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ORIGINAL PAPER

A bid-rent land-use adaptation model for mitigating road network vulnerability and traffic emissions

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Abstract Disruptions of vulnerable links in transportation networks have been widely recognized as a serious safety issue, generating both traffic congestion and significant traffic emissions. This paper aims to consolidate a proposed land-use adaptation (LUA) strategy into transportation vulnerability assessment, quantitatively exploring the question about how to optimize spatial patterns in long-term land-use planning to improve network reliability, protect existing vulnerable links and critical locations, and reduce traffic emissions. To mitigate regional network vulnerability, the LUA model employs the bid-rent theory to describe the agents' behaviors in the land market. Using the genetic and frank-wolf algorithms, this paper analyzes the relationship between link vulnerability and geographical distribution of land-use patterns. The amount of traffic-related CO emissions is used to evaluate the environmental impacts of the vulnerable link closure. The case study indicates that the long-term LUA strategy at land-cell level effectively reduces road network vulnerability, significantly improves the performance of existing urban road systems, and reduces traffic emissions. The model results also show that road networks tend to become more vulnerable with an increase in travel demand. Furthermore, without considering accessibility reduction caused by vulnerable transportation links, the land-use development is more likely to make the existing vulnerable links more susceptible. The proposed LUA methodology could allow urban system managers and planners to take proactive actions, thereby mitigating negative environmental impacts caused by network disruptions rather than being obliged to react to them.

Keywords Land-use adaptation model · Vulnerability · Bid-rent theory · Traffic emissions

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Introduction

For resilient and sustainable urban development, mitigation of road (transportation) network vulnerability has been considered as an important research topic (Berdica 2002). The degradation of vulnerable links in road networks could result in accessibility reduction and significant travel time delay. For instance, the American Road and Transportation Builders Association (ARTBA) states that nearly 75 % of freight transportation in the USA is carried on vulnerable links (e.g., highways and traffic bottlenecks) that cause truckers about 243 million hours of delay annually (Cambridge Systematics 2005; Nagurney et al. 2010). The degradation of vulnerable links directly affects the future land-use development and environmental emissions. This is because transportation accessibility is an important factor that influences land-use development. Furthermore, the resulting travel time delay causes remarkable traffic emissions. On the other side, land-use development patterns shape the travel demand in road networks, which is one of the determining factors of network vulnerability and traffic emissions (Trucco et al. 2012). Therefore, exploring the role of network vulnerability in an integrated land-use and transportation framework is critical for making road networks less vulnerable to disruption, thereby reducing the total travel time delay and mitigating traffic emissions.

Most of network vulnerability-related studies focus on identifying critical links, including certain evaluation criteria and full network scan approach (Jenelius et al. 2006; Scott et al. 2006). Based on a simple assumption that land-use variables are constant, some studies used indicators of accessibility as the evaluation criteria to rapidly identify the most vulnerable sections in a large-scale network (Berdica 2002; Lu and Peng 2011; Taylor 2008; Tampere et al. 2008). However, these criteria cannot evaluate the spatial–temporal effects of land-use development on vulnerable links. Compared with the evaluation criteria method, the full network scan method provides a complete simulation analysis, but requires a traffic assignment for each link closure which is computationally burdensome. In response, "impact area"- and "sub-networks"-based vulnerability analysis approaches have been developed to reduce the search space and time of traffic assignments (Chen et al. 2012; Knoop et al. 2008).

Once vulnerable links are identified, various approaches have been developed to mitigate road network vulnerability. From a practical viewpoint, transportation modelers more favor the change of service as means, such as building new alternative links, removal of vulnerable links and detouring traffic flows, adopting policies to avoid problematic areas, and incorporating adequate road design (Matisziwa and Murraya 2009; Chen et al. 2012; Keller 2002). Although these existing approaches aim to mitigate the vulnerability from a transportation angle, they fail to connect transportation with land use that fundamentally generates travel demand.

Many integrated land-use and transportation models have been developed for coordinating the development of urban land use and transportation, optimizing spatial resource allocation, and improving air quality (Iacono et al. 2008; Dur and Yigitcanlar 2014; Yigitcanlar and Teriman 2014; Zhao and Peng 2010). It is well believed that substantial degradation in road networks will reduce accessibility, depreciate the real estate property in critical locations, and eventually affect the location choice of household, employment, and developers in the land market. In this study, an agent-based framework is used to capture the location choice behavior of household, employment, and developers in the land market. Agents-based models describe the influence of human's decision-making on land use in a mechanistic, formal, and spatially explicit way, taking into account social interaction, adaptation, and decision-making at different levels (Matthews et al. 2007; Lambin and Geist 2006). To model the land-use market, the bid-rent theory assumes that the market follows an auction mechanism which assumes the land will be developed by the highest bidder (Martinez 1996; Martinez and Henriquez 2007; Zhao and Peng 2012).

By combining the bid-rent theory and agent models, this paper proposes an integration of land-use adaptation (LUA) strategy in transportation vulnerability assessment. It aims to explore the question of how to optimize spatial patterns in long-term land-use planning to improve network reliability and protect both existing vulnerable links and critical locations. Furthermore, the relationship between network vulnerability and traffic emissions is investigated, as well as the efficacy of reducing traffic emissions by the LUA model. First, both link vulnerability and measurement of regional network vulnerability will be defined. Second, the agents' location choice behaviors are captured with vulnerability consideration. The LUA model is developed based on the bid-rent theory and agents behaviors. Then, the environmental impacts of the degradation of vulnerable link are assessed. By a designed algorithm, the analysis of spatial–temporal LUA planning, network performance, and environmental impacts is conducted by comparing two scenarios: (1) a base land-use scenario without considering the accessibility reduction caused by vulnerable transportation links, and (2) a land-use scenario that adapted land-use pattern from the proposed model. This study was conducted in both Gainesville, Florida, USA, and Wuhan, Hubei Province, China, in 2013.

Materials and methods

Link vulnerability

As it may result in link failure that has potential, adverse socioeconomic impacts on the community, link vulnerability can be defined in the following terms: A network link is critical if loss of the link significantly diminishes the accessibility of the network (Taylor and D'Este 2007). Identifying an effective approach to calculate the vulnerability index for road networks is useful for the purpose of road management, and assessment of regional or local effects of varying degrees of vulnerability (Husdal 2006). To connect the vulnerability with agents' behaviors in the land-use development, this paper focuses on the change in the generalized cost of travel between two locations if a given link fails.

We denote the generalized cost of travel from origination node r to demand destination node s when link a has failed by $c_{rs}^{(a)}$, representing the cost of the initial network without disruptions. All travelers are assumed to follow the user equilibrium principle, which implies they choose a route from origination to destination that minimizes their travel cost. The generalized cost $c_{rs}^{(a)}$ is the overall assessed cost of travel for specific OD pair and is taken as the network travel cost under user equilibrium condition. This means the value of $c_{rs}^{(a)}$ is uniquely defined.

The consequences of the link a closure can be evaluated by the relative change in network efficiency. Usually, the network efficacy is measured by the travel time savings over the entire work between all demand nodes, or weighted travel demand. For the sake of land-use-related analysis, the latter method is adopted, which is measured by summing the time difference for each OD demand (q_{rs}) across all individual links and dividing that sum by total demand. The demand weighted link vulnerability can be defined as follows:

$$V_a = \frac{\sum_r \sum_s q_{rs}\left(c_{rs}^{(a)} - c_{rs}^{(0)}\right)}{\sum_r \sum_s q_{rs}} \tag{1}$$

Regional network vulnerability

Regional network vulnerability is a measurement of how the total efficiency of road transport system is affected by road closures in the region in question. It expresses how dependent the whole road transport system is on the region. In this paper, the measurement of regional vulnerability is originated from the idea of "regional exposure" (Jenelius et al. 2006). We calculate the expected effects for all users of transportation system of each link disabled sequentially in the region. The vulnerability of the whole region can be formulated as follows:

$$R_V = \frac{\sum_a p_a \sum_r \sum_s q_{rs}\left(c_{rs}^{(a)} - c_{rs}^{(0)}\right)}{\sum_r \sum_s q_{rs}} \tag{2}$$

where w_a denotes the closure probabilities, defined by the length of the links and probability of being affected by the casual accidents (e.g., weather, storm, traffic accidents). p_a denotes the probability that the link a in question is cut by casual events which are extremely small but not zero since they have happened.

Bid-rent-based agents' behaviors in the land market

Inevitably, the substantial degradations in road networks result in accessibility loss and property depreciation. Property owners collectively make decisions to maximize the largest positive difference between expected reductions in property values and their costs. Decision-making behavior of household, employment, and developer agents plays a leading role in land-use market. Household and employment are considered as the demand side, whereas developer agent constitutes the supply side in the land-use market. The land market equilibrium is achieved via the bid-rent theory. In this section, we consider that agents choose the location responding to spatial characteristic, travel cost, and property depreciation under the risk of the built environment affected by substantial degradation in the road network and surrounding area. In order to spatially produce more accurate LUA strategy, the geographic area is further divided into small grid cells. Under the bid auction processes, through presenting agents' perspective on road network vulnerability, the willingness-to-pay function of type h household choosing location i in land type k (including residential, industrial, commercial and service, and institutional) can be formulated as follows:

$$B_{ik}^{h} = -D_{ik}(R_V) - b_{hk} + E_{hik} - \sum_{p} N_h^p \varphi_{hik}^p(t) \tag{3}$$

where D_{ik} refers to the potential property depreciation under substantial degradation in the road network, denoted by a function of the regional network vulnerability of the impact area where the cell i is located. For simplicity, the impact area for cell i is its located and adjacent traffic analysis zones (TAZs). b_{hk} denotes the monetary disutility bid for agent of type h according to their baseline affordability. E_{hik} represents how agents value the environment attributes of location i, including neighborhoods characteristics, open resources, and school accessibility. With the consideration of vulnerability, the transportation accessibility denoted as the last term in Eq. (3) is generated from the degraded network with closure of vulnerable links. It is calculated under different trip purposes p for location i, where N_h^p denotes the number of trips with purpose p. $\varphi_{hik}^p(t)$ represents the expected travel cost that can be calculated based on $c_{rs}^{(a)}$. Usually, the households agent are sensitive to the risk of vulnerability for more trips and travel cost.

Assuming the bid function as a random variable following a IId Gumbel distribution with dispersion parameter θ, the bid probability, and $\mathrm{Pr}_{ik}^{h,\mathrm{bid}}$, that the agent h is the highest bidder for location i can be formulated as follows:

$$\mathrm{Pr}_{ik}^{h,bid} = \exp\theta\left(B_{ik}^h\right) / \sum_h \exp\theta\left(B_{ik}^h\right) \tag{4}$$

In the auction side, the location in the supply side is assumed to offer the agents with the highest payment;

therefore, we can induce the rent of location r_{ik} by the expected highest bid. For agent h, the location yields the largest positive difference between bidding price and rent is chosen. Same as the assumption of bid probability, the choice probability can be denoted by the following:

$$\Pr_{ik}^{h,cho} = \exp\theta\left(B_{ik}^h - r_{ik}\right) / \sum\nolimits_i \exp\theta\left(B_{ik}^h - r_{ik}\right) \quad (5)$$

In the bid-rent land market, the spatial allocation of agents is based on the choice probability, while the land supply is based on the bid probability. When all agents are located with the land development, the land market achieves equilibrium.

Land-use adaptation (LUA) model

Most current, existing solutions to vulnerability mitigation and critical location protection focus only on improving transportation network while ignoring the interactions between transportation and land use. In this section, the LUA model is used to quantitatively explore how to optimize spatial patterns in the long-range land-use planning to improve network reliability, protect existing vulnerable links, and protect critical locations. For sustainable land-use development, an optimal strategy should consider both mitigation of entire network vulnerability and reflect the authenticity in the land market. The LUA model is developed as follows:

$$Z = \min_{(x_{ik},N_{ik},b,r)} \left(\varpi R_{V,i} + \sum_h N_{ik}^h b_{hik} + \sum_{i\in\Omega_0} \sum_k x_{ik} S_{ik} r_i + \frac{1}{\theta} \sum_h \sum_{i\in\Omega_0} \sum_k x_{ik} \exp(\theta(B_{hik}(b_{hik}) - r_{ik})) \right) \quad (6)$$

$$\text{s.t} \quad \mathrm{x_{ik}} = 0 \text{ or } 1 \text{ and } \sum_{\mathrm{k}} \mathrm{x_{ik}} \le 1 \quad (7)$$

$$\sum_i N_{ik} = N_k \quad (\forall k = 1,\ 2,\ 3,\ \text{and } 4) \quad (8)$$

where output $t_{rs}(0) = \bar{t}_{rs}(T)$ denotes whether cell i will be developed into land type k, which represents the long-term land-use development strategy. $R_{V,i}$ is the regional network vulnerability of location i for the whole study area explained in Eq. (2). ϖ is a penalized variable to make the measure of regional network vulnerability to be consistent with the outcome of the real estate market considering individual agent's benefit. S_{ik} denotes the supply of type k land in cell i. The combined last three items are equivalent to the bid-rent-based theory in the real estate market. The optimal conditions indicate the achievement of the bid-rent land-use equilibrium when all agents are located, namely $N^h = \sum_i \sum_k N_{ik}^h$. The following equation can be deduced from the optimal conditions

$$N_{ik}^h = N_k^h \frac{x_{ik} \exp(\theta(B_{hik}(b_{hk}, t) - r_{ik}))}{\sum_i \exp(\theta(B_{hik}(b_{hk}, t) - r_{ik}))} = x_{ik} N_k^h P_{ik/h} \quad (9)$$

$$N_{ik}^h = \frac{x_{ik} S_{ik} \cdot \exp(\theta B_{hik})}{\sum_h \exp(\theta B_{hik})} = x_{ik} S_{ik} P_{h/i} \quad (10)$$

Both Eq. (9) and (10) represent the equilibrium between the supply and demand side based on the bid-rent theory, which is consistent with Eqs. (4) and (5).

Interactions between the LUA Strategy and Travel Demand

To quantify the regional network vulnerability R_V and B_{ik}^h in Eqs. (2) and (3), the travel cost $c_{rs}^{(0)}$ and $c_{rs}^{(a)}$ can be calculated from the user equilibrium (UE), expressed by the following programming problem (MJ et al. 1956).

$$\min Z = \sum_a \int_0^{f_a} c_a(v) dv \quad (11)$$

$$\sum_l f_l^{rs} = q_{rs}, \quad \forall r, s \quad (12)$$

$$f_l^{rs} \ge 0, \quad \forall r,\ s,\ l \quad (13)$$

$$f_a = \sum_{rs} \sum_l f_l^{rs} \delta_{a,l}^{rs} \quad a \in A \quad (14)$$

where a is the link in the transportation network and A is a set of all studied links. f_a is the flow on link a. $\delta_{a,l}^{rs}$ equals to 1, if link a belongs to path l which is between the OD pair rs. The Bureau of Public Roads (BPR) function (Hamdouch et al. 2007) can be used to calculate the link travel time $c_a(v)$. The generalized travel cost, $c_{rs}^{(0)}$, can be calculated by the sum of $c_a(v)$ over links belonging to the route between OD pair rs.

Both land-use spatial patterns and agents' location choice results from LUA determine the new travel demand distribution, which is the input variable for the VI user equilibrium. The travel demand produced by different land-use patterns is calculated using a logit-based model. For agents of type h in TAZ r, the utility of chosen TAZ s as destination of a trip with purpose p, denoted by U_{hr}^{sp}, consists of two parts: (a) distance dis_{rs} and (b) the attractiveness of TAZ s, ψ_{sp}, which could be a function of the area of land types that can provide service for trip purpose p in TAZ s. Assuming the utility U_{hr}^{sp} follows the IId Gumbel distribution with dispersion parameter $\tilde{q}_{rs}(T)$, the probability that agent of type $N_h(T)$ choose TAZ r as a destination with trip purpose p can be formulated as

$\exp(\phi \cdot U_{hr}^{sp}) \Big/ \sum_s \exp(\phi \cdot U_{hr}^{sp})$. The total travel demand q_{rs} can be deduced as follows:

$$q_{rs} = \sum_h \sum_p \frac{N_r^h M_h^p \cdot \exp(\phi \cdot U_{hr}^{sp})}{\sum_s \exp(\phi \cdot U_{hr}^{sp})} \quad (15)$$

where N_r^h means the number of type h agents in TAZ r, and $N_r^h = \sum_k \sum_{i \in r} N_{hik}$; M_h^p denotes the trip rates for trip purpose p. From the model inputs and outputs aspect, travel demand q_{rs} is a necessary input to calculate the travel cost using UE method and further generate the regional network vulnerability, while the variable N_r^h, and the attractiveness of TAZ, ψ_{sp} (second part of utility function U_{hr}^{sp}), could be updated from LUA.

Environmental impacts of vulnerable link closure

The degradation of vulnerable links causes significant travel time delay, which results in additional traffic emissions and further impacts negatively the environment. It will be important and challenging to explore the relationship between vulnerable links and traffic emissions, as well as to examine the efficiency of the proposed LUA model on environmental improvement. In this section, to evaluate the environmental effects of vulnerable links, we conduct a quantitative comparison of traffic emissions from both the degraded network with the closure of vulnerable links and normal transportation networks.

CO emission (g CO/h) has been regarded as an important indicator for evaluating the degree of atmospheric pollution generated by vehicular traffics (Alexopoulos et al. 1993; Yin and Lawphongpanich 2006; Wang et al. 2013). In this paper, to investigate the relationship between network vulnerability and traffic emissions, estimation of total CO emissions from transportation networks uses the same equation that has been applied in transportation software (Wallace et al. 1998):

$$Em = \sum_a f_a \cdot 0.2038 \cdot c_a \cdot e^{0.7962(L_a/c_a)} \quad (16)$$

where f_a is the flow on link a, which can be calculated from the UE problem. c_a denotes travel time on link from BPR function when it carries flow f_a. L_a is the length of link a in kilometers. To explore the relationship between link vulnerability and traffic emission, the environmental impact (Im_a) of the degradation of each link in transportation network is estimated as follows:

$$Im_a = Em^{(a)} - Em^{(0)} \quad (17)$$

where $Em^{(0)}$means the total CO emissions from normal transportation network, while $Em^{(a)}$ denotes those from the degraded network with closed link a. If the environmental impact value $Im_a > 0$, the amount of CO emissions in degraded network is larger than those in the normal network. The higher the value of Im_a is, the more negative environmental impact of the closure of link a will have.

Algorithm design

A combination of genetic algorithm (GA) algorithm, the bid-rent-based equilibrium loop, and Frank-Wolf algorithm is used to solve the model. For LUA, the land development variable x_{ik} is a 0–1 vector, which is handily implemented in the genes encoding via the genetic algorithm. The bid-rent equilibrium can be achieved by the loop algorithm (Briceño et al. 2008). The algorithm flowchart is designed as Fig. 1 to (1) identify the most vulnerable links and calculate the accessibility of degraded network and regional network vulnerability in the willingness-to-pay function; (2) solve the LUA strategy using GA and produce the travel demand based on the current land pattern; (3) update the travel time and network vulnerability according to the new travel demand and verify the end condition; and 4) repeat this process until the optimal LUA strategy is achieved.

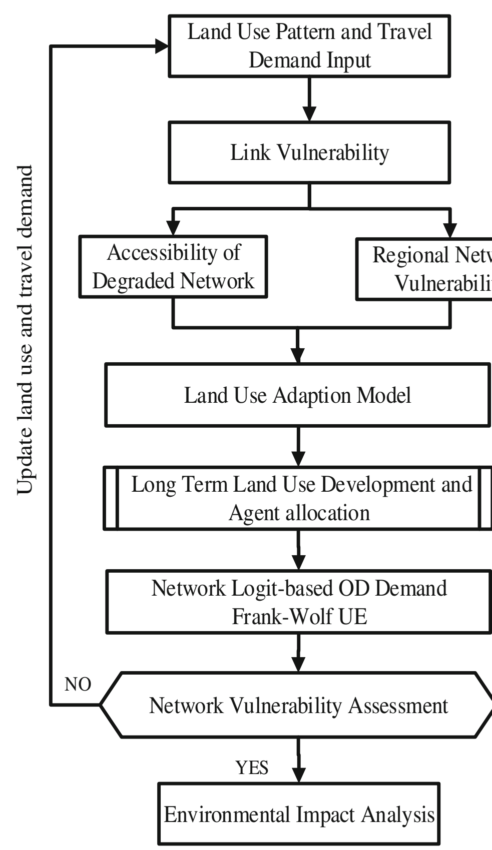


Fig. 1 Flowchart of algorithm for the proposed LUA model

Step 1 Initialize inputs of land-use types ($T = 0$) using a matrix *Land* (T) representing the raster-based land-use GIS data. Define the impact area for each cell i. Input transportation network G (including link, node, free flow travel time, and capacity), and initialize travel demand $q_{rs}(T)$, iteration time $m = 1$, and year $T < T_{end}$. Solve the UE problem using Frank-Wolfe algorithm under the normal network G, based on the travel demand $q_{rs}(T)$ to calculate travel zonal cost $c_{rs}^{(0)}(T)$;

Step 2 Calculate link vulnerability $V_a(T)$: According to $q_{rs}(T)$, $\forall a \in A$, delete each link a sequentially, solve the UE problem in the network $\bar{G}_a$ to calculate $c_{rs}^{(a)}(T)$, calculate the link vulnerability $V_a(T)$, delete most vulnerable link, and calculate transportation accessibility of degraded network. Get the regional vulnerability R_V, accessibility under degraded network, and spatial environmental attributes E_{hik} for each vacant cell. Update the bid function for each agent

Step 3 Generate the optimal LUA strategy using GA. Input the land-use demand $N_k(T)$, the number of population *Npop*, and the probability of cross and mutation. Initiate the feasible solutions of land development $pop = \{[x_{ik}]\}$. For each $[x_{ik}]$, implement the bid auction process and calculate the fitness function via $fit([x_{ik}]) = 1/Z$. Use the choosing, breeding, and mutation process in GA according to $fit([x_{ik}])$. If the desired iteration time is reached or max $fit([x_{ik}])$ falls within a desired error ε_1, the iteration loop will be terminated. Output the optimal solutions of $[x_{ik}]$, b_{hk}, r_{ik}, and N_{ik}^h; otherwise, repeat *Step 3* based on the best land allocation strategy population

Step 4 Check the termination condition. If the objective function $Z^{(m)} - Z^{(m-1)} \leq \varepsilon_2$ is satisfied, calculate the environmental impacts, set $T = T + 1$, and update $q_{rs}(T)$, *Land* (T) according to $[x_{ik}]$, when $T < T_{end}$, go to *Step 1*; otherwise, update $q_{rs}(T)$, go to *Step 2*, and continue searching the best land strategy for year T

Results and discussion

A simulated urban area is used for the case study. Figure 2 shows the land-use development and transportation network for the initial year $T = 0$. To better examine the effects of the LUA strategy on mitigating network vulnerability, cell level land-use size is adopted at small level. In the study area, there are 225 cells, 9 TAZs, and 24 links. Based on the developed LUA strategy, vacant cells will be developed from year $T = 0$ to year $T = 3$. It is supposed that the cell number of each land type k for each year is assumed as 10, 10, 8, and 5, and the maximal land supply (developer agent) of each cell (S_{ik}) is assumed as 100. The number of agents $\left(N_r^h\right)$ located in the study area for each year is 1000 household agents, 1000, 800, and 500 employment agents for $k = 1, 2, 3$, and 4, respectively. The value of M_p^h for each trip type (work, shopping, and school) is (5, 4, 3), (5, 1, 0), (3, 5, 0), and (1, 0, 5), respectively, for agents type h. For simplicity, the logit parameters θ and ϕ are taken as 1. The environment attributes E_{hik} in Eq. (3) is calculated as the number of the corresponding land types in its Moore neighborhood (eight cells surrounding a central cell) of cell i.

Land-use adaptation strategy analysis

To assess the impacts of the LUA strategy on mitigating transportation network vulnerability, basic scenario and adaptation scenario are compared. Basic scenario undertakes the accessibility in normal network as the input of land-use development and ignores all impacts of network vulnerability. Adaptation scenario is the optimal results produced from the LUA strategy. Both *Matlab 9.0* and *ArcGIS 10.1* are used as implementing tools. By the designed algorithm, Fig. 3 shows the land-use patterns from two scenarios for $T = 0$, 1, 2, and 3. Intuitively, the basic scenario is more like cluster development, while the adaptation scenario is dispersed in the study area. For each TAZ, the land-use types in the adaptation scenario are more mixed, whereas the same land types are more agglomerate in the basic scenario.

Agents location choice and LUA strategy

To investigate the effects of LUA on the agents' location choice with vulnerability consideration, the most vulnerable links and their corresponding land-use strategy were identified. The five most vulnerable links for the adaptation scenario are shown in Table 1 for each year. For the initial year, most vulnerable links fall into TAZs 1, 4, and 5. In the LUA strategy, for the next year in Fig. 3b, only two new residential cells are developed in these three TAZs, whose development is clustered near existing residential cells. It is because the household is more sensitive to the accessibility loss and property depreciation caused by substantial vulnerable transportation networks. In TAZ 1, several industrial and service lands are developed because these employment agents are less sensitive, and their existing surrounding residential cells bring more profits.

Fig. 2 Initial land use and transportation network for year $T = 0$

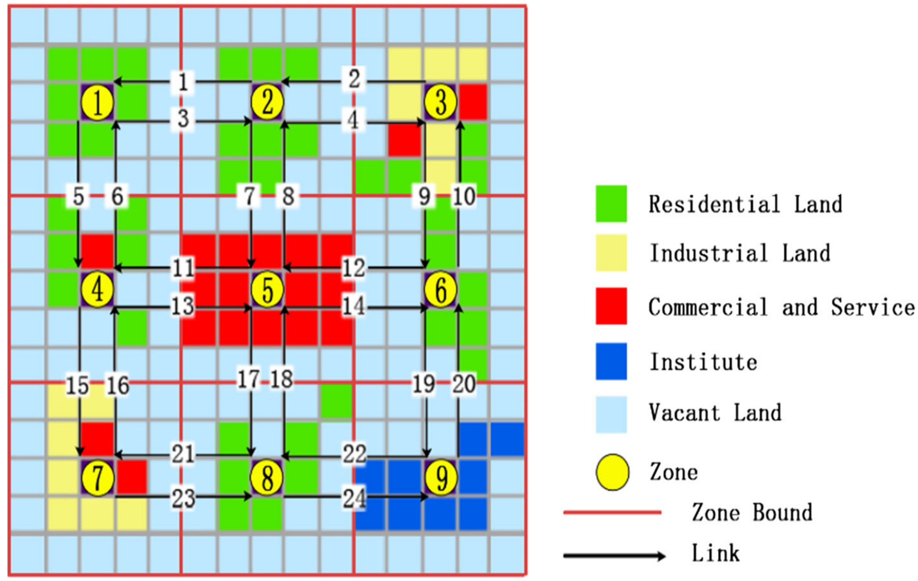
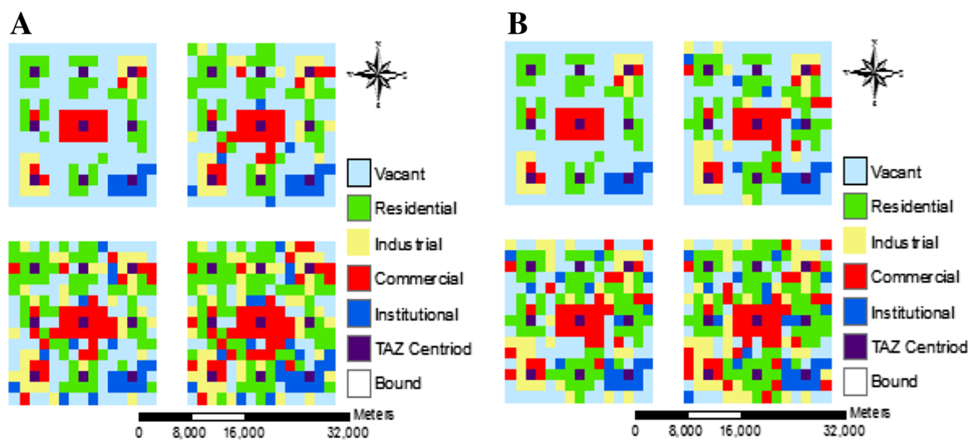


Fig. 3 The land-use patterns for two scenarios for year $T = 0, 1, 2, 3$: **a** Basic scenario; **b** adaptation scenario



Link vulnerability analysis

To examine the effects of different land-use patterns on link vulnerability, Fig. 4 shows the single link vulnerability for both scenarios over four periods ($T = 0$, 1, 2, and 3). For both scenarios, along with land development and increase in travel demand, it is obvious that the average of link vulnerability becomes higher. For instance, in the adaptation scenario, the maximal vulnerable value for $T = 0$ equals 0.83 for Link 5, while for year $T = 3$, all link vulnerability falls in the interval (0.89, 19.24). This shows that road links tend to become more vulnerable with an increase in travel demand.

In road networks, lower values of link vulnerability indicate better performance/reliability. For each link, the values of link vulnerability are much lower in adaptation scenario than those in the basic scenario. In Fig. 4, the highest link vulnerability in adaptation scenario is 19.24 for Link 4, whereas in the basic scenario, it reaches 71.69 for Link 9. This implies that the LUA strategy could significantly mitigate the link vulnerability. In the basic scenario, the link vulnerability increases sharply over time, especially for those vulnerable links. In contrast, the increase of link vulnerability in adaptation scenario appears much gentle, and the most vulnerable links can be protected even in the worst case. The most vulnerable links over years are different in adaptation scenario, as shown in Table 1, which are links (5,13,11), (19 24 5), (4,10,14), and (9, 2,4) for each year, respectively. The results for basic scenario indicate that without considering the vulnerability index, the land-use development is more likely to make the vulnerable link worse. In the adaptation scenario, the critical links can be protected from being more vulnerable.

Regional vulnerability and transportation performance

Land-use pattern determines travel demand that is reflected in the transportation network performance. To explore the relationship of the LUA strategy with transportation

Table 1 The five most vulnerable links for adaptation scenario

Vulnerable links	$T = 0$		$T = 1$		$T = 2$		$T = 3$	
	Link #	TAZ#	Link #	TAZ#	Link #	TAZ#	Link #	TAZ#
1	5	1, 4	19	6, 9	4	2, 3	9	3, 6
2	13	4, 5	24	8, 9	10	3, 6	2	2, 3
3	11	4, 5	5	1, 4	14	5, 6	4	2, 3
4	7	2, 5	14	5, 6	13	4, 5	19	6, 9
5	15	4, 7	22	8, 9	7	2, 5	10	3, 6

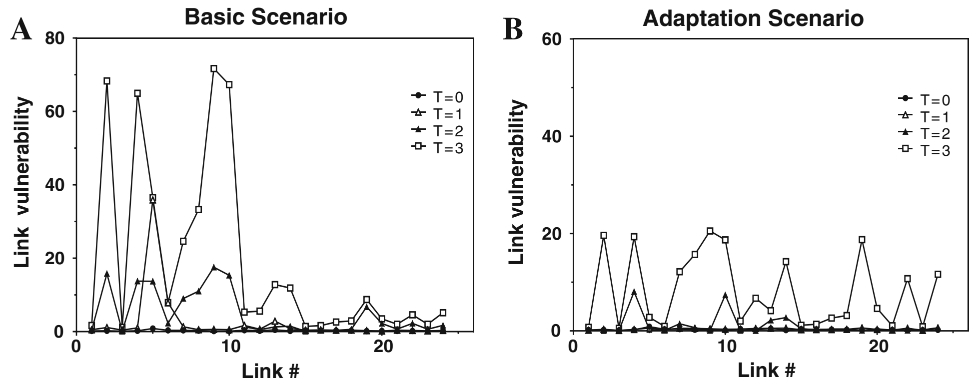


Fig. 4 Comparison of link vulnerability. **a** Basic scenario; **b** adaptation scenario

performance, the transportation system cost is measured by a sum of the products of OD demand and the travel cost in transportation networks. Figure 5 compares the transportation system cost and the calculated regional vulnerability (Eq. 4) between the base and adaptation scenario over time $T = 1$, 2, and 3. The comparison suggests that the regional vulnerability for the adaptation scenario is much lower than that in the basic scenario, whereas there is no significant difference in transportation system cost for both scenarios. In particular, for years $T = 2$ and 3, the transportation system for both scenario is nearly identical. Based on the above results, we may safely make the conclusion that transportation network reliability can be enhanced without many increases in transportation system costs by only adjusting the land-use spatial distribution.

In the light of the above analysis, a quantitative understanding in network vulnerability indicates that the use of the LUA strategy in the long-term design and planning of land use helps road networks less vulnerable to disruptions. Rather than solely relying on building roads or closing vulnerable links that are directly associated with transportation networks, land-use patterns are also important in accounting for mitigation of link vulnerability, as demonstrated by the LUA model.

Link vulnerability and traffic emissions

For the LUA scenario, Fig. 6a) presents the simulation results of environmental impacts over time ($T = 0$, 1, 2, and 3). For all links during this period, the findings show that environmental impact value $Im_a > 0$, indicating that the link closure will cause worse traffic emissions. For instance, in year $T = 3$, CO emissions from the network with Link 4 closure is 71,882 g CO/h higher than that in normal network. The environmental impacts tend to be more serious with an increase in travel demand/population over time. Some high vulnerable links have significant environmental impacts. For example, as shown in Fig. 4b), links 4 and 10 are among the five most vulnerable links. In year $T = 3$, the degradation of links 4 and 10 results in additional CO emissions of 77,882 and 63,857 g CO/h, respectively. So, mitigating vulnerability of the whole transportation network can reduce environmental impacts of vulnerable links degradation.

In urban areas, the land-based methodologies have been regarded as the most viable approach for emission reduction (Liao et al. 2013). To examine the efficiency of the LUA strategy on mitigation of traffic emissions, CO emissions from different land-use patterns are calculated by Eq. (16) for two scenarios (Fig. 3). Figure 6 b) shows CO emissions for the basic and LUA land-use patterns over 3 years. With the increase in travel demand/population, total CO emissions increase within the designed road network. In the LUA scenario, CO emission is less than that in the basic scenario. These results imply that mitigating network vulnerability by reallocating spatial distribution of land use via the proposed LUA model is also effective for reduction of CO emissions. Therefore, from the

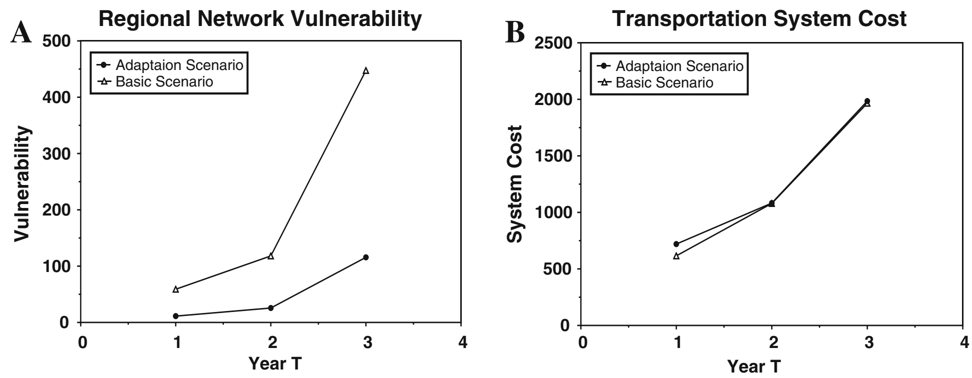


Fig. 5 Comparison of basic and LUA scenarios. **a** Regional network vulnerability; **b** transportation system cost

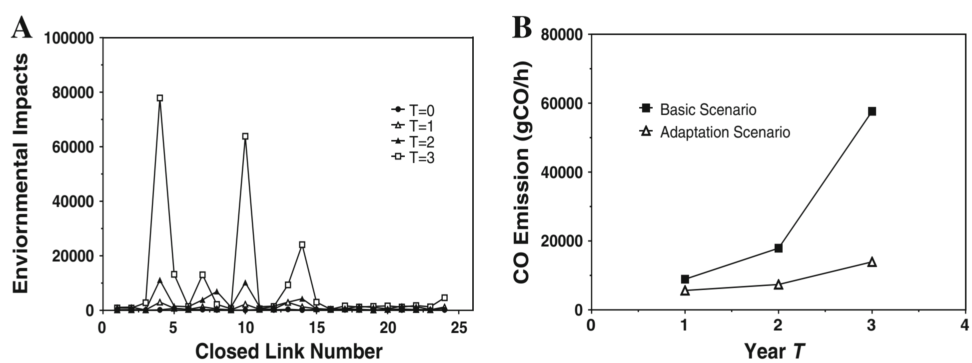


Fig. 6 Environmental impacts numerical results. **a** Environmental impacts of link closure; **b** traffic emissions for both scenarios

environmental viewpoint, land-use planning is important and effective for reduction of traffic emissions, thereby improving air quality and achieving environmental protection.

Conclusion

This paper develops the LUA model to rationalize the spatial–temporal interactions between long-term land-use development and transportation network vulnerability, thereby mitigating network vulnerability and reducing traffic emissions. From the viewpoint of integrated land use and transportation, the quantitative analysis of how the degradation/closure of vulnerable links plays an important role in traffic emissions provides a novel angel to supplement the traditional environmental assessment. Stemming from integrated modeling land use and transportation, the LUA model takes in account of transportation accessibility, regional network vulnerability, and the bid-rent based agents' behaviors in the land market. The amount of CO emissions is used as an indicator for environmental assessment. A combination of genetic and Frank-Wolf algorithms is employed to numerically solve the LUA model.

The case study shows that the LUA optimized strategy can dramatically mitigate network vulnerability and reflect agents' bid-rent location choice considering the vulnerability impact. With the increase in land-use development, travel demand, and congestion level, the transportation network tends to become more vulnerable. The LUA findings suggest that the consideration of network vulnerability in the long-term land-use planning enhances the reliability and robustness of the investigated transportation networks, without additional investment in transportation system development. Moreover, mitigating vulnerability of the whole transportation network could reduce environmental impacts; therefore, the LUA optimized land-use patterns are capable of effectively and remarkably reducing traffic emissions.

The contributions of the paper are twofold. First, the proposed LUA model presents a quantitative understanding in the relationship between land-use patterns and transportation network vulnerability, which is a lack in the literature. A quantitative analysis of such relationship explores how to optimize spatial patterns in the long-range land-use planning to improve network reliability, protect existing vulnerable links, and protect critical locations. Second, the case study reveals how the produced spatio-temporal LUA strategy from the designed model and algorithm can mitigate network vulnerability, significantly improve network performance of the existing urban road system, and further reduce traffic emissions. For existing urban systems, the practical benefit is still a debate between changing land use and changing transportation system; however, this LUA model will help land-use planners to better manage the future land-use change for the purpose of protecting vulnerable links and critical locations, thereby achieving sustainable and reliable development for urban systems.

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