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Multi-agent programming to enhance resiliency of earthquake-prone old metropolitan areas by transit-oriented development under public-private partnership

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Deteriorated urban areas in large cities have poor living standards, are inaccessible and small-sized, and have unstable building structures. Earthquake hazards may turn such situations into human disasters. In most cases, neither the governments nor the owners of these properties have enough budgets for renovating them. The purpose of this paper is to take advantage of Transit Oriented Development concepts to simultaneously solve two major urban area problems: (a) renovation of deteriorated urban areas and prevention of urban sprawl, and (b) design of transit network and promotion of transit-oriented development to reduce traffic congestion, pollution, and other unwanted outcomes of the extensive automobile use in large metropolitan areas. This paper proposes a bilevel multi-agent programming in which each agent maximizes the respective benefits while being subjected to the results of the decisions by others. We formulate the problem and solve it by a novel meta-heuristic algorithm. After analyzing the set of solutions to a test problem, we apply the algorithm on this rather large, real case urban area, and discuss the results. The solution results indicate that the proposed methodology: (a) reduces the total travel time in transportation networks of the city, (b) turns the deteriorated urban developments into a new and attractive environment, (c) provides a profitable investment for the construction industries in the context of Build-Operate-Transfer scheme, and (d) upgrades urban life for the city in general, and alleviates earthquake hazards for the inhabitants of the deteriorated urban areas, in particular.

Keywords: *Transit-Oriented Development (TOD), deteriorated urban areas, Build-Operate-Transfer (BOT), earthquake hazards, meta-heuristic algorithms, transit network design.*

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1. Introduction

Metropolitan areas and seismic threats
Settlements along earthquake belts are highly at the risk of earthquake hazards. The Alpine-Himalayan Belt (Wikipedia, 2020) is one of the major earthquake belts, crossing many populous countries and cities in Europe and Asia, where the population centers originated several hundred (and even thousand) years ago. High population densities and conventionally built aged structures are two major vulnerability concerns of the developments, along such belts, that confront the danger of frequent high magnitude earthquakes. Iran is situated on (and rather surrounded by) this belt, having vulnerable large historical cities with considerable portions of masonry buildings that can barely withstand, if at all, a moderate earthquake (Moinfar et al, 2012).

Expansion of metropolitan areas
Yet, metropolitan areas in the world are expanding; London in Europe (Holden & Turner, 1997), Mexico city in America (Aguilar et al, 2003), and Beijing in Asia (Zhao, 2010). This could result in lower-density developments, which, in turn, results in lower urban services (due to limitation of resources) and could accentuate the dependency of citizens on automobiles. This, in turn, increases trip length, air pollution, and higher consumption of limited resources. For example, Beijing experienced a city expansion of 88% for a 38% population increase from 1990 to 2001, which resulted in lowering the population density from 157 to 115 persons/ha. Expansion of this city caused a 6.6% increase in auto trips, but only a 3.3% increase in transit trips during 2000-2005 (Zhao, 2010).

Auto vs. transit-oriented development
To prevent urban sprawl and to renovate the deteriorated urban areas, several approaches were employed in the first half of the 20th century. At first, these approaches were based on automobiles, which resulted in small towns with a lower cost of living around the mother metropolitan areas. These satellite towns were dependent on larger cities for their service needs and thus were connected to them by roads and highways. In the late 1980s, the negative outcomes of auto-oriented urban developments revealed higher usage of limited resources (land, fossil fuels, etc.), which were found to speed global warming trends. Hence, Transit Oriented Development (TOD) was proposed to prevent such negative aspects of the previous approach: traffic congestion, air pollution, and low-income city periphery developments (Carlton, 2009; Ziegler, 2009). This latter phenomenon caused many other urban problems, such as an increase in crime rate, urban environment degradation, and higher city running costs. Similar attempts in Iran, to curb urban development deterioration and population increase during the last four decades, were also based on auto transportation, ignoring public transportation, thus were not effective. While consuming much of the government budgets, they were not only unsuccessful to renovate the deteriorated sections of the large metropolitan areas (ISNA, 2018), but also unable to prevent the expansion of city boundaries.

Reluctance to renovate deteriorated areas in developing countries
In many developing countries, such as Iran, city expansion occurs at a time when there are deteriorated regions occupying a significant portion of cities. These regions are identified by having small lots of land (e.g., more than 50% that is less than 200 m^2), inaccessibility (e.g., more than 50% of the blocks being surrounded by roads less than 6 m wide), and instability (e.g., 50% having no structure to withstand even a moderate earthquake). The roots of many daily transportation-related problems, for people living in deteriorated zones, are in the three above-mentioned specificities of these areas; e.g., long walking distance in unsuitable pedestrian walkways to the nearest public transportation stations and service centers in highly populated areas, heavy traffic in the narrow and poorly connected street network, and poor parking facilities.

Areas with such characteristics usually exist in almost all large metropolitan areas with considerable history.

In developing countries, city transportation infrastructure projects are executed by city authorities, independent from the deteriorated land use renovation projects that are mostly undertaken by their owners. No improvements are made in the quality of services in the renovated neighborhoods, which brings in the following new problems: (a) Construction of new housings, widening of the adjacent roads, would increase the demand for automobile use. (b) Low-income households in the partly renovated areas would never find the opportunity to join the neighboring renovation efforts. This would cause inconsistent and non-coherent developing areas, in which a small portion of the land has a new (and usually mosaic) face, and the large portion of the area remains unattended and unchanged. (c) By replacing old houses with new higher story buildings, and assigning the freed land to improve access (transportation) for the new buildings, no land would remain to be assigned to lacking services (water, electricity, emergency, hospitals, schools, parks, or green areas), leaving the area deprived of these services as ever before.

One reason that investors prefer to develop new places in city peripheries rather than city centers, in developing countries, is to avoid getting involved in the problems of obsolete infrastructures. For example, Ahvaz is one of the historical cities in Iran, with a population of over 1 million, being the 7th most populated city in the country. There is over 1500 ha deteriorated area in the city, housing over 200,000 people (IMRUD, 2016). The City of Ahvaz is planning to develop two new towns 30 km from it, to house a part of the city population, even though this city, with its 200 km^2 area, is the 3rd largest city in the country. High industrial developments in such a city in recent decades, along with poor air quality , resulted from environmental degradation of the nearby wetlands due to mismanagement of these ecosystems, as well as global warming, led the authors of the WHO report of the year 2011 to put Ahvaz top on the list of the most polluted cities in the world (WHO, 2011). Moreover, there is no easy vehicular access to the potential victims of probable natural disasters, fires, or medical emergencies. If such areas are also prone to severe natural disaster damages, due to their poor structures, one may easily envisage the levels of disaster that would happen.

Potential metropolitan area problems and solutions

Seismic threats of the historical metropolitan areas with vast deteriorated land use areas, their transportation-related problems, their perpetual expansion for housing new population increments (due to natural growth, as well as the migration of low-income job-seekers to the city periphery, particularly in the developing countries) have turned them into time bombs, awaiting a devastating earthquake. The purpose of this paper is to propose a TOD-based approach for renovating urban deteriorated land developments, where they face serious earthquake hazards, i.e., where the renovation problem is urgent, and the inhabitants are experiencing significant transportation congestion and air pollution problems. The joint solution of deteriorated development renovation and transportation problem requires Public-Private Partnership (PPP) in significant large scale investments, which brings about considerable new jobs and expose the inside of the renovated area to the outsiders who refrain from coming inside to avoid the aforementioned costs and negative points. To implement the idea, we need to draw the attention of the residents in the deteriorated land area to participate in this joint endeavor. Thus, the problem is multi-agent programming, in which each agent maximizes its benefits subject to the decisions of the other agents. The solution to this joint problem directs renovation of the deteriorated land (thus, relieving them from natural and man-made environmental hazards) along the transit line (and, thus, a TOD) while enjoying PPP in the context of Build-Operate-Transfer (BOT) scheme. The results of the proposed implementation would be useful in reducing urban air pollution and travel time (as government objectives), profitable investing for private sector entrepreneurs in land uses that are missing in the area for a long time, and living in safe houses and pleasant new environment at the same place for the deteriorated landowners, as well as safer and more accessible areas for the public at large.

The proposed plan may create opportunities for entrepreneurs and capital holders to create jobs in the construction industry, which covers a wide spectrum of primary and secondary occupations and has a rather short capital return period.

In what follows, we first review the literature in section 2 and discuss the methodology and mathematical models of the problem in Section 3. We describe the solution algorithms in Section 4 and solve a medium scale problem with the proposed model in Section 5, to analyze its solution behavior. Later, in Section 6, we apply a novel Ant System to solve the same problem more efficiently. Finally, we summarize the results and propose future directions for the research in Section 7.

2. Literature survey

Creation of a clear and suitable motivation for each party

Renovation Plans and policies of deteriorated developments for low-income households in urban areas in the 20th century may be divided into three different eras (Carmon, 1999). First comes the era of Bulldozers, from 1930 to 1960, when local governments built new areas around the city at high costs and moved people from the old developments by force. The second era of Rehabilitation happened from 1960 to 1980, when concentrations were on public participation to raise their education, health, and skills. The third era of Revitalization was during 1980 to early 1990's, when governments' supports regarding laws and regulations, loans and subsidies targeted businesses in all scales to motivate them to invest in low-cost lands of the city centers. These endeavors were not found to have reached their goals, mostly because of (a) failure to understand the socio-economic dimensions of the lives of the people involved, as well as the high cost of moving them to the outskirts of the city in the first era (Carmon, 1999), (b) inability to financially support the program to cope with the rise in demand (Banfield, 1974) and the distance between promise and realization (James, 1978) in the second era, and (c) movement of low-income people to city borders to form new poor area developments in the third era (Smith, 2005).

After half a century of thinking about urban development, independent from transportation systems, in early 1950s , Integrated Land-use and Transportation (ILT) concepts (Wegener, 2004) emerged. It was felt that ILT would affect the benefits of different agents in these areas; agents such as local governments, private investors, real estate agencies, transportation agencies, and public at large (Waddell, 2011). In the past, ILT models were used to deal with determining housing locations and getting services based on better private transportation. Briceño et al (2008) proposed a single-level ILT model to minimize the total costs of residence and transportation for the city population, where traffic assignment is performed for private cars on the road network for the work demand. Little attention has been paid to the transportation system, as it affects city life. The bi-level ILT model of Zhao & Peng (2010), despite considering more detailed information on land and transportation structures, considers only auto trips in the minimization of total residential and transportation cost.

Since the introduction of TOD and its world-wide reception by planners and authorities from large metropolitan areas, a unified solution process was thought to have been found for important urban problems, such as traffic congestion and dependence on automobiles, resulting in numerous other related problems (excessive travel time, fuel consumption, traffic accidents, etc.). TOD is now expanding in many megacities of the world (Carlton, 2009; Ziegler, 2009), such as Shanghai, China (Cervero & Day, 2008), Brisbane, Australia (Kamruzzaman et al, 2014), Copenhagen, Europe (Knowles, 2012), and San Diego, USA (Duncan, 2011). Thus, researchers paid considerable attention to the possible resulting changes that might evolve by implementing this concept in the city, such as studies on changes in user behaviors and land values (Taki et al. 2017). Two decades of TOD experiences in various parts of the world showed a reduction of car ownership (Bunt & Joyce, 1998), higher inclination to walk (Besser & Dannenberg, 2005), decrease in vehicle-kilometer travelled (Bento et al, 2003), and higher public transport market share (Curtis et al, 2009). Cervero et al (2004) describe the primary and secondary effects of TOD. These include the provision of the opportunities to attract private sector investments, conservation of open spaces, and reduction of urban crimes.

Nevertheless, despite considerable studies on TOD principles and development strategies, quantitative analyses of this concept lack deserving stance (Ma et al. 2018), and literature leans toward qualitative and micro-elemental analyses of the concept. TOD problems are complex by the virtue of its position in the early stages of urban planning (i.e., land-use planning) and its coordination with the other major urban activity (i.e., transportation, in the ILT process). It is complex, because it is highly nonlinear, multi-faucet, multi-objective, and multi-modal, to mention some of its attributes. Wang et al. 2017 mention some of the problems in the latter aspect of the complexity, namely ignoring mode choice and traffic assignment issues in the studies in TOD environment.

The private sector investments in TOD become attractive in two dimensions: (a) increase in the transit ridership (Bailey, 2007; Cervero, 1994; Goldstein, 2007; Lund et al, 2004), and (b) increase in the values of properties around public transit stations (Kay et al, 2014; Mathur & Ferrell, 2009; Weinberger, 2001). Therefore, in recent TOD models, financing construction of public transportation buildings, stations, and lines are proposed to be done by private sectors (Xiaosu, 2013). Ma & Lo (2013) consider TOD a sustainable development scheme for congested cities. They presented a study framework to analyze the effects of TOD on the choice of housing location, selection of transportation mode, and land values in Hong Kong, where rail transportation services are exemplary in both quality and profitability. In this city, the Metropolitan Transit Rail Company employs private investors to invest, own, build, and operate rail infrastructure systems, as well as the developing residential buildings at rail stations.

Above all TOD structural and conceptual development issues, as well as problem formulations and their solution procedures, there is yet another important problem to tackle with. Governments in many large metropolitan areas have thought of local financial problems in the implementation of TOD, for constructing high-volume rapid transit lines and stations, some of which are successful and some are not (Thomas et al, 2018). However, the authors have not come across any study to see such financial components as an integrated part of the infrastructure development, bringing in Public-Private Partnership Power (4P’s) into play, and in connection with alleviating past developmental deficiencies that have turned bold in the era of fast technological advancements. This study tries to address these issues and put them in a seamlessly integrated position.

In developing countries, on the one hand, governments are faced with shortages of funds to invest in ILT projects. On the other hand, private sectors are reluctant to invest in city transportation systems due to low return on investments. To save the low-income population in deteriorated land-use areas (living in worthless, if not costly, houses) from the threat of earthquake hazards, and to award the area new service systems of transportation, shopping, health care, education, recreation, etc., in a new space of upgraded amenity, safety, and security systems, one needs reform in PPP. We were not successful in finding such a model, in the literature, that quantitatively brings these two (public authority and private financial) powers together, to engage in a socially fruitful Pareto optimal endeavor. In the following proposal, efforts are made to form multilateral cooperation (public sector, private investor, deteriorated development landowners, and the general public) to materialize a TOD of city deteriorated land use.

In contrast to all past approaches, the proposed method has the following characteristics: (a) It relies on the willingness (not a compulsion) of the deteriorated-land owners to participate in the program and rescue themselves from the danger of earthquakes. (b) The government does not have to bear the high cost of new homes, as it is financed by the private sector. (c) The plan leaves room for the development of land uses, of which the old areas are deprived of (such as regional-level-significant health care, education, cultural, shopping, recreational, and green area land-uses). (d) The private sector investors have their motivations to step in, which is the guaranteed profit from the investments at the agreed-upon minimum attractive rate of return, and there is no need for government incentives in terms of loans and subsidies. (e) The residents stay in their area where they historically belong, and there is no need to create new low-income residential areas in remote areas of the city, no new-comers are imposed to the area, all historic and cultural heritage (that are peculiar to the older areas of the cities) are preserved and exposed to others, and (f) new jobs are created where the residents need them most.

3. Problem definition

3.1 Proposed plan components

To put the concept into being, tri-partite cooperation among the government (G), private sector (P), and the residents (R) of the deteriorated development needs to be designed and constructed. In the proposed partnership: (i) The government builds a (Bus) Rapid Transit (BRT) line along an arterial roadway and provides the interested private sector companies with the opportunity to build higher density residential buildings along the RT line (on the government premises), under TOD plans and based on a BOT (Build-Operate-Transfer) scheme. The new buildings will be designed according to the latest seismic design codes by educated designers and built by experienced knowledgeable professionals. (ii) The interested private sector agrees with the local deteriorated land-use residents along this line to trade their lands with equivalent values of new apartments along the BRT line in the same zone. (iii) The private sector, in return, receives the permission to develop equivalent (in value, capital plus interest) regional level ‘commercial’ buildings (at a vantage point of the land that is freed from the current residents’ ownership in the deteriorated area). By “commercial” it is meant any land-use development that (a) the region or city is deprived of, and has regional- (not local-) level significance as mentioned above, and (b) is commercially attractive to the builders for sale, tenancy or lease. Thus: (1) G gets the land from P and gives commercial land-use permission in return, (2) P gives the new residential apartments to R and gets the deteriorated land in return, and (3) R gets the new apartment buildings from P and gives the deteriorated development land to P in return. All transactions are made at an equivalent value basis at the time of making the agreements, and in zones where over α-percent (say 90%) of the residents are willing to trade-off their lands with apartments. The remaining lands (after all trades are made) will be used to supply the zone or the related region with the services it was deprived of previously. This ensures that such zones, in their entirety, will be treated as TOD, and that (almost) all parts of the zones’ land will be taken over by the government to pay P, in return for their investments and to secure the service land-uses.

It is important to emphasize what happens in these transactions. G defines an RT line. For the given line, P reaches an agreement with α-percent (say 90%) of the landowners in a (or each of the several different) zone(s) to trade lands with apartments along the line at the current market rate(s). This (these) agreement(s) with the residents of the deteriorated land-use is (are) based on the solution of a problem which maximizes the net profit accrued to P. The solution to this problem has two consequences: (1) P gets the permission to construct the “commercial” establishments in the zone, and (2) R gets the new apartments, and a new traffic equilibrium arises in the city (basically, in the form of new mode shares). Of course, G gets the excess land freed in these transactions. Thus, for the given set of RT-line projects, there is one series of events that take place in the area: Movement of R to a safe place and new transportation pattern based on TOD, and possession of new establishments by P in the form of BOT. This resembles a network design problem, where for any network provided by the upper decision-maker (G), a problem is solved by the actors involved in the lower problem (between P and R), to specify the extent of the trade-offs in different zones (with more than α-percent resident participation rates) which maximizes P's profit, while satisfying R's wishes of land-floor area trade-offs at a α-percent level.

Figure 1 shows the set of decisions that each of the three parties has, and Table 1 describes the investments (costs) and the primary and secondary benefits that each party would receive. As shown in Figure 1, G presents the RT lines to minimize the total travel time, for which there would be a transaction between P and R that conforms with two basic principles: For P, TOD happens along the lines that maximizes P's profit, while satisfying the demand of at least α-percent (say 90%) of the deteriorated land-use landowners.

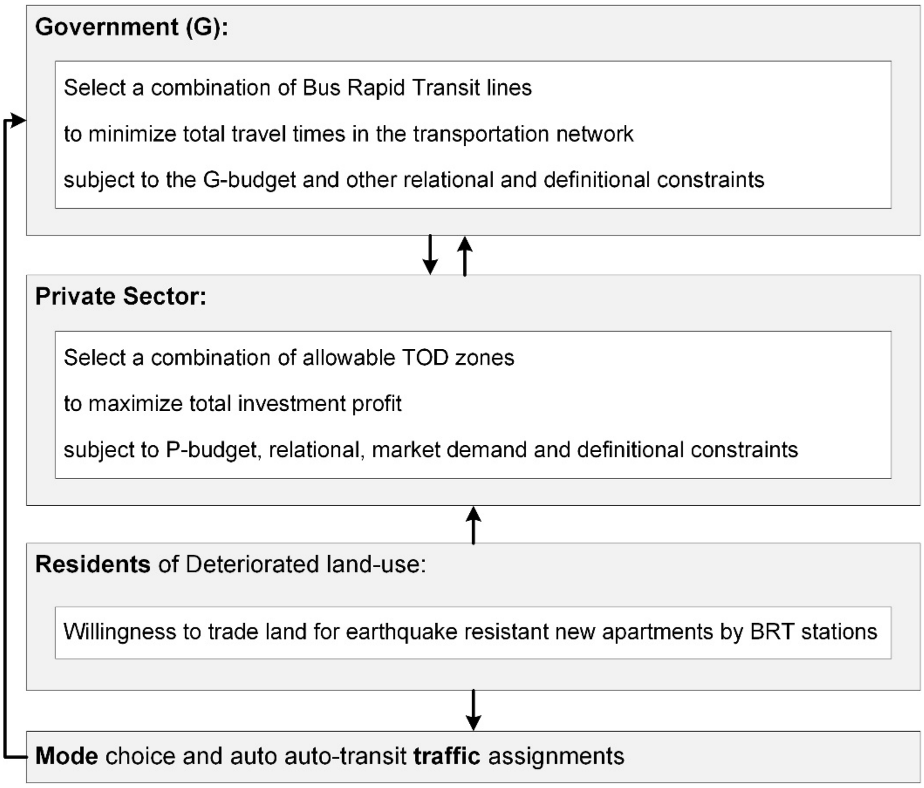


Figure 1. The structure of the proposed method

Table 1. The benefits and costs of TOD implication for agents

Agent	Cost	Initial benefit	Secondary benefit
Government	• Transit lines and stations construction cost	• Travel time reduction • Network veh-km reduction • Ownership of released lands	• Improving general health • Social justice in the distribution of services
Private sector	• Residential and commercial buildings' construction cost	• Capital recovery with an attractive rate of return	• New investments and construction in the service sector in released lands of deteriorated area
People living in the deteriorated area	• Land of deteriorated housing	• Ownership of new homes free from earthquake hazards • High access to mass transit	• Improving the quality of life • Improving property values

3.2 *Assumptions*

Suppose household *j* in the deteriorated zone *s* may trade-off A_{sj}^{l} (m²) of their land for A_{sj}^{b} (m²) of the new residential apartments along the RT lines in the same zone. We denote the ratio of these two areas by $k_{sj}^{b/l} = A_{sj}^{b} / A_{sj}^{l}$. For the n_s households in zone *s*, we may sort it in increasing order and renumber them to gain an S-shaped willingness-to-trade curve as in Figure 2. According to this curve, to satisfy the requirements of α% of the households in zone *s* to trade their lands with the new apartments, we should supply them with $A_{sj}^{b} = A_{sj}^{l}.k_{sj}^{b/l}$ (m²) apartments. Thus, at α% satisfaction level, say α=90, the private sector, P, would receive (approximately, α-percent of) A_s^l (m²) of the zone's land (to be given to the government, G), and P would supply $(\frac{\alpha}{100}).n_s.\overline{A}_s^b = A_s^l.k_s^{b/l}$ (m²) newly built residential apartment, where $\overline{A}_s^b$ is the average floor area of these apartments in zone s.

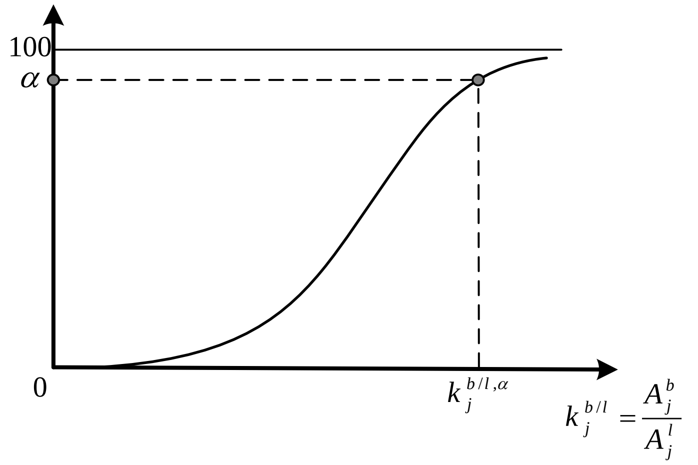


Figure 2. The tendency of deteriorated land transformation to new buildings (homes)

We assume the followings in this study:

1. The permission to start the deal in any zone *s* would be given by the government, when at least α% of the households of that zone, say $\alpha = 90$, are willing to participate in the program.
2. The shortage of financial resources for the governments in the developing countries on one side, low investment cost and high flexibility in the relocation of bus lines from another side, as well as the suggestions of some researchers to prefer Bus- for Rail- Rapid Transit in TOD (Currie, 2006) from a third side, makes us build our model based on BRT. In such cases, if for any reason (such as sustained high demand), Metro lines are constructed underground to better meet the demand, we may relocate the corresponding BRT lines to other places. Moreover, (exclusive) BRT network is an ideal network for emergency vehicle movements in the event of a severe earthquake incident.
3. Investments of the private sector include $n_s.\overline{A}_s^b$ (m²) residential apartments along the BRT lines and A_s^c (m²) trans-zonal commercial buildings at a vantage point of the zone *s* at a cost of c^b Units of Money (UM)/m². To assure the agreed-upon return on the investment of P, G permits P to run/operate the commercial buildings and take advantage of the returns on the facilities for *N* years (a generation age, about 30 to 50 years), a BOT concept. Assume that the minimum return on the commercial building investment is the yearly rent

(I_s^c UM/m²) gained on these investments. Hence, based on the cash flow in Figure 3, the investment of P should be assured at a minimum attractive rate of return, i^*.

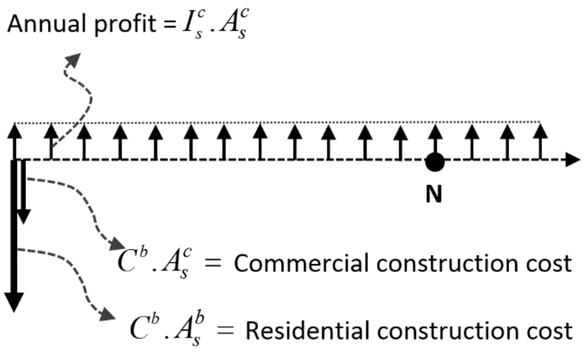


Figure 3. *The investment and income flow of the private sector*

4. To curb excessive construction of "commercial" areas that adversely affects the equilibrium of such land-uses in the area, and even in the greater city boundary, an upper bound is determined by G for zone s to hold the newly built commercial land-use (of any type) within an appropriate limit, U_s^c. (Without loss of generality, we take the liberty of having one type of "commercial" land-use in our example problem.)
5. The yearly rent, I_s^c, of the newly built commercial buildings would be reduced by the construction of higher A_s^c. This is shown in Figure 4. Thus, P would be looking for the area A_s^c, within 0 to U_s^c, which would maximize its profit.

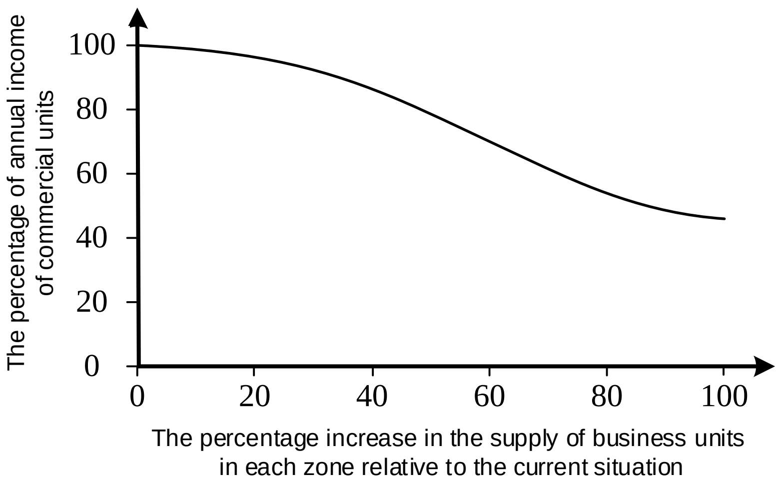


Figure 4. *Change in the annual revenue of commercial units versus supply change*

6. In this study, we choose the morning peak hour trips for design purposes which constitutes, basically, work and school trips. As the new residential buildings are constructed in the same zones and in the proximity of the deteriorated residential areas that the moving households live, origins and destinations of the residents would not change (appreciably). Since the access time and quality of services of BRT in the TOD's improve, the improved services act to boost the BRT ridership, and thereby change the flow of traffic in the region. Of-course, the construction of new regional-level commercial land-

uses induces new travel demand and may change the existing patterns of these trips. To account for these changes, travel estimation routines may be embedded in the model. For simplicity of the problem, we ignore these trips for the time being. It is worth noting that such changes in the patterns are expected to occur outside of the morning peak period that is of concern under this assumption.

7. It is also assumed that the non-basic (retail) employment of each zone *s* (which belongs to the residents) are willing to move at the same level as those residents, and they all will be settled at the zones' BRT stations. The cost of building these stations, and the retail store complex therein, next to the new residential buildings, will be covered by the local government, basically by G's general city tax revenues, because the citizens will enjoy a better life, in return.

3.3 The problem formulation

Conceptual view of the proposal

We have three agents that should come into agreement to materialize the proposed plan. G undertakes the construction of a set of RT lines (to design its network) and identifies a set of stations and/or lines where TOD may be exercised. For any given decision of G regarding the RT lines, P searches for a set of zones to implement the TOD plans for the respective deteriorated land-uses to maximize its profit subject to its budget and other guidelines set forth by G. R's agreement is vivid: whenever a trade-off rate is offered to the residents of a zone, which is higher than α-percent (say, 90%) of the value that they demand trading their lands for the safe apartments by the BRT lines, the deal takes place. Therefore, the problem is equivalent to a bi-level multi-agent problem, in the upper level of which G searches for a set of RT lines that when implemented, P-R would undertake the development of a set of zones to maximize its net profit, so that the resulting total travel time is minimized. (It is expected that a high number of residents will also move to safe places, thereby fulfilling the safety objective in case of severe earthquake incidents, as will be seen in numerical examples.)

Before presenting the problem formally, it is worth noting that depending on how we see the problem in its entirety, we may call it bilevel or trilevel. In the trilevel vision of the problem, G's decision on lines-to-build is level 1, P's decision on zones-to-choose is level 2, and R's decision on mode-path-to-travel is level 3. However, we call it *bilevel multi-agent*, to observe that G decides on lines first, and P-R agree on the trade-offs next and that P-R agreement has a one-time consequence of R's moving to safe homes and adopting new travel patterns, while P benefit from its investment. In this sense, P and R are at the same level of interaction: level 2.

The scenario

Let $N(V, A)$ be an original network with the set of nodes V and the set of links A. Let W be the set of ordered origin-destination (O/D) pairs, $(k,s) \in W \subseteq V \times V$.

Transportation aspect of the scenario

When a BRT line is constructed along an arterial street or an expressway, a lane is taken off the links along this line in each direction of movement. For line *m*, let $y^m = 1/0$, if it is decided to be built or not, we would have $y_{ij} = 1/0$, for all $(i,j) \in m$, and construct a pseudo-link from k (the origins of line *m*) to s (its destinations). Let the pseudo-link (k,s) represent the abstract transit link to convey transit passengers from origin *k* to destination *s*, $(k,s) \in W$, and represent the set of such pseudo-links as $\bar{A}$. Thus, the joint auto-transit network may be denoted as

$N(V, A_y \cup \bar{A}_y)$, where y is the vector of BRT line projects, $y = (y^m; m = 1\, to\, M)$. It is clear that A is a function of y (in taking a lane off the original link), and so is $\bar{A}$ which receives one pseudo-link for every (k,s) BRT line built.

Let T^{ks} be the fixed travel demand from origin k to destination s in passenger/hour (pass/hr), that may use either of the two private or transit modes, $(k,s) \in W$. This demand flows through the network, either through path $p, p \in P^{ks}$, where P^{ks} is the set of paths in car network, or the pseudo-link $(k,s) \in \bar{A}$ of the abstract transit network.

Let x_p^{ks} denote the flow in path $p \in P^{ks}$ in the car network forming part of the flows in link (i,j), x_{ij}. Let $\bar{x}_{ks}$ be the flow of passengers through the pseudo-link $(k,s) \in \bar{A}$ (also, called the (k,s) - excess demand, $(k,s) \in W$). $\bar{X}_{ks}$ is, in fact, the demand for the BRT line jointing k to s, $(k,s) \in W$.

Consider the (average) travel time (cost) function of link $(i,j) \in A$ the strictly increasing function of FHWA type, as follows:

$$t_{ij}(x_{ij}, y_{ij}) = a_{ij} + b_{ij} \left[\frac{x_{ij}}{Q_{ij} - y_{ij} . q_{ij}} \right]^4 \tag{1}$$

where a_{ij} and b_{ij} are two link-specific constants, representing the free flow travel time and congestion effect parameter, respectively, both in minutes. In this relationship, Q_{ij} is the practical capacity of link (i,j), and q_{ij} is the capacity of the lane taken off the link for BRT flow. Thus, this function uses practical capacity of $Q_{ij} - q_{ij}$ when $y_{ij} = 1$, or Q_{ij} when $y_{ij} = 0, \forall (i,j) \in m$, for which $y^m = 1$ or 0, $\forall m = 1 \text{to} M$. (We ignore the interactive effect of Q_{ij} and q_{ij}, and assume, without loss of generality, that the average car occupancy rate, CO, is 1 pass/car).

The pseudo-links $(k,s) \in \bar{A}_y$ in $N(V, A_y \cup \bar{A}_y)$ are instrumental to imbed a logit model to govern the mode-choice between $(k,s) \in W$ O/D pair (Sheffi, 1985). They carry the excess (complementary) auto demand passengers, $\bar{X}_{ks}$, representing transit demand from origin k to destination s, in pass/hr. The transit time from k to s is $\hat{t}_{ks}$ (in minutes), a constant, and the pseudo-link has the following cost function:

$$t^{ks}(T^{ks} - \bar{X}^{ks}) = \frac{1}{\eta} \ln \left[\bar{X}^{ks} \big/ (T^{ks} - \bar{X}^{ks}) \right] + \hat{t}^{ks} \tag{2}$$

For any given network of the private car and (Bus) RT lines, solution of the following user equilibrium flow may give the auto volumes in the car network $((x_{ij}^*), \text{in}\, veh/hr)$ and the passenger flow in the (B)RT network $((\bar{x}^{ks*}), \text{in}\, pass/hr)$, where mode choice is based on the following model:

$$x^{ks} = \frac{e^{-\eta t^{ks}}}{e^{-\eta t^{ks}} + e^{-\eta \hat{t}^{ks}}}; \quad \bar{X}^{ks} = T^{ks} - X^{ks} \tag{3}$$

The problem is as follows:

Assign $\left[N(V, A_y \cup \hat{A}_y)\right]$:

$$\min U = \sum_{(i,j)\in A_y} \int_0^{x_{ij}} t_{ij}(u, y_{ij})du + \sum_{(k,s)\in \hat{A}_y} \int_0^{\hat{x}^{ks}} \left[\frac{1}{\eta}.\ln\left(\frac{w}{T^{ks} - w}\right) + \hat{t}^{ks} + y^m(\hat{t}^{ks}_{new} - \hat{t}^{ks})\right]dw \quad (4)$$

$s.t.$:

$$(i) \quad \sum_{p\in P^{ks}} CO.x_p^{ks} + \hat{x}^{ks} = T^{ks} \qquad \forall k, s \in W \quad (5)$$

$$(ii) \quad x_{ij} = \sum_{(k,s)\in W} \sum_{p\in P^{ks}} x_p^{ks}.\delta_{ij,p}^{ks} \qquad \forall (i,j)\in A \quad (6)$$

$$(iii) \quad t_{ij}(x_{ij}, y_{ij}) = a_{ij} + b_{ij}\left[\frac{x_{ij}}{Q_{ij} - y_{ij}.q_{ij}}\right]^4 \qquad \forall (i,j)\in A \quad (7)$$

$$(iv) \quad x_p^{ks}, \hat{x}^{ks} \geq 0 \quad (8)$$

The first constraint is conservation flow, (ii) represents the relation between link and path flows, (iii) is the link travel time function, and (iv) is the non-negativity of flows.

Given the (B)RT O/D demand $(\hat{x}^{ks*})$, one may solve a transit assignment, such as optimal strategy (Cepeda et al, 2006; Spiess & Florian, 1989) problem, to find details of passenger movements from origin to destination. Let $\hat{N}(\hat{V}_y, \hat{A}_y)$ be the associate public transport network for $N(V, A_y \cup \hat{A}_y)$. The set of transit nodes $\hat{V}_y$ and the set of transit links $\hat{A}_y$ may be defined by y, the vector of the proposed combination of BRT lines. Then, solution of the following transit assignment problem would give $\hat{x}^*_{ij}$, the passenger flow in link (i,j)$\in \hat{A}_y$; $\hat{x}^*_i$, the passenger flow passing node i; as well as $\hat{t}_{ij}$, link (i,j) transit time; acc_i^*, walking time to transit station i; and w_k^*, the sum of transit waiting time at node k.

$Opt.St \left[\hat{N}(\hat{V}_y, \hat{A}_y)\right]$

$$\min_{\hat{x}_{kj}} V = \sum_{(k,j)\in \hat{A}_y} \hat{t}_{kj}.\hat{x}_{kj} + \sum_k w_k \quad (9)$$

$s.t.$:

$$(i) \quad \sum_{(k,j)\in \hat{A}^+_{yi}} \hat{x}_{kj} - \sum_{(j,k)\in \hat{A}^-_{yi}} \hat{x}_{jk} = (\hat{x}^{ks})^* \qquad \forall k \in \hat{V}_y \quad (10)$$

$$(ii) \quad \hat{x}_{kj} \leq f_{kj}.w_k \qquad \forall (k,j)\in \hat{A}^+_{yi}, \quad \forall k \in \hat{V}_y \quad (11)$$

$$(iii) \quad \hat{x}_{kj} \geq 0 \qquad \forall (k,j)\in \hat{A}_y \quad (12)$$

$$(iv) \quad (\hat{x}^{ks})^* = Sol.\ of\ \ Assign\left[N(V, A_y \cup \hat{A}_y)\right] \quad (13)$$

The objective function is the sum of the in-vehicle travel time and the waiting time at the station k. (i) is the conservation of passenger flows, where $\hat{A}^+_{yi}$ and $\hat{A}^-_{yi}$ represent the set of out-going and in-coming transit links at transit node *i*, and the right-hand side shows the transit O/D demand, which comes from problem Assign $\left[N(V, A_y \cup \hat{A}_y)\right]$, as shown in constraint (iv). Constraint (ii) is a technical condition, where f_{kj} is the rate of vehicles' (bus) arrivals to transit link (k,j) and w_k is the total waiting time at transit node k. Constraints (iii) are non-negativity constraints, and (iv) states that the transit O/D demand comes from the solution of Assign $\left[N(V, A_y \cup \hat{A}_y)\right]$ problem.

Where private sector come into play

Now, let $\mathbb{V}^{TOD}$ be the set of all proposed TOD nodes, among which the private sector may decide to undertake new residential development on those stations along the lines that the Government builds. Let $\mathbb{V}_{y1}$ be the set of stations on selected lines, *m*, for which y^m, and the respective y_{ij} are set equal to 1. Then, $\mathbb{V}_{ay} = \mathbb{V}^{TOD} \cap \mathbb{V}_{y1}$ is the set of the proposed (or allowable) TOD nodes on the selected lines in vector y that the private sector may choose from, for TOD. Then the private sector problem is to maximize the net benefit from the investment on TOD, as follows:

Let I_s^c be the unit area (m²) yearly rent of "commercial" floor area in zone s. Let c^b be the unit cost of building construction (either residential or commercial), the same throughout the city. Let $B_{private}$ be the potential budget that the private sector would invest in this problem, A_s^b and A_s^c the residential and "commercial" floor areas built by the private sector, and U_s^c the upper bound on the commercial floor area in zone s. Moreover, let $d_s^{c^{-1}}(A_s^c) = I_s^c$ be the inverse demand function for A_s^c, showing the rent for the unit commercial area in zone s as a function of the supply of this area. This is a monotonically decreasing continuous function: The higher A_s^c, the lower I_s^c.

(BLD)

$$\max_{(z\,(\mathbf{y})),(A_y^c)} P(\boldsymbol{I},\boldsymbol{C},\boldsymbol{z}) = \sum_{s\in\mathbb{V}_{ay}} \Big[\Big(I_s^c.f\big(P/A,i^*,N\big) - C^b\Big)A_s^c. - (A_s^b.C^b)\Big].z_s \tag{14}$$

$s.t.:$

$$(i) \qquad \sum_{s\in\mathbb{V}_{ay}} \Big[C^b(A_s^b + A_s^c)\Big].z_s \le B_{private} \tag{15}$$

$$(ii) \qquad 0 \le A_s^c \le U_s^c \qquad \forall\, s \in \mathbb{V}_{ay} \tag{16}$$

$$(iii) \qquad I_s^c = d_s^{c^{-1}}(A_s^c) \qquad \forall\, s \in \mathbb{V}_{ay} \tag{17}$$

$$(iv) \qquad z_s = 0/1 \qquad \forall\, s \in \mathbb{V}_{ay} \tag{18}$$

$$(v) \qquad (1-z_s)\,A_s^c = 0 \qquad \forall\, s \in \mathbb{V}_{ay} \tag{19}$$

$$(vi) \qquad A_s^b = (k_s^{b/l}.A_s^l).z_s \qquad \forall\, s \in \mathbb{V}_{ay} \tag{20}$$

$$(vii) \qquad (k_s^{b/l,\alpha} - k_s^{b/l}).z_s = 0 \qquad \forall\, s \in \mathbb{V}_{ay} \tag{21}$$

The objective function is the net profit for the private sector, where $f\big(P/A,i^*,N\big)$ is the factor which converts the yearly commercial rent for the concession period N to the equivalent present value at the guaranteed minimum attraction rate of return i^* per year. Constraint (i) is the budget constraint, (ii) is the range of the allowable commercial floor area in zone s, (iii) is the rent level estimate as a function of the commercial floor area, (iv) is the acceptance $(z_s = 1)$ or rejection $(z_s = 0)$ of zone s for TOD purposes by the private sector, (v) guarantees that if $z_s = 1$ then $A_s^c \ge 0$, otherwise for $z_s = 0$, no commercial area is allowed to be built in zone s $(A_s^c = 0)$. Similarly, constraint (vi) guarantees that $A_s^b = k_s^{b/l}.A_s^l$ or 0, if $z_s = 1$ or 0, where $k_s^{b/l}$ is the trade-off rate of residential floor area for 1 unit of the deteriorated zone s land area. Finally, constraints (vii) declares that if $z_s = 1$ (chosen), then α-percent (say, 90%) of the families should be convinced (satisfied) to trade lands for apartments along BRT lines (i,e., TOD).

Here comes the government

Then, the government problem is to choose the BRT lines (y^m) such that to minimize the total travel time in the system (auto and transit networks) subject to the results of the interaction between the private sector and the owners in deteriorated land area and other respective conditions. The Transit-oriented Network Design problem is proposed as follows:

(TND)

$$\underset{\mathbf{y}}{\mathrm{Min}}\, T(\mathbf{x}^*(y), \mathbf{y}, \mathbf{z}^*(y)) = \sum_{(i,j)\in A_y} CO.x^*_{ij}.t_{ij}(x^*_{ij}, y_{ij}) + \sum_{(i,j)\in \hat{A}_y} \hat{x}^*_{ij}.\hat{t}^*_{ij} + \sum_{i\in \tilde{V}_y} w^*_i + \sum_{i\in \tilde{V}_y} \hat{x}^*_i.acc^*_i \quad (22)$$

$s.t.:$

$$(i) \quad y^m = 0/1 \qquad \forall\, m = 1, 2, ..., M \quad (23)$$

$$(ii) \quad y_{ij} = 1 \qquad \left\{\forall\,(i,j)\in m \,\middle|\, y^m = 1\right\},\ \forall\, m = 1, 2, ..., M \quad (24)$$

$$(iii) \quad \sum_{m=1}^{M} C^m.y^m \le B_{gov} \quad (25)$$

$$(iv) \quad acc^*_s = acc_s.(1 - z^*_s) + acc_{TOD}.z^*_s \qquad \forall s \in \tilde{V}_y \quad (26)$$

$$(v) \quad \mathbf{z}^*(y) \text{ is the solution of } BLD\,(y) \quad (27)$$

$$(vi) \quad \mathbf{x}^*(y) \text{ is a solution of } Assign\left[N(V, A_y \cup \tilde{A}_y)\right] \quad (28)$$

$$(vii) \quad \hat{\mathbf{x}}^*(y) \text{ is a solution of } Opt.St\left[\hat{N}(\hat{V}_y, \hat{A}_y)\right] \quad (29)$$

The government TND problem is the upper-level problem, and (BLD) is the lower-level problem of the bi-level optimization under study. The $Assign\left[N(V, A_y \cup \tilde{A}_y)\right] - Opt.St\left[\hat{N}(\hat{V}_y, \hat{A}_y)\right]$ problems estimate the consequences of the decision, y, made by G, which determine the $P-R$ trade-off in (BLD), which in turn leads to the change in the two measures of concern: (a) the total transportation cost, which is the objective function of the upper problem, and is estimated by $Assign\left[N(V, A_y \cup \tilde{A}_y)\right] - Opt.St.\left[\tilde{N}(\tilde{V}_y, \hat{A}_y)\right]$; and (b) the number of people moved from deteriorated houses to safe apartments along BRT lines, which is the side measure of effectiveness (TOD):

$$\text{Safely housed population} = \sum_s (0.01\alpha.pop_s).z_s \quad (30)$$

The objective function of TND is comprised of (from left to right) total in-vehicle pass-hr in private and public transportation (1st and 2nd terms) and waiting and access times as out-vehicle travel time (3rd and 4th terms).

G's decision variables are BRT lines (y), which have to satisfy the 1/0 (build/ no build) constraints of (i) the lines, and (ii) the links forming the lines. Moreover, the materialization of the lines must bear the constraint of (iii) government budget.

This model may also be conceived of as a "TOD-led BOT-type renovation of the deteriorated land-use".

Remarks.

1. Selection of the BRT lines $(\boldsymbol{y})$ by G, and the deteriorated land use zones $(\boldsymbol{z}(\boldsymbol{y}))$ by P, would lead to a coordinated public transit and land development, TOD. As a result of these choices, a given number of households in those zones move to their respective new residential apartments, which are now very close to the BRT stations, and have access to the retail stores at these stations for their daily shopping needs. Based on the (basic)

similarity of O/D morning peak period trips (work and school) before and after the evolution of the deteriorated land use area, mode choices favor the public transportation more because of the improvements in both the travel times and services of the BRT system (compared to the poor/ nonexistent services in the narrow streets of the deteriorated land use area). Traffic flow in the new public- private network structure may be estimated by the traffic assignment procedure.

2. Clearly, there would be other changes in traffic pattern in the study region due to changes in land use in the deteriorated zones (e.g., induced demand). However, we avoid dealing with such details for the following reasons: First, the authors believe that it is a secondary issue that may be left for a later development of the model, particularly that we focus on the morning peak traffic. Second, estimation of these changes could be made possible by available transportation planning techniques. Third, introduction of the new rapid transit system would alleviate some of the potential problems in this respect, by creating excess capacity in this system, as well as relieving the existing road network by transferring demand to public transport systems.

3. In the $Opt.St.\left[N(V_y,\hat{A}_y)\right]$ routine for the detailed assignment of passengers to transit lines, care is exercised by an iterative procedure to keep the vehicle (buses) load factor to 0.5 in all- round trips, to observe real bus capacity, and therefore provide realistic bus frequency of service in various lines.

4. A proposed solution procedure

This section is devoted to a Double Ant System (DAS) procedure to solve the proposed TOD of the deteriorated land use area, based on a BOT scheme. The problem in Section 3.3 includes a number of integers, as well as continuous decision variables: Problem (TND) is looking for the minimum total travel time network by the help of the BRT lines that the local government may construct by the budget allocated to this purpose (a binary integer decision variable, y^m, on building line *m* or not). Problem (BLD) is searching for the combination of TOD zones (binary integer variables, z_s), and in each zone an area A_s^c of BOT commercial buildings (a positive continuous variable) that maximize the private sector net profit. DAS, including an Ant System searching for z_s, within another one searching for y^m, is devised to look for the better combination of these two integer variables, which are accompanied by a TRM (Trust Region Method (Conn et al, 2000)) to find the size of the commercial area in each chosen deteriorated zone, A_s^c.

4.1 The ant system

Ant System (AS) is an efficient meta-heuristic procedure for solving combinatorial optimization problems (Colorni et al, 1992). Poorzahedy & Abulghasemi (2005) have devised a version of AS to solve a discrete network design problem such as TND. Thus, the two similar binary integer problems of TND and BLD (on y and z, respectively) are solved by this procedure, one nested in the other, to form a Double Ant System.

The procedure of Poorzahedy & Abulghasemi (2005) constructs a decision graph $G(V,E)$ (see Figure 5). The vertices of the graph are *objects* to be selected (the decision variables), and the edges of the graph define the objects collected in one attempt (the set of decisions made), by joining them through a path in the graph. The graph is fully connected (i.e., undirected edges connect every two objects in the graph). Each edge (in the direction of moving along it) carries the information regarding the head vertex object choice (such as the cost and the benefit of that object). Each attempt is simulated by the movement of an Ant in search of food, starting from a nest (the nest could be a separate vertex in the graph, as in Figure 5, or be either of the objects, as in Poorzahedy & Abulghasemi (2005)).

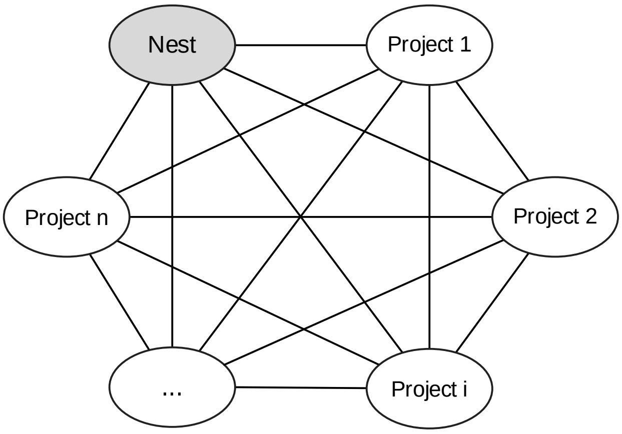


Figure 5. *Project decision graph*

AS Pseudo-Code

Step 0. Initialization. Prepare the decision graph, input the number of ants (n), and initialize graph edge pheromone and graph vertex visibility.

Step 1. Move. Find n feasible random solutions by the n ants based on the current pheromone and visibility values of the edges.

Step 2. Pheromone updating. Compute the solutions' objective function values. Identify the incumbent best solution. Compute the average objective function values for Elite solutions and update the respective edge pheromone values, considering "evaporation" of the previous pheromone values.

Step 3. Stopping Criteria. If stopping criteria are met, STOP, and Go To *Step 4* for a specified number of times (say, 3 times). Else, Go To *Step 1*.

Step 4. Local optima avoidance. Perform the devised operations to escape local optima. □

Appendix A describes the AS algorithm in more detail.

4.2 The trust region method

The Trust Region Method (TRM) (Conn et al, 2000) is a numerical method to solve the Non-Linear Optimization Problem (NLP).

TRM Pseudo-Code

Step 0. *Initialization.* Find a solution as the current solution.

Step 1. Approximate model. Consider a trusted approximate (linear/ quadratic) model objective function and a simple domain in the current solution neighborhood.

Step 2. The direction of movement and step size. Find a direction of descent (in minimization) and step size to find a new solution that minimizes the model in the specified domain.

Step 3. Update the solution. If the new solution does not improve the objective function, reduce the domain, otherwise the new solution will replace the current solution.

Step 4. Stopping criterion. If the domain becomes too small, STOP. Else, Go to *Step 1*. □

Appendix B describes the TRM algorithm in more detail.

4.3 The proposed algorithm

The proposed algorithm is composed of two AS algorithms, one nested in the other, to form a Double Ant System (DAS). We present it as follows, which is a straightforward extension of the above-mentioned AS and TRM algorithms.

General description

The choice of BRT lines is done at the higher level of our bi-level programming problem, by the government (G), within an AS framework (TND Problem). The choice of BRT lines by G specifies the possible TOD zones and triggers another choice process by the private sector (P), to choose among these zones within a nested AS procedure in the G's Ant System. In this process, P simultaneously specifies the commercial building area to be built in the chosen zones, to maximize the net profit in BLD Problem. This is done by TRM. Having specified the BRT lines (by G) and the TOD zones (by P), the transit access times are updated in the TOD zones, the assignment problems are solved for auto and transit systems, and the performance measures may be computed (total travel times in the network, total number of people transferred to safe places in the TOD zones, etc.). The assignment problems are two-staged: First, a joint mode choice-assignment problem is solved to find the transit share and assign auto to the road network, adjusted for the BRT system, by user equilibrium (Sheffi, 1985) ($Assign\left[N(V, A_y \cup A_y)\right]$ Problem). Then, the computed transit passengers are assigned to the transit network by the Optimal Strategy method (Cepeda et al, 2006; Spiess & Florian, 1989) ($Opt.St.\left[N(V_y, \hat{A}_y)\right]$). The DAS algorithm follows.

DAS Pseudo-Code

Step 0g. Initialization. Prepare the BRT line decision graph, input the number of ants (n_g), and initialize graph edge pheromone and graph vertex visibility.

Step 1g. Move. Find a feasible random BRT line combination solution by one of the n_g ants, based on the current pheromone and visibility values of the edges.

Step 0p. Initialization. Prepare the TOD zone decision graph, input the number of ants (n_p), and initialize graph edge pheromone and graph vertex visibility.

Step 1p. Move. Find a feasible random TOD zone solution by the n_p ants based on the current pheromone and visibility values of the edges

Step 2p. Pheromone updating. Compute the TOD zone solutions' objective function values. Identify the incumbent best solution. Compute the average objective function values for the Elite TOD zone solutions and update the respective edge pheromone values, considering the "evaporation" of the previous pheromone values.

Step 3p. Stopping Criteria. If stopping criteria are met, STOP, and Go To *Step 4p* for a specified number of times. Else, Go to *Step 1p*.

Step 4p. Local optima avoidance. Perform the devised operations to escape local optima.

Step 2g. Pheromone updating. Compute the BRT solution's objective function values. Identify the incumbent best solution. Compute the average objective function values for the Elite BRT solutions, and update the respective edge pheromone values considering "evaporation" of the previous pheromone values.

Step 3g. Stopping Criteria. If stopping criteria are met, STOP, and Go To *Step 4g* for a specified number of times. Else, Go to *Step 1g*.

Step 4g. Local optima avoidance. Perform the devised operations to escape local optima. □

Appendix C describes the DAS algorithm in more detail.

5. Numerical example

The proposed model will be applied to an example case of the City of Ahvaz, Iran, to evaluate the changes that it may bring in terms of: (1) the total travel time in the network, (2) the number of citizens in the deteriorated areas that are freed from the danger of severe earthquakes, and (3) the number of transit passengers, for different levels of the investments. Such investments are made by (a) the local government (on BRT system), and (b) the private sector (on the renovation of the deteriorated land uses based on TOD). Figure 6 shows the basic transportation network of the city, comprised of 25 nodes, each being the center of a traffic zone with peak hour demand matrix in Table D.1., and 46 two-way links. The zone centers are both trip production and trip attraction points. The links are of three types: freeways, arterials, and local streets, with capacities 1200, 1000, and 800 vehicles per hour per lane, and free-flow speeds 80, 60, and 50 km/h, respectively. Appendix D presents more information in this regard.

Figure 7 depicts the proposed RT network and the locations of the deteriorated land use areas. As BRT lanes are exclusive, they only pass through freeways and arterial networks. Implementation of the proposed TOD concept in the study region is only possible in those parcels of deteriorated land-use areas where BRT lines and stations are in their proximity. Thus, the deteriorated land-use in zones (nodes) 3 and 4 may not experience TOD, because of being away from BRT lines. BRT vehicle headways are 2 minutes, and each bus has a capacity of 180 passengers. Relevant Information regarding population, real estate values, etc. are given in Appendix D.

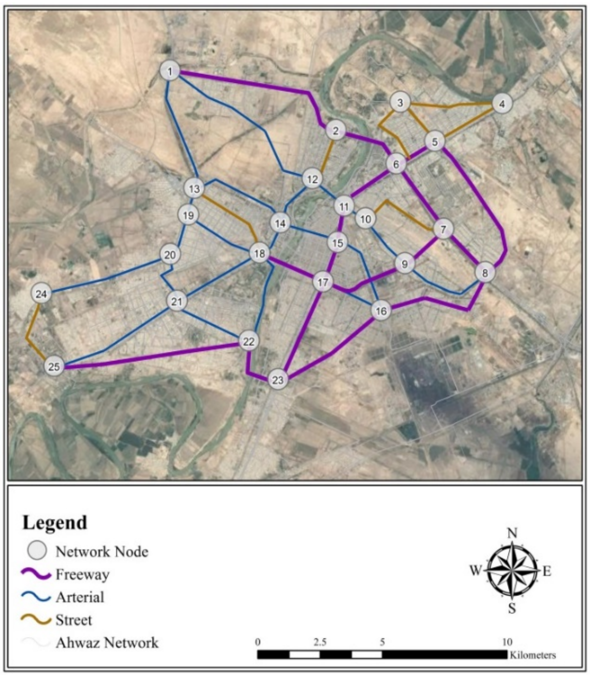


Figure 6. Ahvaz network (links and nodes)

Figure 7. Proposed BRT lines and positions of deteriorated land use areas and TOD zones

In the proposed procedure, property values of the deteriorated land-use residents do not change, as the values of the traded new residential buildings are equal to the values of their respective land lots. (Of course, it is expected that residential floor area values rise for the new apartments because of the investments in renovations and environmental enhancements.) Thus, the trade-off rates for all parcels of lands are known based on the current prices of lands and apartments, as given in Table D.2. The agreed-upon BOT investments by the private sector has a concession period of 30 years with a 15% guaranteed minimum attractive rate of return. The average construction cost of the BRT network (including the rolling stocks) is about $1 M/km, the average construction cost of the new residential buildings is $200 per m^2. BRT network cost totals $68.7M (to be provided by the local government), and the new building construction amounts to $670M (to be supplied by the private sector) based on the price acceptable to α= 90% of the land-owners in the deteriorated areas.

It is assumed that the financial constraints allow a 50% total cost budget on both sides of the local government and the private sector. The problem is solved for the above-mentioned situation and the results are presented in Table 2. The solution is made possible by an exhaustive enumeration of the feasible solutions, for analytical reasons and discussion purposes. We apply our DAS solution procedure to solve the same problem, in what follows next.

Table 2: Col.1 shows all RT lines, and Col.2, all possible feasible combinations of these lines (in terms of local government budget). For each combination of RT lines, Col.3 lists the possible deteriorated land use zones that could be considered for TOD, and Col. 4 shows the respective no. of combinations of the zones for joint development. Private sector investors in Problem (BLD) choose, among these combinations, the ones that have collectively the maximum net profit and fit within their budget limits. These solutions are given in Col.5 (using Trust Region Method, TRM), and the respective BOT commercial area gained in each zone in Col. 6, summing into the figures given in Col. 7. The respective sums of the new residential apartment areas, built by the private sector, are given in Col. 8. Next, Col's. 9 and 10 depict, respectively, the total private sector investments and the corresponding present worth of the net profits of the 30-year BOT concession period, for the solutions under discussion.

As a result of the transfer of people from the deteriorated land-use to the new residential apartment buildings, built by the private sector, a number of people are rescued from the potential threats of severe earthquakes as shown in Col. 11. Choice of the BRT lines by G in Col. 2, and selection of TOD zones by P in Col. 5, would change the access and travel times of the residents in TOD (and of course, other) zones. This instigates a shift of passengers from auto to BRT lines without (an appreciable) change in origins and destinations of the morning peak hour work and school trips. (Of course, some changes occur in shopping and other trips during the day, but mostly to the benefit of the bus network due to the central role of BRT in the related zones). Estimates of the transit passengers, total Veh-km traveled, and total Veh-hr. spent in the network are given in Cols. 12 to 14, respectively. It is evident from Table 2 that building lines 1 and 4 of BRT would result in the minimum total travel time in the network (Row 7). Maximum transfer of people to safe homes happened for the set of lines 1 and 3 of BRT (Row 8), with little sacrifice in the total travel time of the network.

Due to the constraints in G's budget, a maximum of 2 BRT lines may be chosen from among the 4 candidates. Results of the problem solutions in Table 2 show that concurrent construction of lines 1 and 4 yields the maximum benefit (minimum total travel time in the transportation network) for G. In this line combination, 7 zones may be candidate zones for selection by P for TOD purposes (Col. 3). Due to P's budget constraint, the four zones of 9, 11, 15 and17, having the maximum net profit for P, are chosen for TOD in this program. This joint venture brings in the following results: (a) A total of 67,975 persons benefit from the improved residential and public transportation facilities. Moreover, (b) total VKT (vehicle-km traveled) and TTT (total travel time) reduce 15.05 and 36.63 percent, respectively. Having taken the role of transportation-land use manager by G, TTT is taken as the primary objective in the upper-level problem in TND, and BRT line combination in Row 7 of Table 2 with the minimum TTT is selected. Had it been for the minimization of the potential earthquake threat, the BRT line combination in Row 8 with the maximum number of rescued people would have been chosen.

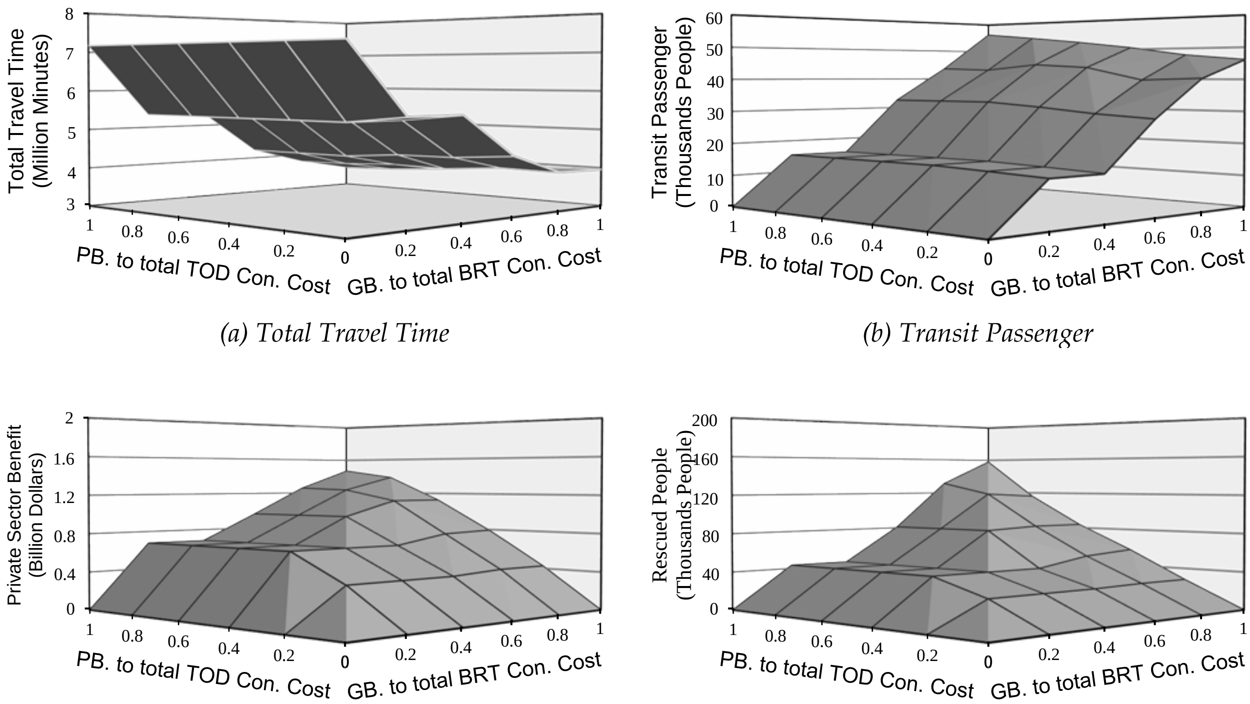
Table 2. The results of project implication in 50% of government and 50% of the private sector budget

Row	Set of transit lines (1)	Selected combination (y) based on government budget (2)	Feasible TOD zones based on y (3)	Number of TOD combinations (4)	Optimal solution of BLD problem (z^*) (5)	Optimal commercial area [A_s^c] (m^2)*(10^3) (6)
1	(1, 2, 3, 4)	(0 0 0 0)	(0)	0	(0)	(0)
2		(0 0 0 1)	(9 , 17 , 18 , 19 , 20 , 24)	64	(9, 17, 18, 20, 24)	(16.6 , 44 , 11.7, 32 , 14.8 ,10.5)
3		(0 0 1 0)	(8 , 9 , 10 , 11)	16	(8 , 9 , 10 , 11)	(8.4 , 16.6 , 28.3 , 32.6)
4		(0 0 1 1)	(8 , 9 , 10 , 11 , 17 , 18 , 19 , 20 , 24)	512	(9 , 10 , 11 , 17 , 18)	(14.3 , 24.7 , 30 , 37.6 , 10.1)
5		(0 1 0 0)	(11 , 15 , 17 , 23)	16	(11 , 15 , 17)	(32.6 , 38.7 , 44)
6		(1 0 0 0)	(11 , 15 , 18)	8	(11 , 15 , 18)	(32.6 , 38.7 , 11.7)
7		(1 0 0 1)	(9 , 11 , 15 , 17 , 18 , 20 , 24)	256	(9 , 11 , 15, 17)	(16.6 , 33 , 38.5 , 43.8)
8		(1 0 1 0)	(8 , 9 , 10 , 11 , 15 , 18)	64	(9 , 10 , 11 , 15 , 18)	(16.6 , 28.3 , 33 , 38.7 , 11.7)

Table 2. The results of project implication in 50% of government and 50% of the private sector budget (continued)

Row	Sum of the built commercial area [$A^c = \sum_s A_s^c$] (m^2)*(10^3) (7)	Sum of the built residential area [$A^b = \sum_s A_s^b$] (m^2)*(10^3) (8)	Net present value of private sector investment [$C^b \times (A^b + A^c)$] ($)*($10^6$) (9)	Net present value of private sector profit [$P(\boldsymbol{I}, \boldsymbol{C}, \boldsymbol{z})$] (*$10^6$) (10)	Number of rescued citizens (person) (11)	Number of transit passengers (person) (12)	VKT in peak hour (veh-km) (13)	TTT in peak hour (min) (*10^3) (14)
1	0	0	0	0	0	0	1,646,600	7,173.7
2	129.5	1,361	298.2	603	73,949	9,571	1,559,800	6,371.2
3	85.8	978	212.9	633	60,322	10,770	1,553,700	6,212.1
4	116.3	1,518	327.0	890	83,693	20,903	1,478,600	5,567.0
5	115.2	1,313	285.7	849	57,204	14,646	1,534,300	6,304.0
6	82.9	944	205.5	674	48,237	15,347	1,488,500	5,345.3
7	131.3	1,502	326.8	946	67,975	28,939	1,398,800	4,545.7
8	127.8	1,456	316.9	954	83,798	32,861	1,367,200	4,640.6

Readers may note that this is a complex multi-dimensional decision-making problem: There are different stakeholders, each with important objectives, whether socially or else. To ponder on the matter further, the problem is solved for five different levels of public and private budget levels (20 40, 60, 80, and 100 percent of the total respective costs), a total of 25 cases. The results, in terms of some of the important possible objective measures of the participants in the problem, are shown in Figure 8: Total travel time in the network and total transit patrons for the local government, total net profit for the private sector, and the no. of deteriorated land residents rescued from the danger of severe earthquakes for the society at large. The dimensions of the base-plane in all four figures in Figure 8 are the budget to the total cost of the public (BRT) or private (TOD) investments (referred to in Figure 8 as GB and PB, respectively), and are dimensionless figures from 0.0 to 1.0. The third dimension in these figures is either one of the four possible objectives of the stakeholders mentioned above.



(a) Total Travel Time *(b) Transit Passenger*

(c) Private Sector Benefit *(d) Rescued People*

Figure 8. The results of model implementation versus public and private sector budget changes

Figure 8a shows the variation in total travel time in the network, concerning the variations in the base-plane budget levels: It is clear that the basic determinant in the reduction of total travel time is the private sector investments, and the government budget is of much lower importance. Figure 8b shows that the reverse is true for the increase of the BRT passengers. Figure 8d shows that both GB and PB levels are important in rescuing people from the earthquake threats, and Figure 8c emphasizes that this would also increase the private sector net benefit. Jumps in surfaces in Figure 8 are due to the choices of new BRT lines by the local government. At full public and private investments in the study area, total travel time in the network improves 44.8%, total transit passengers increase by 21.9%, 157688 persons move to safe homes, and private investors enjoy a benefit-cost ratio of 2.23.

6. Evaluation of the performance of the proposed algorithm

Having observed the different aspects of the problem for the various combinations of the BRT project lines that fit in the given (50% of total project cost) budget levels for G and P, we now solve the same problem by the proposed algorithm and compare the results with the above analysis by an exhaustive enumeration. The number of ants for G's AS is 4, equal to the number of BRT lines, however, this number for P's AS is variable, equal to the possible TOD zones specified for different BRT lines. The pheromone evaporation rate is specified as 0.5 for both AS's. The visibility measures for both AS's are computed as described in Appendix C. The budget levels for G and P are taken as 50% of the total cost if all alternatives are constructed by G or P, as for the case in Table 2.

The problem is solved 50 times to account for the probabilistic nature of the proposed solution for the problem. Table 3 compares the results of these runs. As may be seen in this table, the algorithm was successful in finding the optimal solution in 82% of the times. Moreover, in other cases, the solutions are near-optimal. It is interesting to note in Table 3 that although we are minimizing the total travel time (TTT) in problem TND, the solution of the problem may not turn out to have TTT as the minimum (as is evident in the last line of Table 3 by comparing TTT= 4,545,685 with 4,487,585). This is because P will not necessarily have a maximum profit for the combination possessing a minimum TTT. In other words, the minimum TTT would have been attained had we not have the constraint imposed by P's profit maximization investment.

Table 3. Comparison of the results of 50 runs of Ant System vs. exhaustive enumeration

Solving method	No. of runs (%)	**ND** obj. fun. (TTT)	**BLD** obj. fun. (private sector profit) ($)	No. of BLD Runs	Best Line	Best TOD Zones	Transit passengers	Rescued people
Ant system algorithm	41 (82%)	4,545,685	946,988,911	Min: 121 Max:435 Ave: 265	(1,0,0,4)	(9,11,15,17)	28,939	67,975
	4 (8%)	4,640,621	954,140,548	292,120,350,138	(1,0,3,0)	(9,10,11,15,18)	32,861	83,798
	1 (2%)	4,487,585	933,714,854	120	(1,0,0,4)	(9,11,15,18,19)	28,815	80,500
	1 (2%)	4,586,623	771,869,933	530	(1,0,0,4)	(9,11,15,18)	20,551	59,008
	1 (2%)	4,618,432	888,411,395	477	(1,0,3,0)	(9,10,11,15)	28,553	74,248
	1 (2%)	4,711,365	882,495,055	374	(1,0,3,0)	(8,10,11,15,18)	28,233	77,721
	1 (2%)	5,567,035	890,827,896	483	(0,0,3,4)	(9,10,11,17,18)	20,903	83,693
	Min	4,487,585	771,869,933	120			20,551	59,008
	Max	5,567,035	954,140,548	530		---	32,861	83,798
	Ave	4,578,132	940,208,534	276			28,901	69,947
exhaustive enumeration	1	4,545,685	946,988,911	936	(1,0,0,4)	(9,11,15,17)	28,939	67,975

The proposed algorithm solved Problem BLD 120 to 530 times, and on average 276 times, while 936 possible cases need to be examined in the exhaustive enumeration case (about 75% saving in computation time). It is expected that this saving in the computation time improves more significantly by the increase in the size of the problem, because it increases the possible combinations of the decisions exponentially, while the AS's computation times are basically linearly (or mildly nonlinearly), depending on the size of the problem (Poorzahedy & Abulghasemi, 2005; Poorzahedy & Rouhani, 2007).

7. Summary and conclusions

This study is an endeavor to apply TOD concepts to the existing land uses (in contrast with the new land developments) in large metropolitan areas. It aims to achieve two major objectives: (1) Reduction of transportation-related problems in the relatively older parts of the metropolitan areas, where premises are small-sized (densely populated), access is low (particularly in emergency cases), and buildings are built by low-quality materials and workmanship and deteriorated over time (thus endangering the lives of its inhabitants, particularly in areas with severe earthquake potential). The other objective is, therefore: (2) saving the lives of hundreds of thousands of people living in these areas.

These objectives gain accentuated importance in that neither the governments have enough funds to solve the transportation and other urban problems pertinent to them in such cases, nor are the majority of the inhabitants financially able enough to take themselves out of such unfavorable (and even threatening) situations. The first is well-known in almost all developing and even many developed countries, and the second is true based on the virtue of the existing unfavorable conditions that not even average-income households come close to such situations. In other words, there are no easy solutions to such critical problems. These urban problems may also be reasons for urban sprawl.

This study proposes a multi-agent programming problem to bring in the three players of the problem into constructive cooperation. These players are the government (G), the private investors (P) and the residents of the deteriorated land uses (R). Suppose a deteriorated residential land use in which over 90% of residents are willing to trade-off their lands for an equivalent value of new buildings built by the private sector and vice versa. For this zone, G will build Bus Rapid Transit (BRT) line(s) (presumably within a network of such a system) and stations capable of housing the zone's retail employment. G permits P to build regional level "commercial" buildings in the best part of that zone. P will build new residential apartment buildings for the inhabitants of the zone in the proximity of the BRT line. R surrenders all the lands it owns in return of gaining the apartments which are programmed to be delivered in a reasonable time (say, a year or two). All transactions are based on equivalent property values (including the minimum attractive rate of return on investment), and enough guarantees for promises to be realized. The land is estimated to be occupied about 50% of its situation before, leaving room for land uses that are mandatory in modern times (such as emergency, services, durable goods, recreation, green areas, etc.) that deteriorated land uses are deprived of. This renovation process also creates jobs at considerable levels, an opportunity so precious in developing countries. Of course, the citizens at large enjoy a better and less crowded transportation network, as well as a safer urban environment.

A mathematical bi-level model is proposed to represent this multi-agent programming problem, and a novel meta-heuristic solution procedure is devised to solve this complex problem. The lower level problem represents the trade-off of land for new apartment floor area between P and R. Thus: G chooses the BRT lines, P chooses the TOD regions (in agreement with R), and R chooses to travel in the transportation networks with better facilities and options. The procedure employs a double Ant System (AS) procedure, one embedded in the other. The inner AS is assisted by a Trust Region Method (TRM) for its objective value computation (the private sector profit). The outer AS procedure optimizes the government decisions in minimizing the total travel times in the city's private and public transportation networks. Each BRT line combination choice by G prompts the reconstruction of a set of TOD zones by P-R agreements, which brings in two major outputs: (a) total travel time reduction and (b) total lives saved from earthquake threats.

It is important to note that in developing countries, the matter of deteriorated land-use is a matter of "racing with an earthquake!" Whoever crosses the finishing line first is the winner: The government that succeeds to finish moving all residents of the unsafe structures to safe places first, or the earthquake that builds significant magnitude to occur. In this sense, and based on the scarcity of the resources, the choice of BRT (rather than Subway Systems or Metros (Litman, 2014)) seems to be wiser for the developing countries, as it may be built with about 10% of the cost of subways (ITDP, 2019), and at much faster construction rate, and maybe relocated, should underground systems happen to be built underneath it.

The model has been applied to a simplified network of Ahvaz, and the results show that the optimal solution to the problem would reduce 47% of the total travel times (compared to the base network), and transfer 24% of the trips to the BRT system. This would decrease the VKT (Vehicle-kilometers Traveled) in the network from 1.65 to 1.4 million (see Table 2). Based on Figure 8a, for a given GB, the private investment increase from 0 to 100% would decrease the total travel time by 10% and increase the transit patronage by 20% (see Figure 8b). At the same time, P gets its investment back with the attractive return. A 100% investment in Ahvaz can save 160,000 persons from earthquake threat. About 50% of the land (around 1.5 million m^2) is freed to be used by the government for other purposes.

Further research may include (a) Studies of the trade-off behaviors of the residents and the private investors; (b) methods of swift construction of the residential buildings, as well as the BRT lines; (c) methods of guaranteeing the return of capital with the promised interest; and (d) the effect of the new "commercial" area supplies on the prices of such properties and other real-estate's prices.

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Appendix A: Ant System (AS) Algorithm

Step 0. Initialization. Create the Decision Graph $G(V, E)$, set number of ants equal to the number of the objects in the decision set, n. Set pheromones equal to 1 for all edges. Visibility of each object j in the decision problem, v_j, is computed as follows: Compute the value of the benefit accrued when only that object is chosen, divided by the cost of this decision. These values are normalized by dividing them by the respective maximum value across all objects, to yield the visibility measure. (Other choices are conceivable.)

Step 1. Move. At any time (iteration), t, DO for ants $k = 1$ to n: At any vertex i in G, choice of edge $(i, j) \in E$ by ant k, to move through, is made randomly according to the following probability (i.e., j is added to the choice set):

$$p_{ij}^{k}(t) = \frac{u_{ij}(t)}{\sum_{r \in F_i^k(t)} u_{ir}(t)} \qquad \forall j \in F_i^k(t) \qquad (31)$$

where $F_i^k(t)$ is the feasible choice set at vertex i at time t for ant k, $u_{ij}(t)$ is the utility of edge (i, j) at time *t*. The latter is a function of the *Pheromone* laid on edge (i, j) by the previous discovering ants (which is accumulated posterior information on the goodness of object j in connection with object i) and the *visibility* of j which shows the inherent goodness of j, v_j (which is in fact a piece of prior information on the goodness of j), as follows:

$$u_{ij}(t) = \tau_{ij}(t) + v_j, \qquad \forall (i, j) \in E \qquad (32)$$

Ants may continue their journeys if they have non-empty feasible choice sets. Or, they may return to the nest randomly to safeguard falling into the pitfall of Braess-type Paradox (Murchland, 1970).

Step 2. Pheromone updating. The pheromone contribution of ant k to edge (i, j) forming its path at time t, $\Delta\tau_{ij}^{k}(t)$, is defined as the benefit (reduction of total travel time, concerning the do-nothing alternative) accrued per unit investment cost of the solution found by k. At time t, n ants are sent in search of food (solution of the problem), and the best solution among them and the incumbent solution is found and held as the incumbent solution.

The pheromone increment of ant k, $k = 1$ to n, $\Delta\tau_{ij}^{k}(t)$, is found. We only value the findings of the Elite Ants, *EA*. The set of *EA* are those whose pheromone increments are more than the average value of all ants. The pheromones of the set of *EA* ants are assigned to the respective solution edges at the end of the iteration, to form the new goodness of the object pairs or edges, $\Delta\tau_{ij}(t)$:

$$\Delta\tau_{ij}(t) = \sum_{k \grave{o} EA} \Delta\tau_{ij}^{k}(t) \qquad \forall (i, j) \in E \qquad (33)$$

The new posterior information for the goodness of each edge (i, j) is found by fading the previous information to some degree, ρ, $0 \le \rho \le 1$, and adding the new information to it:

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}(t) \qquad \forall (i, j) \in E \qquad (34)$$

Normalize pheromones by dividing them by their respective maximum value.

Step 3. Stopping criteria. If the stopping criteria are met, the process is terminated for this round of the search process. Else, Go to *Step 1*.

Step 4. Local optima avoidance. Administer a further round of executing the algorithm by the following initial pheromone values on the edges. Double the initial pheromone values on those edges, the final pheromone values of which in the previous round were less than their average value on all edges. □

Appendix B: Trust Region Method (TRM)

TRM Algorithm.

Step 1. Consider an initial feasible solution and a quadratic (or linear) model of the objective function which is trusted in a simple region, a sphere (or a disc) of specified radius in a specified norm. This region is a neighborhood of the current solution, and the model is trusted as a representation of the objective function of the original problem in that region.

Step 2. Find a direction of descent (in minimization) and a step size in that direction in the sphere to minimize the model objective function, which is considered to replace the current solution objective function.

Step 3. If the direction and step-size does not improve the objective function, reduce the region, otherwise the improved solution replaces the current solution.

Step 4. Continue the procedure by a new neighborhood around the new solution, until the radius of the sphere becomes too small. □

Appendix C: Double Ant System (DAS) Algorithm

AS-g Algorithm

Step 0g. Initialization. Create the Decision Graph $G_g(V_g, E_g)$, set the number of ants equal to the number of the projects in the decision set, n_g. Set pheromones equal to 1 for all edges. The visibility of each line j_g in the decision problem, v_{j_g}, is computed as the value of the benefit accrued when only line j_g is chosen, divided by the cost of this decision. These values are normalized by dividing them by the respective maximum value across all lines, to yield the visibility measure. (Other choices are conceivable.)

Step 1g. Move. At any iteration t_g, DO for ants $k_g = 1$ to n_g: At any vertex i_g in G_g, choice of edge (i_g, j_g) by ant k_g to move through is made randomly according to the following probability:

$$p_{i_g j_g}^{k_g}\left(t_g\right) = \frac{u_{i_g j_g}\left(t_g\right)}{\sum_{r \in F_{i_g}^{k_g}\left(t_g\right)} u_{i_g r}\left(t_g\right)} \qquad \forall j_g \in F_{i_g}^{k_g}\left(t_g\right) \tag{35}$$

where $F_{i_g}^{k_g}(t_g)$ is the feasible choice set at vertex i_g at time t_g, $u_{i_g j_g}(t_g)$ is the utility of edge (i_g, j_g). The latter is a function of the *Pheromone* laid on edge (i_g, j_g) and the *visibility* of line j_g, v_{j_g}, as follows:

$$u_{i_g j_g}\left(t_g\right) = \tau_{i_g j_g}\left(t_g\right) + v_{j_g} \tag{36}$$

Ants may continue their journeys if they have non-empty feasible choice sets. Or, they may return to the nest randomly to safeguard falling into the problem of Braess' Paradox (Murchland, 1970).

<u>AS-p Algorithm</u> (Given the BRT lines)

<u>Step 0p.</u> Initialization. Create the Decision Graph $G_p(V_p, E_p)$, set number of ants equal to the number of the zones in the decision set, n_p. Calculate the new residential area in each TOD zone based on $k^{b/l,\alpha}$ ($\alpha = 90$ *percentile* trade–off). Set pheromones equal to 1 for all edges. Visibility of each object j_p in the decision problem, v_{j_p}, is computed as the value of the benefit accrued when only zone j_p is chosen, divided by the cost of this decision. These values are normalized by dividing them by the respective maximum value across all lines, to yield the visibility measure. (Other choices are conceivable.)

Step 1p. Move. At any iteration t_p, DO for ants $k_p = 1$ to n_p: At any vertex i_p in G_p, choice of edge $(i_p, j_p) \in E_P$ by ant k_p, to move through, is made randomly according to the following probability:

$$p_{i_p j_p}^{k_p}\left(t_p\right) = \frac{u_{i_p j_p}\left(t_p\right)}{\sum_{r \in F_{i_p}^{k_p}\left(t_p\right)} u_{i_p r}\left(t_p\right)} \qquad \forall j_p \in F_{i_p}^{k_p}\left(t_p\right) \tag{37}$$

where $F_{i_p}^{k_p}(t_p)$ is the feasible choice set at vertex i_p at time t_p, $u_{i_p j_p}(t_p)$ is the utility of (i_p, j_p). The latter is a function of the *Pheromone* laid on edge (i_p, j_p) and the *visibility* of zone j_p, v_{j_p}, as follows:

$$u_{i_p j_p}\left(t_p\right) = \tau_{i_p j_p}\left(t_p\right) + v_{j_p} \tag{38}$$

Ants may continue their journeys if they have non-empty feasible choice sets. Or, they may return to the nest randomly to safeguard falling into the problem of Braess-type Paradox (Murchland, 1970).

a. For the given set of TOD zones: Calculate the optimal private sector investment, the respective residential and commercial building area, and the maximum profit, using the TRM method.

b. Identify the best combination of TOD Zones.

c. Update access time to the transit station in TOD zones and link capacity in the selected routes.

Step 2p. Pheromone updating. The pheromone contribution of ant k_p to edge (i_p, j_p), forming its path at time t_p, $\Delta\tau_{i_p j_p}^{k_p}(t_p)$, is defined as $P\left(z^*(y)\right) / \sum_s \left[C^b\left(A^b + A^c\right)z_s\right]$ the profit, concerning the do-nothing alternative) accrued per unit investment cost of P for the solution found by k_p. At time t_p, n_p ants are sent in search of food (solution of the problem), and the best solution among them and the incumbent solution is found and held as the incumbent solution.

The pheromone increment of ant k_p, $k_p = 1$ to n_p, $\Delta\tau_{i_p j_p}^{k_p}(t_p)$ is found. Find the set of Elite Ants, $EA_p(t_p)$, whose pheromone increments are more than the average value of all ants. The pheromones of the set of $EA_p(t_p)$ ants are assigned to the respective solution edges at the end of the iteration, to form, $\Delta\tau_{i_p j_p}(t_p)$:

$$\Delta\tau_{i_p j_p}(t_p) = \sum_{r \in EA} \Delta\tau_{i_p j_p}^{r}(t_p) \qquad \forall (i_p, j_p) \in E_p \tag{39}$$

The new pheromone (i_p, j_p) is found by:

$$\tau_{i_p j_p}(t_p + 1) = (1 - \rho_p)\,\tau_{i_p j_p}(t_p) + \Delta\tau_{i_p j_p}(t_p) \qquad \forall (i_p, j_p) \in E_p \tag{40}$$

Normalize pheromones by dividing them by their respective maximum value.

Step 3p. Stopping criteria. If the stopping criteria are met, the process is terminated for this round of the search process. Else, Go to *Step 1p*.

Step 4p. Local optima avoidance. Double the initial pheromone values on the edges, the final pheromone values of which in the previous round of algorithm execution were less than the average value on all edges. Redo AS-p Algorithm.

Step 2g. Pheromone updating. For given BRT lines chosen by G, and TOD zones chosen by P:

a. Solve the auto-transit network assignment problem by using Frank-Wolfe algorithm (Assign $\left[N(V, A_y \cup \bar{A}y)\right]$)

b. Determine the share of transit modes.

c. Solve the transit-network assignment problem by Spiess and Florian algorithm ($Opt.St\left[\hat{N}(\hat{V}_y,\hat{A}_y)\right]$).

d. Calculate the total travel time, $T\left(x^*, y, z^*(y)\right)$.

The pheromone contribution of ant k_g to edge (i_g, j_g), forming its path at time t_g, $\Delta\tau^{k_g}_{i_g j_g}(t_g)$, is defined as $\left[T(x^*,0,0) - T\left(x^*, y, z^*(y)\right)\right] / \sum_{m=1}^{M}(c^m.y^m)$ the benefit (reduction of total travel time, with respect to the do nothing alternative) accrued per unit G investment cost of the solution found by k_g. At time t_g, n_g ants are sent in search of food (solution of the problem), and the best solution among them and the incumbent solution is found and held as the incumbent solution.

The pheromone increment of ant k_g, $k_g = 1$ to n_g, $\Delta\tau^{k_g}_{i_g j_g}(t_g)$ is found. Find the set of Elite Ants, $EA_g(t_g)$, whose pheromone increments are more than the average value of all edges. The pheromones of the set of $EA_p(t_g)$ ants are assigned to the respective solution edges at the end of the iteration, to form, $\Delta\tau_{i_g j_g}(t_g)$:

$$\Delta\tau_{i_g j_g}(t_g) = \sum_{r\grave{o}EA}\Delta\tau^{r}_{i_g j_g}(t_g) \qquad \forall(i_g, j_g)\in E_g \qquad (41)$$

The new pheromone (i_g, j_g) is found by:

$$\tau_{i_g j_g}(t_g+1) = (1-\rho_g)\,\tau_{i_g j_g}(t_g) + \Delta\tau_{i_g j_g}(t_g) \qquad \forall(i_g, j_g)\in E_g \qquad (42)$$

Normalize pheromones by dividing them by their respective maximum value.

Step 3g. Stopping criteria. If the stopping criteria are met, the process is terminated for this round of the search process. Else, Go to *Step 1g*.

Step 4g. Local optima avoidance. Double the initial pheromone values on the edges, the final pheromone values of which in the previous round of algorithm execution were less than the average value on all edges. Redo the algorithm.

Step 5. Report:

1. The best combination of BRT lines,
2. The best combination of TOD zones,
3. The commercial area in each zone, and
4. Equilibrium network flows. □

Appendix D: Example Case Data

Table D.1. Peak hour demand matrix

node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	sum
1	0	137	0	0	0	63	77	0	0	44	132	114	109	95	33	33	72	33	101	0	0	48	0	0	0	1,089
2	71	0	248	66	50	112	264	71	114	123	202	0	290	1,016	1,030	291	41	1,224	269	0	218	276	191	87	100	6,350
3	51	1,400	0	0	404	515	371	452	422	551	1,817	1,171	175	861	1,139	342	174	798	163	6	225	195	123	0	44	11,397
4	15	407	0	0	63	368	1,077	131	123	458	965	341	51	251	331	100	51	669	47	0	65	57	36	0	13	5,618
5	0	42	177	528	0	306	228	153	192	179	428	36	0	167	351	0	0	564	0	0	0	0	0	0	0	3,350
6	198	556	1,422	380	129	0	698	516	1,346	680	1,173	465	257	752	2,259	684	167	1,620	239	35	237	198	186	203	139	14,535
7	0	338	2,217	592	0	638	0	371	284	271	999	283	56	159	374	71	0	585	52	0	0	0	45	0	16	7,348
8	0	0	0	0	0	62	45	0	62	23	0	0	34	0	144	123	83	81	32	0	0	0	0	62	22	771
9	63	498	474	127	45	1,410	240	840	0	155	495	416	202	368	1,505	1,530	182	773	188	38	293	39	246	74	114	10,311
10	33	263	879	235	31	647	97	310	106	124	383	220	66	171	650	427	63	403	61	10	91	10	90	19	39	5,429
11	68	191	737	197	77	476	140	0	131	57	0	159	0	140	656	66	65	213	0	0	63	0	62	0	22	3,515
12	128	0	443	118	89	200	471	126	204	219	360	0	517	1,814	1,839	519	74	2,186	481	0	389	492	341	156	178	11,339
13	492	729	90	24	28	214	36	122	33	49	163	610	0	2,482	1,605	44	227	2,076	0	76	763	347	567	116	245	11,138
14	156	252	0	0	0	0	0	0	0	0	0	211	177	0	170	45	0	339	165	0	59	47	0	0	0	1,619
15	53	1,235	308	82	53	602	174	270	69	128	363	1,033	330	761	0	1,049	750	1,868	307	0	53	446	174	0	62	10,165
16	138	490	608	162	35	945	344	608	597	314	546	409	407	908	4,260	0	720	2,199	378	0	152	411	416	0	149	15,193
17	42	223	237	63	0	279	164	351	344	116	41	187	233	279	3,605	1,268	0	1,095	217	0	122	123	330	0	118	9,434
18	0	58	48	13	0	0	0	57	0	0	0	49	81	164	48	99	48	0	76	0	0	146	0	0	0	886
19	458	678	83	22	26	199	33	114	31	46	152	567	0	2,308	1,492	41	211	1,930	0	71	709	323	527	108	227	10,357
20	0	96	0	0	0	0	0	0	0	0	0	80	1,411	248	170	38	42	209	1,312	0	38	228	38	29	24	3,958
21	0	404	68	18	0	62	74	137	0	68	246	338	867	1,268	1,683	150	92	1,292	806	137	0	2,709	198	372	204	11,188
22	33	763	287	76	54	44	99	33	66	45	47	638	386	3,059	1,397	800	126	4,266	359	66	2,228	0	234	210	159	15,470
23	44	345	167	44	527	494	146	998	36	59	96	289	251	489	2,645	4,269	1,470	776	234	126	138	87	0	168	60	13,955
24	27	49	27	7	0	0	0	0	0	0	0	41	329	195	198	0	0	408	306	0	755	54	89	0	32	2,516
25	26	145	71	19	194	182	54	367	13	22	35	122	214	252	1,047	1,573	542	436	199	46	329	52	33	62	0	6,034
sum	2,095	9,300	8,588	2,774	1,802	7,812	4,828	6,025	4,171	3,729	8,641	7,778	6,442	18,200	28,626	13,558	5,196	26,039	5,990	609	6,922	6,286	3,923	1,664	1,966	192,966

Table D.2. Summary of zones data

zone	Population (person)	Family size	Deteriorated texture (%)	Average area of deteriorated houses (m^2)	Price per m^2 of deteriorated land ($)	Price per m^2 of new apartment ($)	Tradeoff ratio of building to land	Annual income per m^2 of the business unit ($)
1	5,158	5.00	0%	0	---	---	---	---
2	27,352	5.01	0%	0	---	---	---	---
3	56,616	4.63	9%	150	---	---	---	---
4	29,367	5.77	19%	153	---	---	---	---
5	61,718	5.15	0%	0	---	---	---	---
6	12,864	5.78	0%	0	---	---	---	---
7	24,396	5.83	0%	0	---	---	---	---
8	32,601	5.71	16%	117	2997	2700	1.11	622
9	33,246	5.51	36%	97	3296	3200	1.03	933
10	105,939	5.61	26%	73	3100	3100	1.00	996
11	33,275	4.57	67%	84	4998	4200	1.19	1,400
12	39,702	4.41	0%	0	---	---	---	---
13	40,276	5.66	0%	0	---	---	---	---
14	5,510	4.75	0%	0	---	---	---	---
15	66,744	4.78	31%	113	8294	5800	1.43	1,089
16	64,778	5.19	0%	0	---	---	---	---
17	85,725	5.17	24%	140	8479	6100	1.39	887
18	21,655	5.85	49%	82	5084	4100	1.24	902
19	85,284	5.80	28%	99	2862	2700	1.06	840
20	60,525	6.27	25%	79	2037	2100	0.97	420
21	67,473	5.60	0%	0	---	---	---	---
22	32,942	5.48	0%	0	---	---	---	---
23	121,179	6.08	21%	81	3014	2200	1.37	459
24	19,186	6.64	59%	79	2320	2000	1.16	467
25	56,803	5.30	0%	0	---	---	---	---