279
.3	92.0500	40.2540	473.1643	88.9920
.2	460.5401	205.3999	2390.7321	453.6959
.1	7348.6102	3292.4000	38235.1022	7271.0529

Figure: Ratio of TE^{γ}_{U-O} to TE^{γ}_{S-O} for the Sioux Falls Network

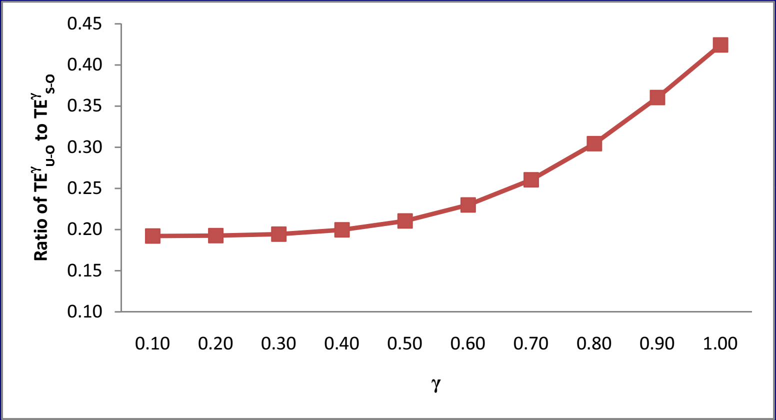
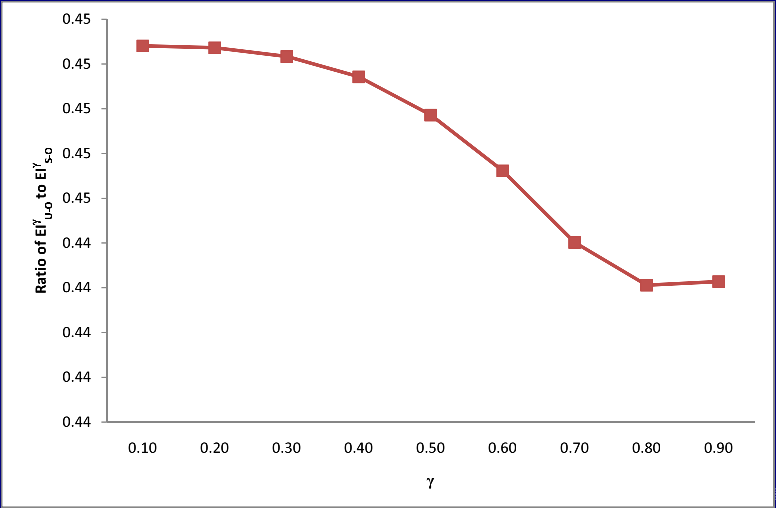


Figure: Ratio of $\mathrm{EI}_{U-O}^{\gamma}$ to $\mathrm{EI}_{S-O}^{\gamma}$ for the Sioux Falls Network



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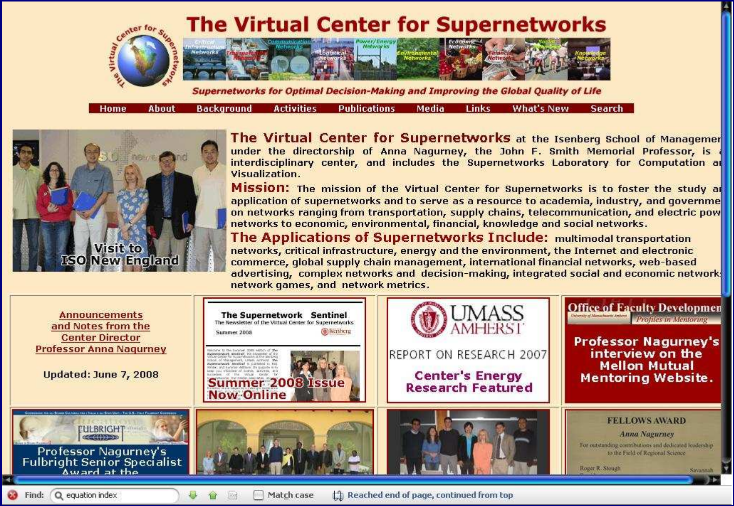
- We proposed environmental impact assessment indicators that allow one to determine the environmental impacts of the degradation in transportation network link capacities.
- The proposed indicators can evaluate the impacts associated with either U-O behavior or S-O behavior.
- We illustrated through numerical examples that there may be ranges of link capacity deterioration for which U-O behavior yields lower emissions than S-O behavior and vice versa.
- We also proposed link importance indicators that allow for the evaluation of the impact on environmental emissions if a link deteriorates to such a degree that it is no longer usable.
- Further research should include the extension of the results in this paper to multimodal transportation networks and multiple pollutants as well as theoretical and computational sensitivity analysis studies.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