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Defining land use intensity based on roadway level-of-service targets

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Abstract: Traditionally, master planners develop an initial land use scenario for an undeveloped site, which is then forwarded to transportation planners for modeling purposes. On the basis of travel demand forecast, several alternatives are provided to master planners and, accordingly, different land use proposals are examined until, finally, a preferred option is chosen. Such trial and error process is inherently cumbersome, time consuming and an optimal outcome is rarely achieved. Usually, by increasing land use intensity, roads will be overly congested, beyond acceptable levels, and under-utilized when lower levels of land use intensity is planned. Hence, defining optimum land use intensity to target traffic level of service on roads is never achieved. The aim of this paper is to introduce an innovative approach, based on a "reverse engineering" process, to define final land use intensity based on desired target volume on roads. This method significantly reduces the number of model runs required for "what if" analysis. It also brings the results of travel demand forecast models closer to the desired outcome.

1 Introduction

Any individual without special skills or training can offer advice on reducing traffic congestion—widening roads, or not building specific junctions. The challenge for transportation planners and engineers is to build an efficient transportation system without further expansion of roads while promoting growth and economic activities.

Authorities striving to maintain free-flowing traffic may face the dilemma of campaigning for smaller or fewer developments. In fact, some authorities actually discourage growth and development in order to maintain their existing traffic volumes. A "no development" approach, however, is synonymous with halting economic growth. In reality, many cities with high population densities are proving themselves capable of moving more and more people in a relatively short time period.

On the supply side of the transportation system, a number of studies examining the impacts of physical changes to roadway capacity and optimization of traffic control systems on trip distribution, mode and route choice have been conducted over the years (Allsop 1974). However, literature on the demand side is not as extensive. In practice, "smart growth" development policies that can lead to reductions in air pollution and gas emissions also promote increased land use density. This, in turn, can bring trip origins closer to destinations and thereby reduce vehicle kilometers traveled, as well as encouraging the use of public transit and non-motorized transportation modes (Cambridge Systematics, Inc. 2009).

The question that remains is how transportation modelers can assist land use planners in supporting high-density development. This study focuses on a new and systematic approach to the definition of land use intensity based on roadway level-of-service targets. The performance measurement used as level of service in this study is the volume capacity (v/c) ratio, in which v represents traffic volume (number of vehicles using the roadway during a specified period) and c represents the capacity of a roadway at its designated level of service. The methodology introduced in this paper was developed in order to maximize land use intensity and thereby achieve high but acceptable target v/c ratios. However, the methodology could be applied for any level-of-service target.

In fact, this methodology would also work in reverse: if the development intensity of a land use proposal resulted in an unacceptable level of service on a roadway, then applying the methodology described in this paper would allow planners to determine the acceptable land use intensity (i.e., how much the development proposal would need to be scaled back to achieve an acceptable level of service).

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The proposed method has been applied and tested in the Algabas area of the city of Almaty, Kazakhstan, as part of a larger project (commissioned by LIMITLESS, an international real estate development company based in Dubai, UAE) to develop a transportation plan for a large undeveloped site with an area of 485 hectares. Throughout its history, Almaty has been a crossroads of cultures in Central Asia. The city was the capital of Kazakhstan from 1929 until 1998, when the government moved to Astana. With a population of 1.2 million, Almaty today is the largest city and commercial center of Kazakhstan, the largest landlocked nation in the world. Almaty is located in the southeast of the country, less than 30 kilometers north of the border with Kyrgyzstan. Almaty remains the financial, economic and cultural center of not only Kazakhstan, but the entire region of Central Asia. A diverse citizenry including ethnic Kazakhs, Russians, Tatars, Uyghurs, Koreans, and Ukrainians gives the city a cosmopolitan atmosphere, and its populace also includes a large number of foreign-born residents, tourists, and students.

The Algabas development is considered an infill development, planned to entice its population to live, work, shop, and play within the site. The concept of Mixed Land Use and grid roadway network supports this planned objective. The street design in Algabas has been planned to support a mix of land uses. Streets are well-connected in a dense network that encourages the use of public transit and non-motorized modes and emphasizes overall quality of travel for those traveling by automobile. The dense roadway network provides travelers with a choice of alternative routes to their destinations. By providing numerous narrow roads, as opposed to a hierarchical roadway system with wide roads, the design facilitates left turn movements and helped overall capacity of roadways.

2 New Urbanism

The planning doctrine known as New Urbanism or Neo-Traditional Planning grew out of a response to the negative effects of sprawl, the inefficient and environmentally degrading spread of population (Calthorpe 2001). New Urbanism promotes "walkable" neighborhoods with a variety of housing and job types. Compact development and mixed land use are important components of the New Urbanist approach to minimizing the separation of origins and destinations. New Urbanism is also strongly influenced by urban design standards that promote non-motorized transportation and Transit Oriented Development (TOD) (Kelbaugh 2002). The ideal New Urbanist transportation network is a well-connected system that utilizes roads efficiently by implementing different forms of grid network. This is intended to provide a variety of route choices between each origin-destination pair, in contrast to conventional roadway systems that funnel traffic into a few major corridors.

New Urbanist roadway design seeks to minimize the number of underutilized roads, allowing a higher land use density in any given area. Conventional roadway system design, based on a hierarchical model, has encouraged sprawl and, therefore, low-density, which has led to an increase in vehicle kilometers traveled (Litman 2010). The guiding principles of New Urbanist roadway design have been implemented in some development projects as an alternative to conventional roadway design with the objective of producing healthier neighborhoods, and have also been used to retrofit existing developments and make them more interactive, walkable, enjoyable, and livable (Burden 2000).

In contrast to conventional road networks, the New Urbanist roadway system is designed to shorten trips and hence reduce overall travel demand, as well as to shift demand from private vehicles to other modes of transportation. Moreover, quality of trips in conventional roadway system is poorer: expressways and wider roads in urban areas provide a very narrow cone of vision for travelers who use roads on daily basis. The dense interconnected roadway system, with narrower roads, is aesthetically pleasant for both travelers inside vehicles and pedestrians, as it more closely conforms to human scale.

Many planners believe this is the way forward for cities trying to cope with traffic. Without such an approach, they will face heavier congestion, rising levels of air pollution, and higher energy consumption. The main advantage of New Urbanist roadway network design is the intense grid system, which allows traffic from any origin-destination pair to have many route alternatives and thereby tends to disperse traffic onto a variety of routes. This characteristic makes new New Urbanist approach suitable for higher-density developments (Kulash 1990).

Not only has New Urbanism been shown to be effective in land use planning, it has been empirically proven to improve traffic flow. However, one of the limitations of conventional transportation modeling methods is that they were never intended to estimate the impacts on travel demand forecasts of measures such as different urban design scenarios such as New Urbanism or neighborhood-level smart growth initiatives. As Pas (1995) noted, travel forecasting is "oriented almost exclusively toward analysis of long-term, capital intensive expansion of the transportation system, primarily in the form of highways." In recent times, the development of sprawl has been increasingly discouraged due to the additional cost that such development patterns impose on infrastructure, as well as its ineffectiveness in solving traffic problems.

Hence, transportation modelers have been encouraged to develop tools focused on assessing potential methods of reducing travel demand and average trip length, rather than on guiding new investment opportunities. While progress has been made in improving large-scale models, most transportation models still suffer from shortcomings in replicating features related to the New Urbanism concept. Some analysts have applied post-processing and direct modeling as alternative methods, in order to capture travel impacts of neighborhood-scale land use plans. These alternative models are still considered "sketch-planning" supplements to, rather than substitutes for, traditional four-step models. Post-processing normally extends the output of four-step modeling by introducing elasticity and sensitivity tests to account for the effects of variables not specifically accounted for in conventional models. Another alternative to the four-step method is off-line or direct modeling of demand. This is done using stand-alone models to directly estimate travel for neighborhoods, most notably ridership for rail projects and Transit Oriented Development (TOD) (Cervero 2006).

The methodology introduced in this paper also extends conventional four-step model outputs but suggests a systematic approach to the definition of land use intensity based on roadway level of service targets in order to satisfy the objectives of New Urbanism.

3 Measures of effectiveness

A variety of evaluation criteria can be used to measure traffic system performance. Traditionally, the ratio of traffic volume to roadway capacity had been used as a measure of effectiveness; this has allowed planners to assess the impact of a policy change or physical improvement on any given stretch of roadway. Besides the volume-to-capacity ratio, other related indicators that have been used in traffic engineering are average traffic speed, average delay per capita, parking convenience and affordability, and crash rate per vehicle-kilometer. The limitation of such conventional approaches is that performance is assessed only in terms of vehicle movement. These measures promote an automobile-centric system, as they ignore non-motorized modes and public transit. Indicators such as accessibility, land use density and mix, quality of traffic, and (most importantly) multimodal level of service should be considered in any transportation study (Litman 2010). Moreover, reliance on the volume-capacity ratio as the only evaluation criteria encourages expansion of roadway capacity, as the solution to congestion problems is considered to lie in achieving the lowest possible ratio.

The traffic study conducted for Algabas not only suggested several measures of effectiveness, but also applied a new methodology to define land use intensity based on volume-to-capacity ratio targets.

4 Problem statement

Data on land use, population demographics, and economic factors are key inputs to travel demand forecast models. Land use scenarios can be tested by changing input assumptions and re-running travel demand forecast models. Land use models can be inserted into this loop. The use of land use models is considered an advanced technique. The need to link travel demand and land use forecasting models has become more evident in recent years. This link should connect land use alternatives with transportation system development patterns in order to understand how land use and transport influence one another.

The mechanism for capturing this interaction can be a set of land use models. Three types of models can be used to predict the interactions between land use and transportation. Stated preference surveys explore traveler behavior by asking travelers what their reactions would be if certain changes were to be made either to land use or the transportation system. Revealed preference studies detect traveler behavior based on analysis of other studies. Mathematical models allow researchers to assess the elasticity of any variable while keeping other factors constant. Lowry's *A Model of Metropolis* 1964 was the first attempt to evaluate the mutual relationship between land-use and transportation system in an operational model. A variety of different approaches to modeling urban land use and transport have evolved in recent years. Michael Wegener's comparative review provides a comprehensive overview of twenty contemporary urban land-use transportation models (Wegener 2004).

In practice, land use intensity must be defined through a heuristic trial-and-error process: an initial land use scenario specified in the development master plan is coded into the transportation model and (depending on the performance measures used in the model) various other scenarios are examined until a preferred land use scenario is selected. General knowledge about mobility and accessibility variables that affect land use, are well established, but the magnitude of each variable's effect is not quantifiable (Hansen 1959). This study has developed an innovative approach to systematically define preferred land use type and intensity based on desired traffic level of service goals expressed in terms of the volume-capacity ratio.

5 Methodology

The methodology applied includes the following steps:

1. Determine the target traffic volume based on the desired v/c ratio on various roadway links.
2. Using an initial land use scenario based on the development master plan, run the transportation model to achieve an initial trip table.
3. Apply the Origin-Destination Matrix Estimation (ODME) methodology to adjust the initial trip table based on the target traffic volumes and estimate the number of new trips entering and leaving each Transportation Analysis Zone (TAZ).
4. Estimate new land use based on desired number of trips.

Application of these steps yields an ideal land use intensity that has relatively similar proportion of the mix comparing to the initial land use, but with a different intensity. The new land use, resulted from our model, caused auto volume being close to target volume on roads. Therefore, the developer managed to maximize density of development while maintaining the desired level of service on the road network.

The following describes each step in detail.

Step 1: Set target volume

Level of service (LOS) generally describes traffic conditions in terms of several variables: average vehicle speed and travel time; traffic volume and road capacity; freedom to maneuver; traffic interruptions; comfort and convenience; and safety. The purpose of setting LOS standards is to provide a quantitative tool to analyze the effects of land use changes to system performance. If actual system performance falls below a given standard, actions must be taken to improve LOS. In many cases the volume-capacity ratio is one of the indicators representing LOS on roadway links. When the capacity of roads is known and the desired v/c ratio has been determined, maximum acceptable volume on each link can be calculated. In this study, desired volumes on all external links to the site were set at 80 percent of link capacity; the developer and the study team believed that any value between 0.70 and 1.10 could be considered acceptable. These targets were set for external roadway links because the site's internal roadway system was planned as grid network, which provided high capacity on interconnected roads and avoided capacity problems. Hence, the target only had to be defined for the gateway routes leading outside the development. These gateway routes were a few external roads, and setting the desired volume for them would specify a level of congestion that was acceptable to both the developer and the planning team.

Step 2: Run model using the initial land use scenario

The master plan of Algabas is based on a strong network of human-scaled streets and pedestrian pathways; mixed-use development that encourages social interaction is one of its main pillars. The plan also includes a transit system that ensures comprehensive accessibility and mobility between various land uses within the site (e.g. workplaces, residences, and amenities). The site plan includes an efficient pedestrian network and transit systems intended to decrease dependence on automobiles and reduce the need to construct new roads, thereby allowing more free space for civic use and green space. Generally, roadways are scaled down to establish an environment conducive to pedestrian mobility.

It was imperative that the main principle of the master plan remain intact. Hence, the transportation network concept could not be modified, as doing so could harm the overall plan. The objective of this project was to change land use to fit the transportation network. The allowable change in land use was to maximize intensity while keeping overall composition unchanged.

A TransCAD-based travel demand forecast model was developed for the peak travel period. By coding initial land use from the master plan into the model, trip generation, distribution, and traffic assignment were modeled. In the absence of a mode choice model, the project assumed a 25 percent share for public transit. The result of this step was an auto trip table for the morning peak period, and a set of estimated traffic volumes on roadway links based on the initial land use scenario. Figure 1 shows a plot of auto volumes for the morning peak period, color coded by v/c ratio. This figure depicts the roadway network of the site and its external access points; the v/c ratios on the roads, based on the initial land use plan, are all within the threshold of 0.0 to 0.8. This result was unacceptable as the roads were generally underutilized and therefore not economically efficient. Moreover, the plan depended on high development density to promote public transit and nonmotorized travel, and to increase the overall vibrancy of the site. Traditionally, any v/c ratio above one is considered to be unacceptable; at the same time, an efficient allocation of resources should also discourage underutilization of roads and low-density development.

Low-density developments tend to produce greater separations between trips origins and destinations, increasing vehicle kilometers traveled and leading to more traffic congestion. Low-density areas also produce an inefficient urban fabric, wide streets, and the need for more off-street parking places. Furthermore, low-density development discourages mixed land use and prohibit nearby convenient markets, restaurants, and other types of commerce. Such factors make these areas more auto-oriented and, therefore, not the best way of utilizing valuable land. This is in contrast to traditional cities, which developed and expanded around pedestrians; their development pattern allowed residents to walk, bicycle, or ride transit to work, corner markets, and other nearby amenities (Holtzclaw 2000).

Step 3: Adjust initial trip table by ODME

The aim of this step is to create a new trip table for a new assignment output, where estimated auto volumes are close to target volumes. A major constraint in this project was that the final trip distribution table had to follow the same trend as the initial trip matrix that had been estimated in Step 2.

In model development and calibration, origin-destination matrix estimation (ODME) methodology is typically used to adjust the results of home interview surveys based on traffic count. The highway ODME procedure in this method is intended to produce an O-D matrix that is consistent with observed link counts. Therefore, a set of observed link counts is required for the procedure. These counts frequently cover a subset of the road network, since counts are not taken on all links of the network. In our study, we used the same method (Nielsen 1998) to create a new trip table based on the initial trip matrix as the output of step two above, but used future target volume on certain links as the base for trip table adjustment instead of traffic counts.

In ODME, it is assumed that these link counts (target volume in case of our study) contain at most a very small portion of intra-zonal trips, i.e., trips that start and end within the same zone. This is because these trips will not be accounted for in the assignment. Therefore, the highway ODME procedure only takes into account trips between zones, and the diagonal in the O-D flow matrix is ignored. If the count includes a significant number of intra-zonal trips, then the count needs to be adjusted to deduct these trips. Because the transportation analysis zones in Algabas are very small, no intra-zonal motorized trips are expected.

The applied procedure ensured that a sufficient number of link target volumes were included to generate valid results. The ODME procedure allows users to specify a weight field to use in conjunction with target volumes. The addition of a weight field makes it possible to determine the importance of certain target volumes in relation to others. For example, the Algabas study was more concerned to have the assignment result volume, in activity centers, as close as possible to target volume. Therefore, those links in activity centers were awarded higher weights. Another option in the ODME procedure is to specify a value change constraint matrix to limit the amount that the O-D flow in the initial matrix was allowed to change. The value change constraint between origin i and destination j (Δ_{ij}), is the allowable fractional deviation of the estimated volume x_{ij} from the input seed volume X_{ij}.

$$x_{ij} = \begin{cases} X_{ij} & \text{if } \Delta_{ij} = 0 \\ \min\left[x_{ij}, X_{ij}(1+\Delta_{ij})\right] & \text{if } \Delta_{ij} > 0 \\ \max\left[x_{ij}, X_{ij}(1+\Delta_{ij})\right] & \text{if } \Delta_{ij} < 0 \end{cases} \tag{1}$$

Thus, the number of trips from home to school was initially stayed the same, so in later stages the number of trips by students could be manually adjusted according to school district policy standards, depending on the final estimated number of residents in the area. In other words, there were initially fewer schools, but when land use density was increased, based on the model result, the number and size of schools were also increased in accordance with Almaty policy guidelines that set the size of schools as a function of the planned population of the site. Because school trips are expected to be internal to the site, this matter will not significantly affect the level of service. Values for industrial zones, for which the magnitude of trip interaction was known also remained the same in adjusted trip table. The results showed an adjusted trip table and an assigned volume, on selected links, which were close to the plan desired target volumes. Figure 2 shows the plot of auto volumes for the morning peak period based on the new output, color-coded by v/c ratio. The sum of rows and columns for the new matrix concluded the new vectors of desired trips for entering and leaving during a one-hour morning peak period. These vectors were aggregated by five districts and used as inputs for the steps that followed.

Figure 1: Morning peak auto volume colored by volume capacity ratio. All links have v/c ratios of less than 0.8, indicating the roads are significantly under-utilized.

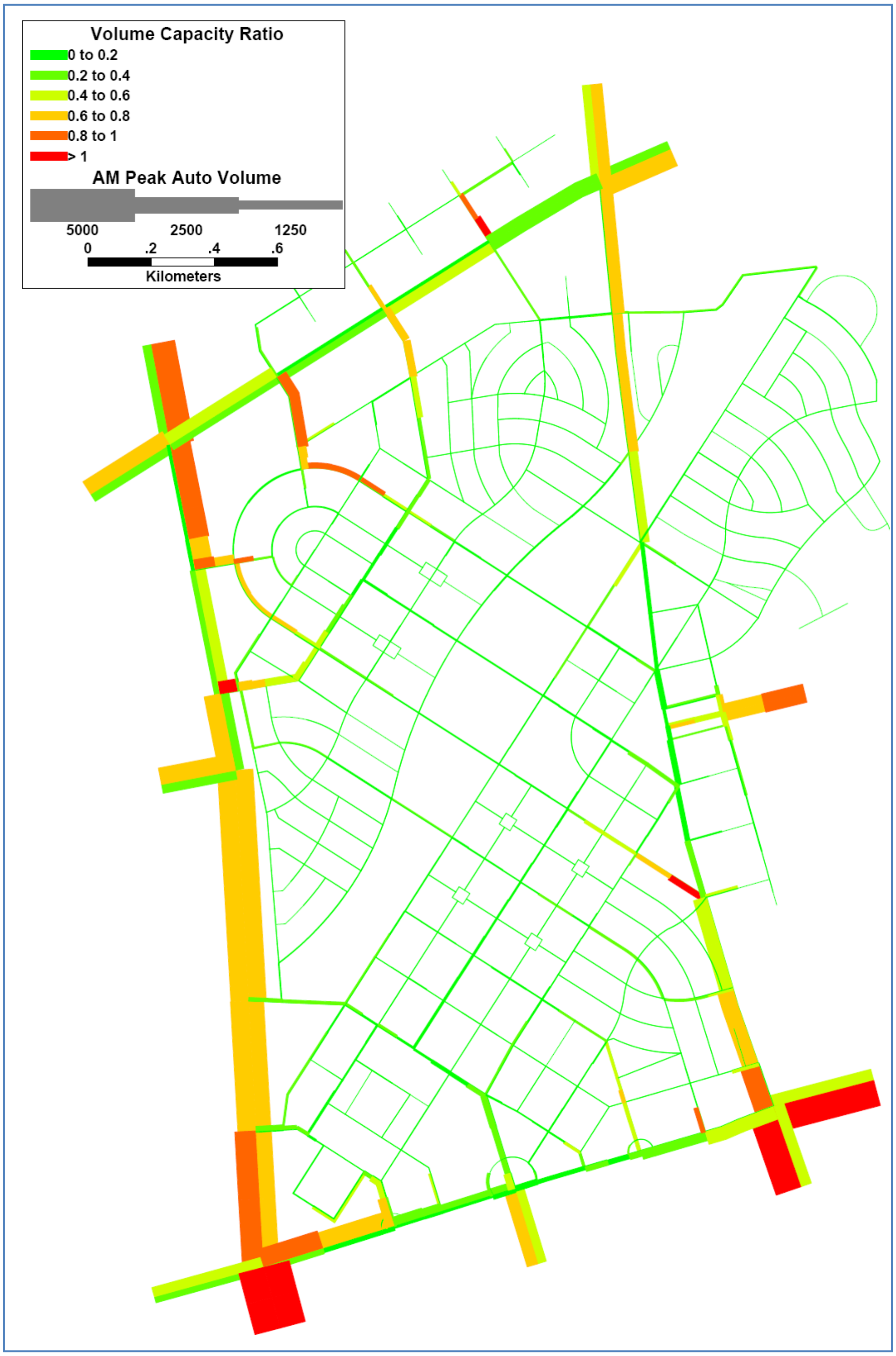

Figure 2: Morning peak auto volume based on the adjusted model, color-coded by v/c ratio, indicating road usage in accordance with planning objectives.

Step 4: Define Land Use Intensity Based On New Trip Targets

In the final step, land use data are redefined based upon the new trip table derived in Step 3. The underlying methodology, in this section, involved the use of linear programming (LP) in solving the following statement (Ferguson 1998):

$$[P \mid A] = [P^* \mid A^*] \tag{2}$$

Subject to:

$$[P \mid A] = [L_{ij}] \times [R_{jP} \mid R_{jA}] L_{ij} \geq 0 \tag{3}$$

Land use limits for schools and industrial zone

Where:

P^*= Optimized trip production

A^*= Optimized trip attraction

$[P^* \mid A^*]$= Matrix of productions and attractions from ODME results

L_{ij}= Quantity of land use type j in district I

R_{jP}= Production trip rate for land use type j

R_{jA}= Attraction trip rate for land use type j

The presumptions made for solving the LP problem were that industrial areas are given and remain the same as the initial land use scenario; school areas were also initially kept the same, but were changed later based upon Almaty policy guidelines, as previously noted. Table 1 presents the initial land use scenario, and Table 2 shows the result of our procedure by each place type. The site has four distinct character zones or place types: 'Town Center' featuring a range of high density uses combining employment and retail functions with high-rise housing; 'Village Center' with moderate density and a higher proportion of mid-rise housing along with local retail, civic, and commercial functions; 'Urban Residential' offering a variety of high-density multi-family residential uses along with open space; low-density 'Hamlets' dominated by housing, with retail and civic uses to complement the residential character; and 'Industrial Areas' consisting of light industrial uses (Calthorpe Associates 2008).

6 Results

Table 3 compares some of the indicators for Scenario 1, based on the initial land use intensity, and Scenario 2, presenting performance measurements derived from the new preferred land use intensity levels that have been calculated in this study.

The results clearly indicate that the study site can support higher land use intensity with approximately the same trip distribution pattern while meeting the objectives and level of service expected on the roads. The flow chart of the process applied in this study is presented in Figure 3.

7 Conclusion

This paper presented an innovative methodology for determining optimal land use intensity for a given site based on target traffic volume on roads. The methodology was applied for an undeveloped site in Algabas, Almaty, Kazakhstan. However, the procedure is globally applicable. The impetus for development of the methodology introduced in this paper is to maximize land use intensity and, therefore, a high (but acceptable) ratio of traffic volume to roadway capacity was set as the target; however, the methodology can be applied for any level-of-service target.

Conventional thinking in coping with traffic congestion has been to minimize the traffic volume-to-capacity (v/c) ratio. This approach has encouraged planning for cars rather than for people. The resulting emphasis on new highways, wider roads, spaghetti interchanges, and low-density developments has led to lower accessibility and greater vehicle kilometers traveled. This, in turn, has created sprawl, which drives further implementation of the same measures. Such a vicious circle has caused cities to allocate their resources in an inefficient manner through a series of high cost "improvements"—converting many cities that once offered residents a sense of belonging to a collection of rough infrastructure facilities designed to accommodate cars. De-population and decentralization should be halted, and growth directed back to the core of cities. To achieve this goal, planners and policy makers should develop tools to optimize the level of land use intensity and avoid underutilization of infrastructure.

The methodology introduced in this paper should be considered by planners and be used as a tool and a guideline to allocate available land more efficiently and effectively. The underlying objective of the methodology described in this paper is to accommodate more users on any given infrastructure while still providing an acceptable level of service, thus, reducing overall cost. Moreover, the application of such a procedure will lead to additional benefits not accounted for in the proposed model, including establishing a better mix of land uses that reduces the need for driving and encouraging the use of public transit.

Table 1: Initial design land use data.

District	Residential Dwelling Units		Gross Floor Area (m^2)		Total Area (m^2)	Students
	Villa	Town House	Office	Retail	Industrial	School
Town Center	0	9370	83875	18300	0	5622
Village Center	0	12874	20750	20750	0	7724
Urban Residential	0	8728	0	0	0	5237
Hamlets	1333	1355	0	8000	0	1826
Industrial Area	0	0	83875	2100	17900	0
Total	1333	32327	188500	49150	17900	20409

Table 2: Recommended land use resulted from the applied methodology. Number of school students remained the same initially, but increased based on the final number of residents.

District	Residential Dwelling Units		Gross Floor Area (m^2)		Total Area (m^2)	Students
	Villa	Town House	Office	Retail	Industrial	School
Town Center	0	13380	108805	26923	0	5622
Village Center	0	19858	36959	26365	0	7724
Urban Residential	0	8210	0	0	0	5237
Hamlets	2261	4777	0	17155	0	1826
Industrial Area	0	0	83875	2100	17900	0
Total	2261	46226	229640	72544	17900	20409

Table 3: Change of trip indicators, initial land use versus adjusted.

Performance Measurement	Model output resulted by the initial land use	Model output resulted by recommended land use
Total morning peak hour trips (entering parcels)	9385	10549
Total morning peak hour trips (leaving parcels)	18552	24964
Trips per km^2 (entering parcels)	19.35	21.7
Trips per km^2 (leaving parcels)	38.25	51.5
Average Trip Length (kilometer)	0.943	1.403
Percent vehicle km traveled on all links with v/c 0–0.8	1%	0.7%
Percent vehicle km traveled on all links with v/c 0.8–1	0%	0.16%
Percent vehicle km traveled on all links with v/c > 1	0%	0.14%

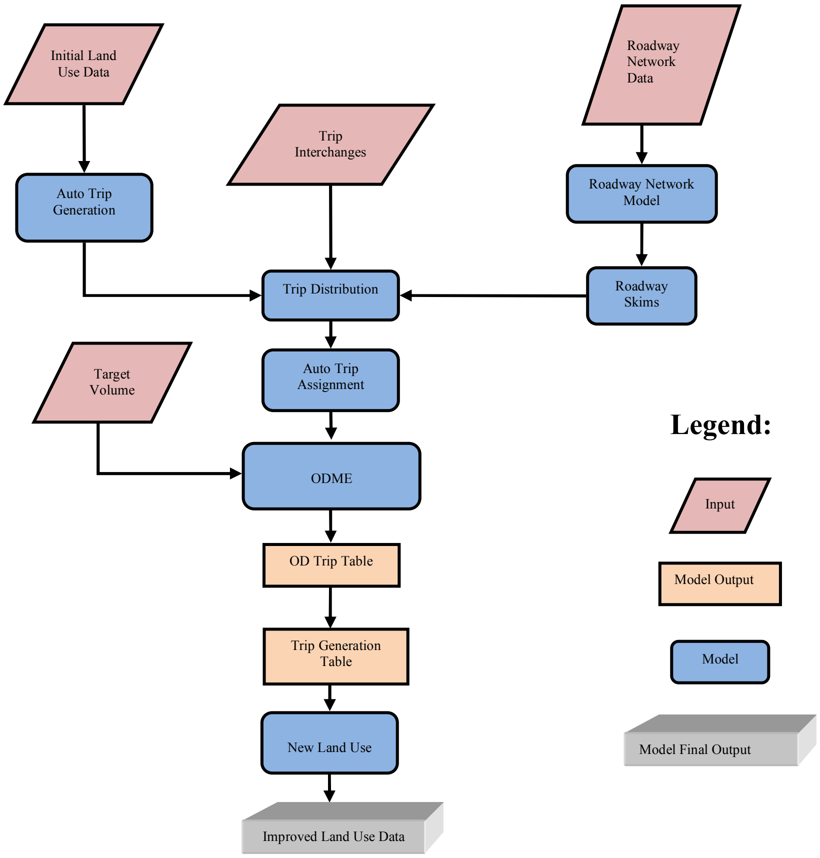

Figure 3: Process used to bring the initial land use close to the recommended preferred land use.

The process described in this paper provides planners with a tool that can be used to create guidelines for more prudent planning. Furthermore, it should enable planners to avoid trial-and-error experimentation, as this process begins with the end product and creates the final land use plan through "reverse engineering."

Finally, this study could be the basis for further research on the optimization of land use plans subject to other constraints, including traffic level of service.

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