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Article

Modeling the Urban Freight-Transportation System Using the System Dynamics Approach

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Abstract: The dynamic and complex interactions between the urban freight-transportation system and population, economy, traffic flow, fuel consumption, and environmental pollution, make policy-making in this system one of the fundamental challenges of urban management. In this regard, a systemic approach in urban freight-transportation system modelling should be considered to solve the problems of the system. One of the main problems of this system is the mismatch between the freight-transportation capacity and the total freight-transportation demand. Considering the lack of sufficient studies in the field of macro and quantitative modeling of this system, the main goal of this article is to model the urban freight-transportation system in order to identify the factors affecting the urban freight-transportation demand and capacity. The main focus of the research is to develop quantitative scenarios which balance the freight-transportation capacity and freight-transportation demand. The urban freight-transportation system is modelled by the System Dynamics (SD) approach and their basic behaviors; as well as this the results of some policy-making scenarios are simulated. The model is validated by the real data of Shiraz. Five quantitative scenarios are designed with two approaches of managing the freight-transportation demand and freight-transportation-capacity sectors. The scenarios are based on four control variables, including the distribution coefficient, trip numbers, vehicle capacity, and vehicle numbers. The simulation results show that the total gap between freight-transportation capacity and freight-transportation demand will decrease by optimizing each of the control variables. However, the combined scenario is the most applicable policy in order to maintain the balance between freight-transportation capacity and demand. Generally, the proposed model can be used to design different quantitative scenarios in order to optimize the freight-transportation system's performance. This study can also help policymakers to manage the urban freight-transportation system more efficiently.

Keywords: urban freight-transportation system; system dynamics; freight-transportation modeling; urban freight-transportation demand; urban freight-transportation capacity

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1. Introduction

The increasing trend towards the concentration of economic activities and the consequent tendency towards urbanization and urban population increase in recent years can be seen in cities all over the world. This trend creates an increasing demand for freight transportation, especially in urban densities, and as a result, increases the number of freight-transportation trips and the necessity of developing urban freight-transportation capacity. The increasing number of freight trips in urban areas and the frequent stops of freight vehicles increase environmental pollutants, the use of road infrastructure and its maintenance costs, the risk of traffic accidents, the time of transportation of goods, fuel consumption, and traffic congestion. Therefore, strategic planning that involves the cooperation of the stakeholders is necessary. However, due to the conflicts of interests between the relevant stakeholders, this strategic procedure should be designed to address the inconsistencies between ecological goals and economic acceptability.

One of the most critical aspects of strategic planning in urban freight-transportation systems is supply demand management. In other words, efficient urban freight-transportation management requires strategies that create and maintain the balance between the freight-transportation capacity and urban freight-transportation demand so that the system does not face excess demand or excess supply.

The urban freight-transportation system is very complex at the urban level due to the interdependencies of internal variables as well as its mutual relationships with other systems. Therefore, a fundamental understanding of the interdependencies between these systems and the decisions and behavior of the urban transportation system is necessary to develop efficient solutions. An urban freight-transportation system should be modeled to create such solutions and strategies and evaluate their results. However, previous studies which used traditional transportation models were not successful in integrating functional behavior with the interdependencies of sub-systems. Therefore, it is necessary to use models that evaluate and analyze the dynamics, complexity, and internal interactions of the urban freight-transportation system.

Specifically, one of the main problems of the urban freight-transportation system is the mismatch between the freight-transportation capacity and the total freight-transportation demand. Therefore, the main focus of the current research is to find solutions that balance the freight-transportation demand and capacity of the urban freight-transportation system. These solutions should be adopted in such a way that, on the one hand, the capacity of the system meets all the available freight-transportation demands, and on the other hand, the system does not face excess capacity. Accordingly, the main goal of this article is to model the urban freight-transportation system to identify the factors affecting urban freight-transportation demand as well as urban freight-transportation capacity and also to identify the causes of the problem in the system and to adopt policies which solve the problem of capacity–demand mismatch in urban freight-transportation systems.

In this article, in order to balance system supply and demand, a system dynamics approach was used. This approach has been used for long-term forecasting, trend analyzing, and investigating the fundamental changes in systems behavior over time. In system dynamics modeling, not only can the behavioral changes of the transportation system variables be examined over time but, also the effect of these changes on urban freight transportation can be observed and analyzed.

The novelty of the present research can be seen in the two methods of modeling urban freight transportation: in a macro way, with a holistic and systemic approach, which has not been observed in past research articles, and using a dynamic method that examines the interactions of all the influencing variables of the system quantitatively and is capable of scenario planning in the urban area by using real data.

2. Literature Review

Current approaches in freight-transportation modeling are mainly classic transportation models that design and evaluate actions and policies while considering interrelated variables. However, most of these approaches have developed in the passenger-transportation system, and there is not any outstanding progress in freight transportation. Although transport models and variables have descriptive characteristics, these models have little sensitivity to behavioral measures and logistic variables. Therefore, the weakness of these econometric models is that it ignores the effect of behavioral characteristics in estimating transportation supply and demand [1]. Econometric models that only evaluate microscopic feedback have changed into models that consider behavioral feedback in separate stages over time. Considering feedback into the transportation models, the sensitivity of models to changes in variables has also increased. Therefore, a freight-transportation model could be evaluated with more criteria. However, due to the heterogeneity of indicators related to stakeholders and the complexity of the freight-transportation system, the behavior-sensitive models in freight transportation developed very slowly. The problem of heterogeneity has been investigated based on the principles of Monte Carlo simulation using optimization methods. Also, factor models which deal with classifying the system's stakeholders and their goals have been presented in the literature.

At this stage, researches need further development and progress from two perspectives. Firstly, they need to use methods that result in managerial and policy-making solutions for the stakeholders of the system. Additionally, secondly, the models did not consider the basis of the four-step approach in freight-transportation.

Goods flow-based models, tour-based models, and hybrid models provided the possibility of considering the four-step approach of freight-transportation according to their reference values. Goods flow-based models have been mainly used in interregional transport planning. De Jong and Ben-Akiva developed a logistic model and applied it to the national freight model systems of Norway and Sweden. This logistic model operated at the level of individual firm-to-firm relationships and simulated the choice of shipment size and transport chain [2]. Tour-based models use various methods such as simulating the decisions of different stakeholders, evaluating the sequence of decisions, and evaluating different goals of decision makers. Wisetjindawat et al. developed a micro-simulation model for urban freight-transportation by considering the behavior of transport agents and their relationship in the supply chain in the Tokyo metropolitan area. The proposed model was a modification of the traditional four-step approach that considered the behavior of each transport agent separately. The results of this model were truck OD and approximate VKT matrices based on each type of truck [3]. Routhier and Toilier presented a tour-based and land-use model for simulating urban goods movement. Using establishment surveys coupled with driver surveys, this research estimated the model of moving goods based on the shippers and the haulers, environment, the characteristics of the establishments, and urban land use [4]. Using data from the city of Toronto, Roorda et al. presented an agent-based microsimulation framework that showed the diversity of roles and functions of actors in the transportation system, how they interact through markets, and how actors in markets interact through contracts. This framework provided sensitivity to technology trends, business trends and policy scenarios [5]. Some researchers have also integrated logistics stakeholders (shipper and carrier) in multi-agent transport simulation. In the research of Schroeder et al., a multi-agent freight-transport model was presented, in which logistics decisions were divided into two different roles of transportation service providers and carriers. Using MATSim traffic simulation, they created an integrated model for freight and passenger transport [6]. Some of other researchers used a hybrid model to simulate freight transport. In the research of Joubert et al., a hybrid model was used to simulate business activity chains, along with private vehicles, for a large-scale scenario in Gauteng, South Africa [7].

Despite the development of freight-transportation models at this stage, one of the problems of the used models was the lack of a systematic approach to transportation. It was necessary to pay attention to the systemic nature of transportation so that the system could be evaluated as interrelated elements and influenced by its environment according to the definition of its boundaries [8]. The necessity of evaluating the effects of economic and social processes on the transportation system, and the complexity of endogenous variable dynamics, led the researchers to use the system dynamics approach. This method simulates the interdependency of the system's main variables, such as population, economic development, number of vehicles, environmental impact, travel demand, transportation supply, traffic congestion, traffic infrastructure, safety, and environmental issues based on cause-and-effect analysis and feedback loop structures. In order to realize the relationship between the economic development and ecological sustainability of Tianjin city, Zhan et al. used system dynamics to find a balance between economic development and ecological protection. This model was built based on three subsystems of the society system, the economic system and the environmental system [9]. The paper of Ruutu et al. presented a simulation model that demonstrated vehicle choice among different types of private cars and public transportation. This model was used to investigate the effects of different policies to reduce greenhouse gas emissions. The simulation results show that policies should be designed in such a way that they work well together and do not undermine each other's effects [10]. In the article by Ercan et al., the transportation mode choice behavior of US passengers and transit transportation evaluated in the context of reducing CO_2 emissions and some scenarios were presented. The results indicated that in order to reduce fuel consumption and CO_2 emissions, marginal and ambitious scenarios should be implemented [11]. The research of Haghshenas et al. aimed to analyze the effects of different transportation policies using the system dynamics model. In this study, three indicators of sustainable city transportation (environmental, economic and social) and a combined index were used, and time-series data of Isfahan city were used to validate the results [12]. The paper of Goh and Love developed two models to show how system dynamics can facilitate and encourage macro- and meso-level analysis of traffic safety policy. The first model was used to evaluate policy options to encourage the purchase of cars with higher safety ratings. The second model was used to evaluate the impact of public transportation policies on travel time and traffic safety [13]. In the research of Cao and Menendez, a model was built to design and evaluate different parking policies to improve the performance of urban parking and the urban traffic systems [14]. Using system dynamics, Liu and Xiao conducted a scenario analysis to evaluate how Electric Vehicles (EV) develop in China [15].

With the development of system dynamics models, freight transportation was modeled in some researches as a part of the transportation sub-system. Indeed, it was not the main focus of these groups of studies. Some other researchers used system dynamics to simulate only a part of the freight-transportation system and supply chain management [16]. With the aim of reducing carbon emissions in the transportation sector, Hong et al. modeled the carbon emission system in the field of road and rail transportation with a systemic approach. By defining the scenario of imposing a carbon emission tax, the results showed that road freight transportation should be transferred to rail transport within a reasonable range [17]. Han and Yoshitsugu developed a system dynamics model to evaluate the CO_2 reduction in intercity transport in China [18]. In Aschauer's study, the system dynamics used to depend logistics strategies and freight transportation. The developed model resulted in a comprehensive description of system operations (logistics strategy parameters) as well as transportation-related factors (toll, CO_2 internalization, infrastructure capacity) [19]. Wang et al. evaluated reducing CO_2 emissions by designing three scenarios in Beijing's urban freight-transportation system [20].

Some other researches, which used system dynamics in road freight transportation, focused only on some minor issues such as overloading, the effects of new technologies, and e-commerce [1]. Qisulfi et al., using the system dynamics method in Brazilian highways, investigated different policies for the loading of ornamental stone vehicles and its impacts on transportation costs, pavement maintenance, and accidents. The results confirmed that the best vehicle-loading policy depends on the relative importance of the relevant economic and social costs [21]. In order to investigate the effects of overweight in China, Hang and Li developed a methodological framework to evaluate truck weight regulation using system dynamics by five subsystems. Since reducing the maximum allowed load carried by trucks was not economically viable, modal shift was a potential way to achieve freight-transportation sustainability and encourage the use of more efficient modes of transportation [22]. In the study of Guo et al., a system dynamics model was developed to investigate the long-term impact of emerging transport technologies (ETTs) on road profit and greenhouse gas emissions. The road transport companies related to Qingdao port in China were taken as a case study. In this study, the economic and environmental impact of the adoption of ETTs was projected from 2020 to 2035 [23].

Another area of research developed dynamic models at a regional–national level, mainly focused on the maritime, railway, air transportation, underground logistics, and suburban sectors. Jeon et al. used system dynamics to reveal the complex nonlinear structure of container freight. The China Containerized Freight Index (CCFI) was investigated through different parametric methods (conventional time-series and system dynamics approaches) [24]. In another article, Jeon et al. investigated the cyclical nature of the container shipping market and proposed a predictive cyclical model of the market using a container freight index. Unlike traditional (univariate) spectral analysis, system dynamics with a multivariate systemic equilibrium approach reflected market drivers on both supply and demand sides [25]. Wang and Zhang's paper presented a dynamic system model consisting of three sub-models of the economic environment, demand–supply, and investment to simulate the interaction between the demand and supply of rail transport in China. In this study, three scenarios have been simulated with the aim of covering the demand–supply gap of railway express freight [26]. Hu et al. used system dynamics to simulate the development of a rail transit network using two sub-models. They used a set of variables affecting system operation, such as metrics of social and environmental externalities, pricing, investment and subsidies. For validation, a case study of Beijing from 2007 to 2035 was used. Three decision variables (i.e., investment policy, network scale, and market competitiveness) were combined in separate scenarios to investigate external benefits [27]. In Manataki and Zografos's research, a mesoscopic model was developed to analyze airport terminal performance, which struck a balance between flexibility and realistic results. The proposed system dynamics model provided compatibility with the configuration and operational characteristics of a wide range of airport terminals. The capabilities of the proposed model are shown through the analysis of the Athens International Airport terminal [28]. Dong et al. analyzed the quantitative relationship between Underground Logistics System (ULS) and the sustainability of urban transportation by using the system dynamics method. Using Beijing city's data, Four ULS implementation strategies were proposed and four indicators (including average speed of road networks in peak hour, congestion reduction, delivery travel time in peak hour and truck PM emission) were selected to evaluate the simulation results [29].

In summary, primitive freight-transportation modeling improved over time due to the low sensitivity of past methods to behavioral-oriented measures and logistic variables. Indeed, they improved the evaluation of the influence of behavioral characteristics in transportation. After moving from optimization methods and factor models toward dynamic models, researchers employed the system dynamics method to consider the heterogeneity of stakeholder indicators and the complexity of the freight-transportation system. The literature review shows that most of these studies used the system dynamics method in modeling the passenger transportation sector. Those research studies that used the system dynamics method in the field of freight transportation were limited primarily to maritime, rail, air transportation, and underground logistics. Research that modeled road freight transportation studied some partial areas such as the effect of overweight, new technologies and e-commerce. Some other research mainly focused on the interdependencies of this system at the national and regional levels. None of these studies have quantitatively validated, simulated, and analyzed scenarios at an urban level.

Here, a lack of sufficient studies can be seen that have developed a model that examines urban freight-transportation management at a macro perspective, and that are able to make policies in the field of urban management based on real data and mathematical equations. In this regard, this article covers the study gap in the literature by modelling an urban freight-transportation system using system dynamics. The urban freight-transportation system is modeled, and the behavior of the system is simulated by identifying many effective variables and formulating their dynamic interactions. So, this model is capable of being used in any urban freight-transportation system for policy-making and scenario-planning. Then, the model is validated using factual quantitative data and finally, different scenarios were designed and evaluated. This made the model capable of including the general and managerial scope of the research in line with policymaking in the field of urban management.

3. Materials and Methods

System dynamics is an approach to discover nonlinear dynamic behavior and study how system structures and variables affect system behaviors. It uses simulation modeling based on feedback system theory that complements system thinking approaches. It applies to dynamic problems arising in complex social, managerial, economic, or ecological systems. The output of the discrete simulation of systems with this approach is the design of effective policies to achieve high levels of efficiency, which means that the structure of each system affects its dynamic behavior. In this approach, an image of the system is created based on feedbacks, so that the dynamic behavior of complex systems can be better understood. In order to carry out the steps of the system dynamics method, based on the methodology of Forrester (the founder of this methodology), in the first step, the problem of the decision makers and the variables affecting it should be identified. Then, the feedback loops of the system are identified and the relationships between the variables are drawn. In the next step, the drawn pattern is formulated based on mathematical equations and transferred to the relevant application software in the form of stock-flow variables. Then, the model is validated and its behavior is compared with the real data. After that, some policies are implemented to improve the system performance, and finally, recommendations are provided to decision makers to improve system performance [30]. System dynamics includes tools to explain the model, determine its boundary, display the causal structure of the variables, and simulate the model. These diagrams include a model boundary diagram, subsystem diagram, causal-loop diagram, and stock-flow diagram. A causal-loop diagram is a tool for drawing causal relationships between a set of variables in a system and explaining the feedbacks in the cause–effect relationships. A stock-flow diagram is a tool for formulating the relationships and simulating the model.

The justification of implementing the system dynamic method in this article can be mentioned from two points of view. Firstly, complexity and dynamism are the most important features of an urban freight-transportation system, and it can be evaluated and classified as a complex and evolved system. These features have made it challenging to understand the system behavior and formulate effective solutions to achieve optimum performance. Such a system's characteristics differ from simple and linear relations, and naturally, their analysis also requires the use of new and creative approaches. To face such problems, it seems more necessary to develop approaches that can create a deep and comprehensive understanding of the system. It is necessary to have a systematic thinking, so that one can develop boundaries of their mental models and use compatible tools which can be used to understand the structure of a complex urban freight-transportation system and its behavior. Secondly, since the system dynamics provide a comprehensive framework to analyze a particular system, it makes other researchers confident about the generalizability of the model design across various contexts and conditions. This is because system dynamics captures the dynamics of real-world phenomena in a particular system, which can be captured in other similar systems to observe how different variables interact to produce certain outcomes. In this case, the model should be validated with the real data of each particular system.

In this article, in the first step the problem definition, system boundary, and endogenous variables were identified. Then, based on the internal structure of the sub-systems and the feedback between each of the variables, the conceptual model was created in the form of causal-loop diagrams (CLD). In the next step, causal-loop diagrams were transformed to stock-flow diagrams and formulated based on mathematical equations. Then, the model was validated, and its behavior was compared with real data. After validating the model, some scenarios were designed and implemented to improve the system performance. Then, the results of each of these scenarios were analyzed. Finally, based on these scenarios, some recommendations were provided to decision makers to improve the system performance.

The main focus of the designed model is on the decision-making and scenario-planning processes based on the interaction of two sub-systems, the freight-transportation demand and freight-transportation capacity. The model intended to simulate the dynamic behavior of freight-transportation demand and examine its interactions with the freight-transportation capacity at an urban level.

In order to verify the problem-solving scenarios, general dynamic hypotheses were developed based on the interaction of the main variables of the system. A dynamic hypothesis is an idea about what structure might be capable of generating behavior like that in the systems' main variables. A dynamics hypothesis can be stated verbally, and in this case it can be expressed as follows:

- An increase in freight-transportation demand leads to an increase in its discrepancy with the freight-transportation capacity and as a result, reinforces the development process of freight-transportation capacity.
- If freight-transportation capacity is more than freight-transportation demand, due to the excess supply in the system, the process of freight-transportation capacity development becomes slower in order to balance supply and demand in the system.
- An increase in the main influencing variables of the freight-transportation-capacity sub-system, such as travel length, number of freight trips, and the numbers and average capacity of the transportation fleet, in accordance with the existing freight demand in the system, leads to an increase in the freight-transportation capacity.
- Optimizing the urban freight-distribution system, by reducing the distribution coefficient, leads to a decrease in total freight-transportation demand.

To calibrate the model and adjust the relationships of the variables and equations of the system dynamics model, the mentioned model was simulated in the freight-transportation system of Shiraz using the data from 2000 to 2022. The projected scenarios evaluated were for the years 2022–2037. Located in Iran, Shiraz is the capital of Fars province and has an area of 193 square kilometers and had a population of 1,872,730 people in 2022.

3.1. *Freight-Transportation-Demand Modeling*

The demand for freight transportation at an urban level is affected by urban structural features and citizens' demand for consumer goods. The amount of consumer goods is influenced by socioeconomic variables. Due to the different influencing variables which determine the consumption of different types of freight, the estimation of the demand of freight was modeled in different groups. Various causal loop diagrams and stock-flow structures were created for each of the so-called groups based on the relationships between each sub-system. These groups include fruit, food, agricultural, construction, and industrial freight. According to "Shiraz's Transportation Master Plan", the urban freight groups are divided into six categories including fruit, food, agricultural, construction, industrial, and oil-petrochemical freight. Oil-petrochemical freights are not affected by urban policies because they are sent to destinations as a one-time distribution freight, and the road assignment and fleet allocation cannot be changed. Also, they account for a small amount of total urban freight according to the statistics. Therefore, the total urban freight was classified into the five categories of fruit, food, agricultural, construction, and industrial freight.

3.1.1. Socioeconomic Structure and Consumption Behavior

Population behavior, household structure, and economic variables, which define the pattern of goods consumption behavior, were developed in the form of a stock-flow diagram, as shown in Figure 1. This diagram shows the interactions and feedback between endogenous socio-economic variables. Population is affected by birth rate, death rate, and net migration rate. The interaction between the population and the household size determines the household numbers. Regardless of the population growth, the number of households increases as the household size decreases. The per capita income of each household determines the household consumption pattern. The interaction of the GDP and the total number of households determines the per capita income of the household. An increase in GDP leads to a rise in household income. If the level of per capita household income increases, the net migration rate will be higher. A low level of per capita income has a negative effect on the migration rate as a deterrent factor. These variables and their interdependencies describe the socioeconomic characteristics of goods consumption.

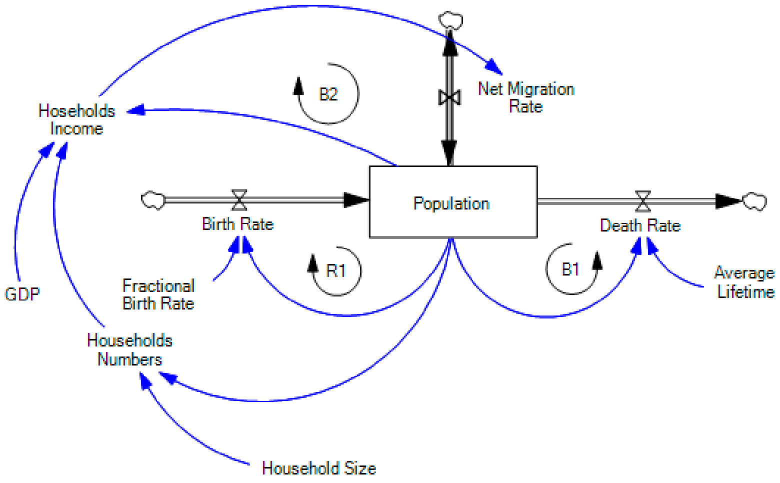

Figure 1. Socioeconomic structure and consumption behavior.

Socioeconomic structure, household structure, and economic variables of urban households determine the consumption demand of each group of fruit, food, agricultural, construction, and industrial freight. In fact, the variables in socioeconomic structure and consumption behavior, such as the number of households and household income, have been used as inputs for the estimation of the consumption freight in each of freight groups.

3.1.2. Consumption Fruit Freight Demand

Socioeconomic variables, such as population, household numbers, and per capita income, determine the demand for fruits and vegetable. The total amount of consuming freight for fruit and vegetable, was estimated in two categories: consumption and passing freights (Figure 2).

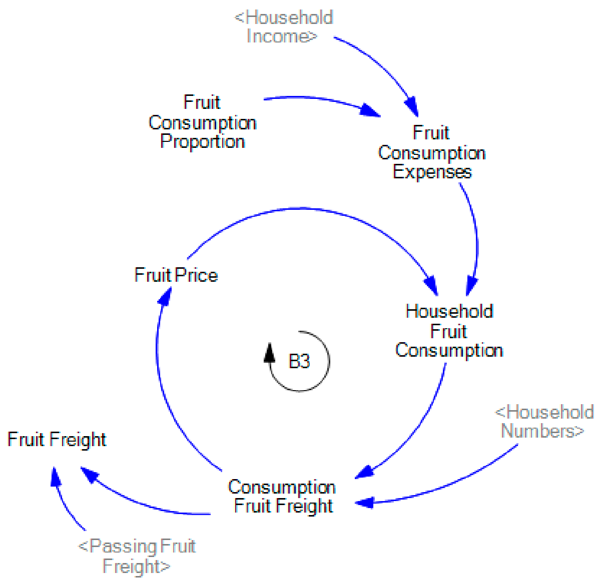

Figure 2. Consumption fruit freight demand.

The consumption demand of fruit freight was determined by the interaction between household numbers and the per capita fruit consumption of each household. The per capita consumption by each household was determined by the fruit's consumption expenses and the average price of fruit and vegetable. Consumption expenses for each household were considered as a coefficient of the per capita income. The fruit-consumption proportion shows how much household income is spent on buying fruits and vegetables. As the consumption proportion of fruits and vegetables rises, the demand for fruits and vegetables will increase. With a decrease in the average cost of fruits or an increase in household numbers, the consumption demand for fruit freight increases. The average price of fruits is affected by the inflation rate. Due to the increase in the demand for fruits and vegetables, the average price of fruits will increase, which will lead to a decrease in the consumption of fruits and vegetables for each household.

Passing fruit freight is a part of the other cities' consumption demand, which is supplied through the central fruit market of the city under investigation. The investigated city is the capital of the province; therefore, a part of other cities' demands for freight is transported through that city. The amount of consumption freight of other cities was simulated similarly to the model designed to estimate the demand of the investigated city.

3.1.3. Consumption Food Freight Demand

Similar to the simulation of fruit freight consumption demand, the total amount of food freight demand was modeled in two categories, consumption and passing freight. It is affected by socioeconomic variables. The passing food freight demand is a part of the consumption freight demand of other cities, which is supplied through the merchant's complex of the investigated city (Figure 3).

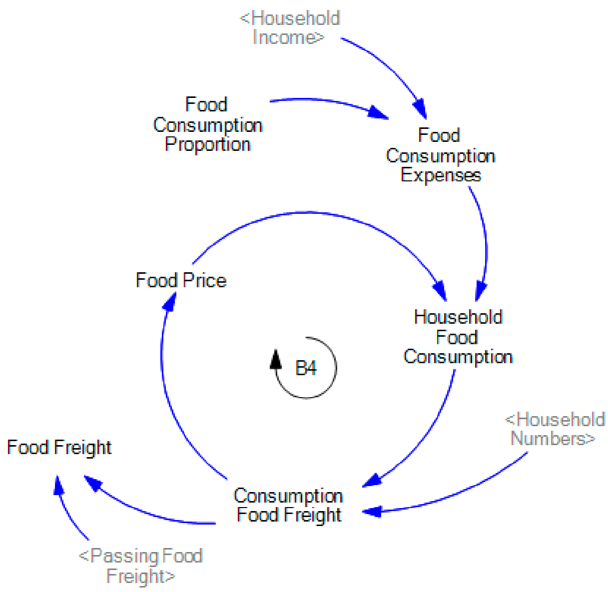

Figure 3. Consumption food freight demand.

3.1.4. Consumption Agricultural Freight Demand

The consumption agricultural freight demand contains the freight demand of two categories: factories that use agricultural products as their raw materials, and stores that distribute toxicants, fertilizers, and seeds (Figure 4). The consumption demand for the mentioned factories was determined by the interaction of the number of factories and the average amount of raw materials needed by each factory. The input rate of the number of factories is affected by the sales of each of them. As the number of factories increases, their profitability decreases according to the existing demand (loop B5). Legal restrictions in establishing new factories in the urban areas will reduce the number of factories. The interaction between the number of stores and the average consumption demand of each store determines the store freight demand. According to the amount of demand for the products of these stores, the more their numbers will be, the less the sales and profitability of these stores will be. As a result, the setting-up rate reduces (loop B6). The area of agricultural land, the amount of harvest, and the amount of poison, seed, and fertilizer identify the demand for store products.

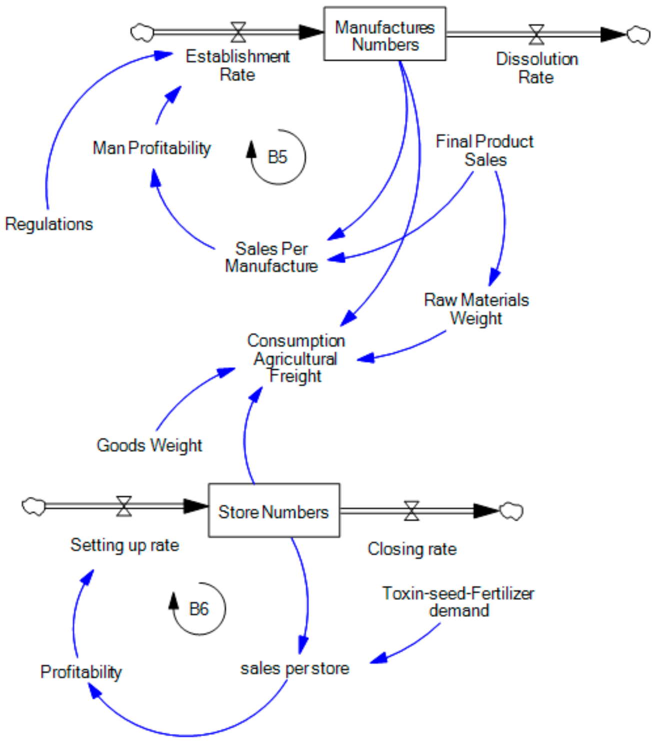

Figure 4. Consumption Agricultural Freight Demand.

3.1.5. Consumption Construction Freight Demand

The estimation of the construction freight demand can be considered two categories: the building construction freight demand and repair-reconstruction freight demand (Figure 5).

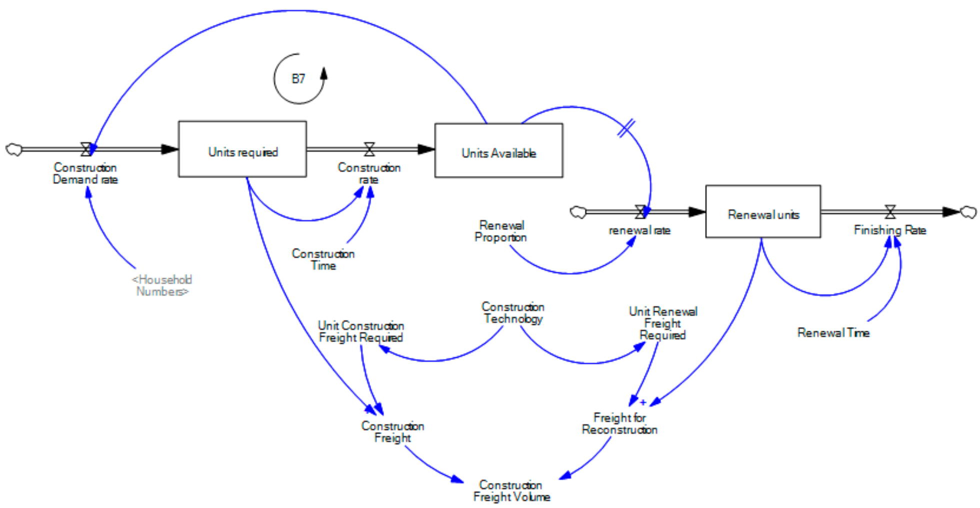

Figure 5. Consumption Construction Freight Demand.

Freight demand for construction results from the interaction of the number of required units (residential and non-residential) and the amount of construction load required to build each unit. The number of required units, regarding residential units, is obtained from the difference between the number of existing units and the number of existing households that apply for residential units. As the number of households increases according to the reinforcing loop of the population and the size of the household, the demand rate of the required residential units increases. The more significant the difference between the demand required for building units and the existing units is, the more the rate of construction demand increases. The interaction of the number of existing units and socio-economic variables, such as the level of demand and economic profitability, identify the required rate of non-residential units. Based on the construction time of each unit and the construction rate, the number of existing units increases, and, accordingly, the demand for the construction of new units decreases (loop B7). The freight required for construction per unit is affected by the construction technology, which determines the weight of materials per square meter of each unit. The freight demand for the repair-reconstruction of building units is obtained based on the number of existing buildings that need reconstruction, the reconstruction time, and the amount of freight required for the reconstruction of each unit. The input rate of renewal unit numbers is estimated from the interaction of existing building numbers, considering a time delay (equivalent to the age of the building) and the renewal proportion (the ratio of reconstructed units to potential reconstruction units). Renewal proportion is subject to change due to economic conditions. In other words, improving economic conditions increases renewal proportion.

3.1.6. Consumption Industrial Freight Demand

Considering the nature of industrial and mineral freight as a part of the supply chain of fruit, food, agriculture, and construction groups, one part of the industrial consumption freight demand was identified by the consumption freight demand of other groups. An independent part of this category includes cars and car parts or home/office appliances and complementary goods.

The amount of freight demand derived from cars and car parts has been influenced by the number of purchased cars and the average weight of each. It has been also identified by the amount of car parts. As the number of cars increase, car ownership increases, and according to per capita income, the number of car purchases decrease (loop B8). Freight demand for home/office appliances was estimated by the interaction between the rate of building new houses and the average amount of freight needed by each unit. The amount of complementary goods was defined by the interaction of existing households and the amount of complementary goods required by each (Figure 6).

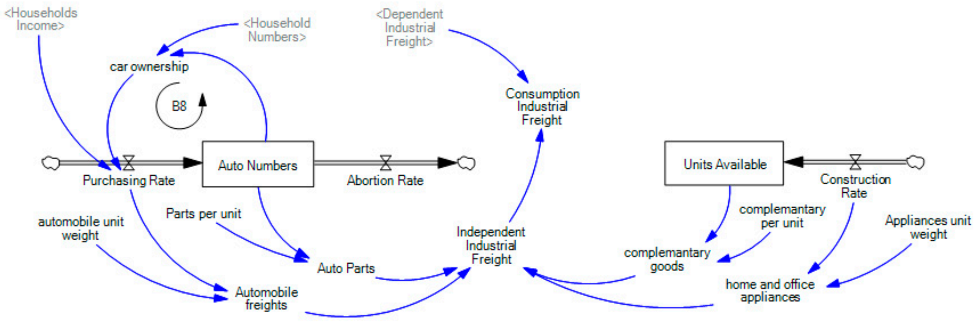

Figure 6. Consumption Industrial Freight Demand.

3.1.7. Urban Freight-Transportation Demand

The estimation of the urban freight-transportation demand is essentially different from the consumption freight demand. The urban freight-distribution system is the cause of this difference. In other words, the interaction between the consumption-freight demand and the number of moved freight in the supply chain, forms the demand for urban freight-transportation. In the simulated model, a different distribution coefficient variable was considered for each product group. The total freight demand was obtained from the total consumption freight demand of each product group (Figure 7). In other words, the causal-loop diagrams of each of the product groups determine the amount of demand for their consumption freight. Then, each of these amounts is converted into freight-transportation demand by considering the corresponding distribution coefficient. Finally, the total amount of freight-transportation demand is obtained from the sum of the freight-transportation demand of each group.

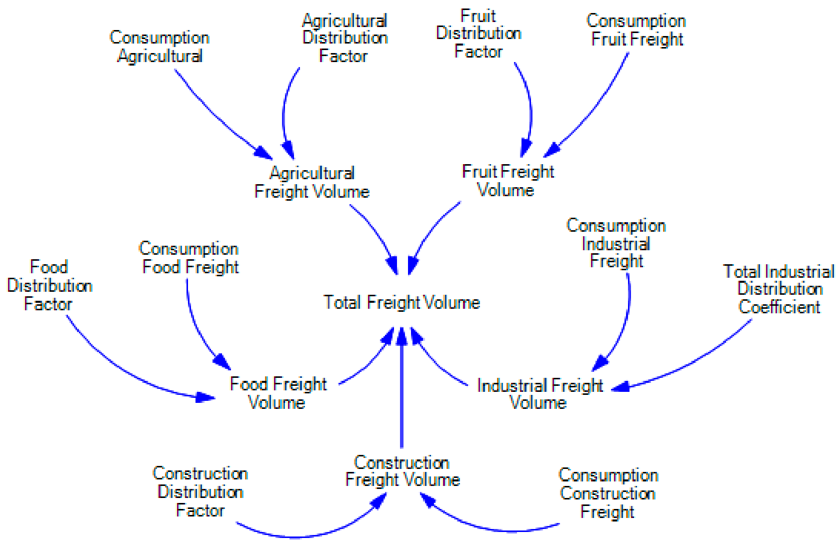

Figure 7. Urban freight-transportation Demand.

3.2. Freight-Transportation-Capacity Modeling

Various factors determine the urban freight-transportation capacity. The transportation infrastructure (number of vehicles, urban road-network conditions, loading and unloading space), vehicle technology (type and capacity of vehicles), and urban and environmental laws and regulations (legal size of vehicles, weight restrictions, and allowed travel time) are the determinants of estimating the urban freight-transportation capacity (Figure 8).

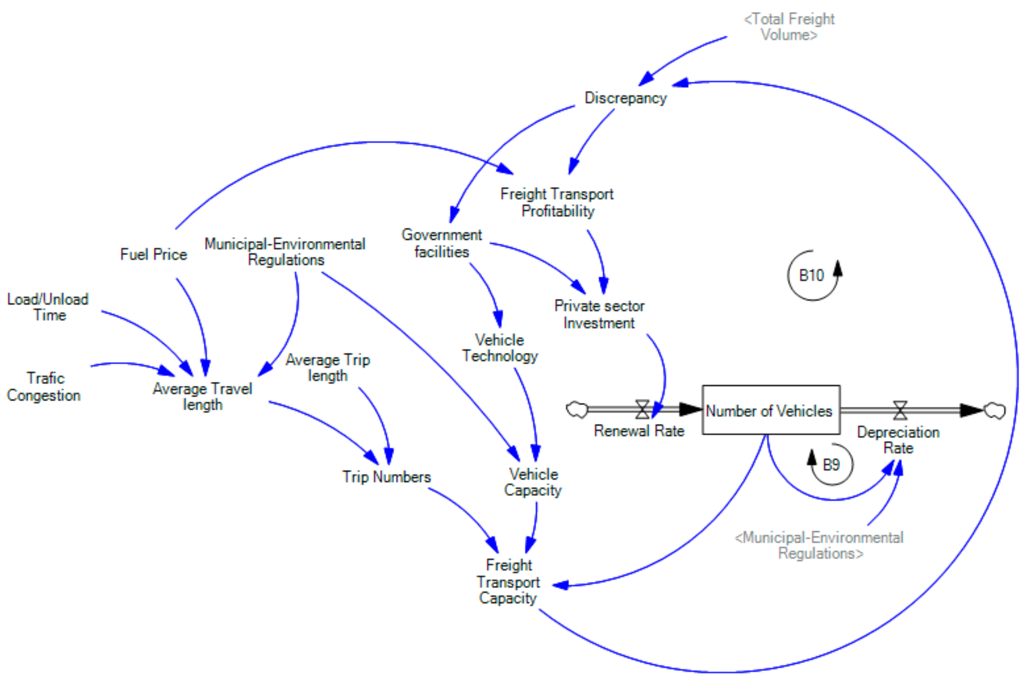

Figure 8. Freight-transportation-capacity modeling.

Urban freight-transportation capacity was identified based on the interaction between the number of trips, the average capacity of vehicles, and the number of vehicles. The average number of trips was calculated based on the average travel length and the length of each trip. The average travel length was influenced by the traffic density, average loading and unloading time, price and amount of available fuel, and urban and environmental laws and regulations, such as the time allowed to travel. Changes in vehicle technology and legal changes affect the average capacity of vehicles. With an increase in three variables, the number of trips, the number of vehicles, and the average capacity of vehicles, the freight-transportation capacity will increase.

As the attractiveness of investment in the transportation sector increases, the rate of purchase and renewal of the transportation fleets will increase. Variables such as economic profitability, government facilities, and fuel prices affect investment in the freight-transportation sector. Based on the interaction between total freight demand and total freight-transportation capacity, as the discrepancy between these two primary variables increases, the investment attractiveness and private sector investment in freight-transportation decreases. This leads to a decrease in the number of vehicles and eventually reduces the capacity for freight transportation (loop B10). The depreciation rate of the fleets depends on the useful life of the vehicles and environmental regulations. As the number of vehicles increases, the impact of depreciation on the reduction in this level variable increases (loop B9). The transportation fleet was separated into three categories of light, semi-heavy, and heavy vehicles, and freight-capacity modeling was performed separately for each of these categories.

4. Results

The model was validated and calibrated based on reference data in the period of 2000–2022 and the scenarios results were simulated for the period from 2022 to 2037. Different scenarios were planned in order to investigate the impact of changes in influencing variables either on the estimated total freight demand or on the estimated freight-transport capacity.

The historical data on population, employment (in ten categories), per capita household income, the price of consumer goods, the share of each group of goods in household expenses, car ownership, vehicle depreciation rate, variables related to construction, land value, land use, and the number of guilds (separated by 87 categories), were extracted from the databases of the "Iran Statistics Center". Since some of the mentioned variables, such as the per capita household income, price of consumer goods, the share of each group of goods in the household expenses, and vehicle depreciation rate, were extracted on average for the entire country and do not exist specifically for the investigated city, the average of the entire country was used in this article. Also, due to the fact that inflation was not available separately for the product groups used in this article, the average annual inflation rate was used for the so-called groups. The data relating to urban freight-transportation demand and capacity were extracted from "Shiraz's Transportation Master Plan", in which the number of vehicles had been gathered from the vehicle survey method, and other variable data, including freight capacity, loaded freight, and the origin and the destination of each vehicle, were extracted from the roadside interview method (in six gate stations, two cordons, and five major freight-production and attraction centers) (Figure 9).

4.1. Model Validation

The validity of the model and the results of the simulation were first checked and confirmed by Vensim software doing the loop test, dimensional consistency test, parameter assessment test, and integration error test. In the extreme condition test, some parameters of the model were significantly changed. The evidence indicated the meaningful behavior of the model in all sub-systems. Sensitivity analysis showed that the change in the main variables due to a change in the main parameters followed a rational behavioral pattern. In order to ensure the appropriateness of the behavior of the model with the actual data, the behavior-reproduction test was used. Figures 10–12 show that the historical trend and the results of the simulation of freight demand of five groups, the total freight demand, and the total freight capacity are the same. These trend lines confirm that the simulated behavior and the recorded data follow a similar pattern. Simulated values are shown with Base Run and actual values are displayed with Reference Mode. Base Run simulation shows the behavior and values of variables, based on the main structure of the system, when no intervention occurs in the system.

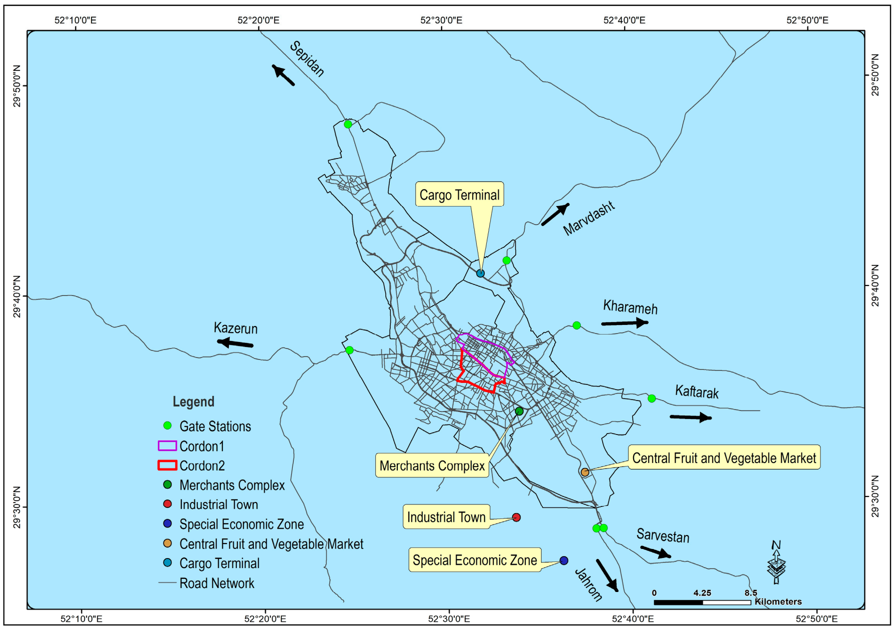

Figure 9. Descriptive diagram of freight transportation in Shiraz city.

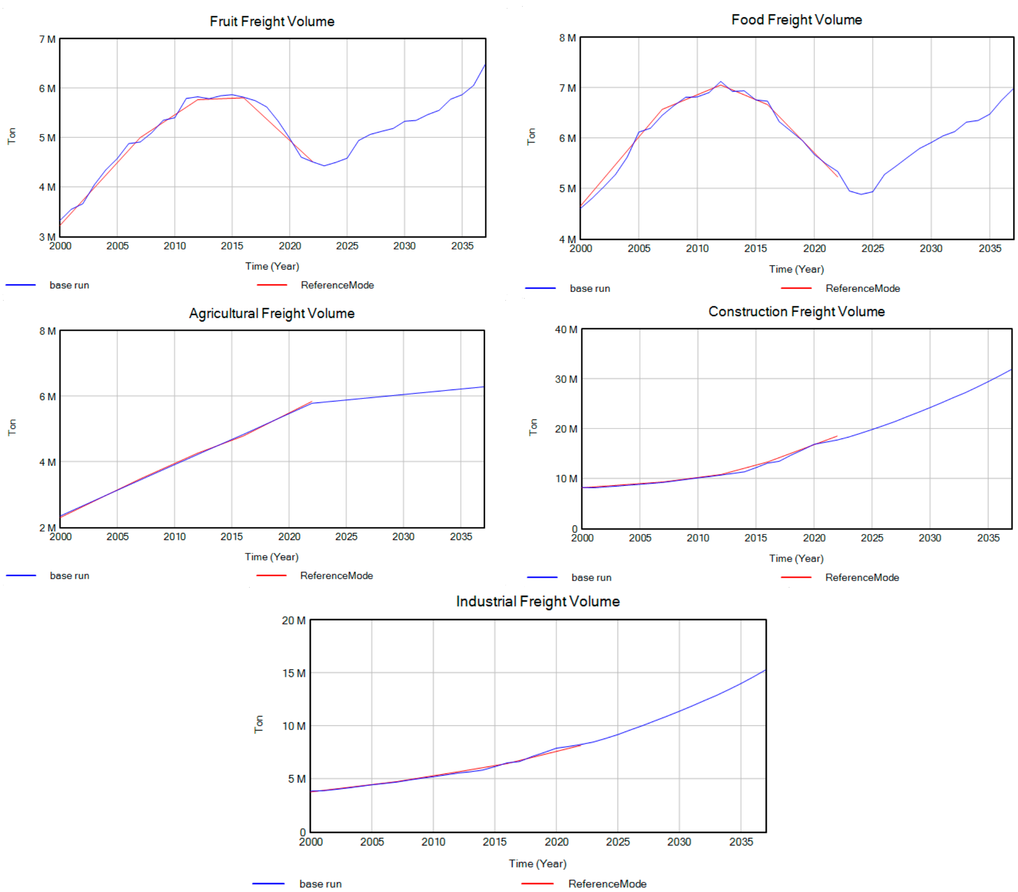

Figure 10. Behavioral reproduction of five freight categories.

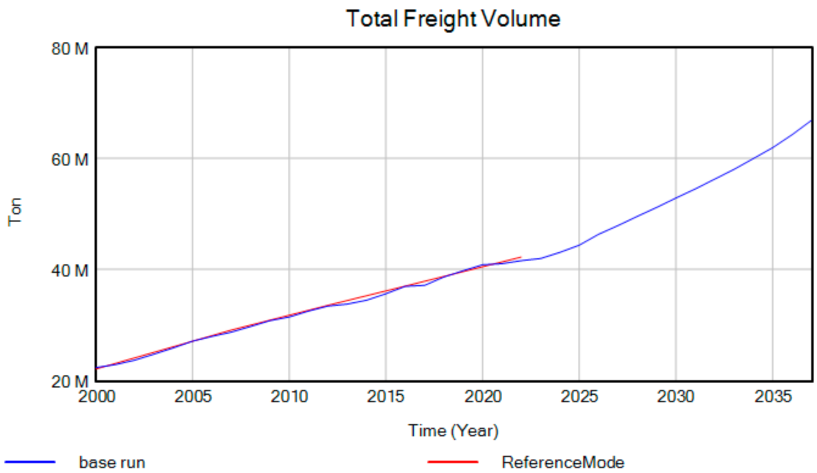

Figure 11. Behavioral reproduction of total freight-transportation demands.

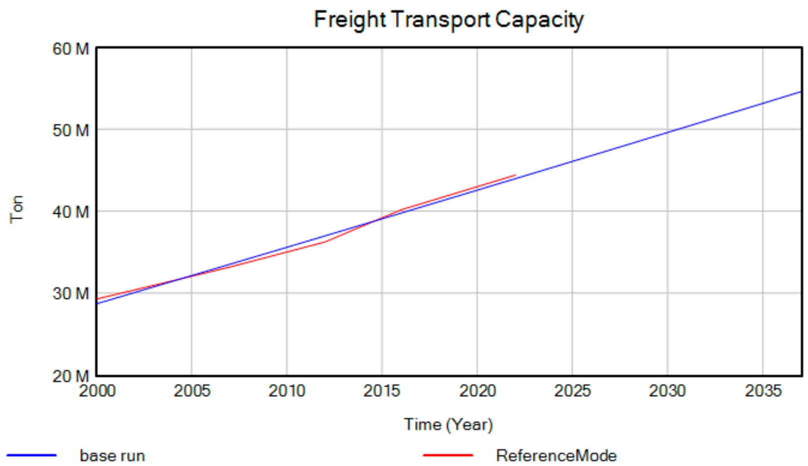

Figure 12. Behavioral reproduction of total freight-transportation capacity.

To validate the simulated results, the error of the key variables was investigated based on quantitative indicators, including RMSPE, the U_{theil} inequality coefficient, and the mean-squared error (error of deviations (U^m), unequal variation (U^s), and unequal covariation (U^c)). The results show that the simulated output fits the actual data well (Table 1).

Table 1. Quantitative test results in model validation.

Variable	RMSPE	U_{theil}	MSE		
			U^m	U^s	U^c
Total Freight Volume	0.01754	0.01485	0.18252	0.00002	0.81746
Freight-Transport Capacity	0.01961	0.02011	0.20251	0.00003	0.79746

4.2. Scenario Analysis

The Base Run simulation results show that the urban freight-transportation capacity exceeds freight demand until 2027 (Figure 13). During 2000–2027, the difference between the freight capacity and freight demand decreased, and in 2027 the freight-transportation capacity will be equal to the total freight volume, and after that the system will face a lack of capacity. Based on the balancing loop between the total freight capacity and the total freight demand variables, freight capacity had a goal-seeking behavior in the simulated system and it was adjusted by the freight-demand amount from 2000 to 2027. In other words, since the system faced excess capacity over these years, the freight-transportation capacity grew at a slower rate than the total freight-transportation demand, and the supply/demand for urban freight-transportation was adjusted. This result confirms the main dynamic hypotheses of the model and shows the correctness of the structural relationships and the main causal loops. Base Run results show that the total freight-capacity growth is not enough to overarch the total freight demand after 2027. In fact, based on the Base Run simulation, if there are no interventions in the system and its endogenous variables, the freight-transportation capacity will not be enough to handle the requested total freight-transportation after 2027. Therefore, it seems necessary to adopt policies to match the predicted freight capacity with the total freight demand.

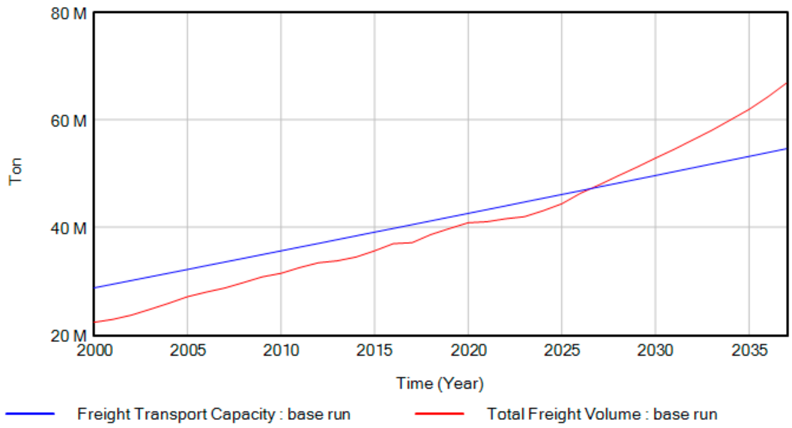

Figure 13. Freight demand and freight capacity on the base run.

These policies can be considered in two approaches, the change in the urban freight-distribution system (total freight-demand sub-system), and the change in influential freight-transportation capacity variables, in order to increase the freight capacity (total freight-capacity sub-system).

4.3. Scenario 1—Changing Urban Freight-Distribution System

Reducing the gap between the total freight capacity and total freight demand can be achieved through reducing the amount of freight demand by adopting policies aimed at reducing the freight-distribution coefficient. Basically, a decrease in each freight group's distribution coefficient results in a decrease in the transportation demand for that specific group. So, the group is expected to have a lower freight-transportation demand and, consequently, the amount of total demand does not exceed the freight capacity. In the current scenario, the effect of a 20% decrease in the freight-distribution coefficient on the amount of freight demand was investigated (Figure 14). Reducing the distribution coefficient can be achieved by adopting policies such as e-commerce, sending goods directly from manufacturers, aggregating the freight of several applicants from the origin, and so on. Considering the features of fruit, agricultural, and construction freight, the distribution coefficient of these groups remains unchanged. In this scenario, the reduction in the distribution coefficient for the food and industrial freight group was considered.

The simulation output shows that if the distribution coefficient reduces by 20% from 2027, the total gap between the freight demand and the freight capacity will reduce by 34.6% during the years 2027 to 2037. But the total freight capacity is not sufficient to meet the total freight demand. As can be seen in the Figure 14, by applying this scenario, the increasing slope of the freight-transportation demand graph will decrease from 2027 to 2037, and as a result, the difference between the freight-transportation demand and freight-transportation capacity will decrease during this period. The further reduction in the distribution coefficient does not seem logical due to the nature of its driving variables. Therefore, to reduce the gap between total freight demand and total freight capacity, it seems necessary to adopt policies aimed at increasing the total freight capacity (scenarios 2 to 5).

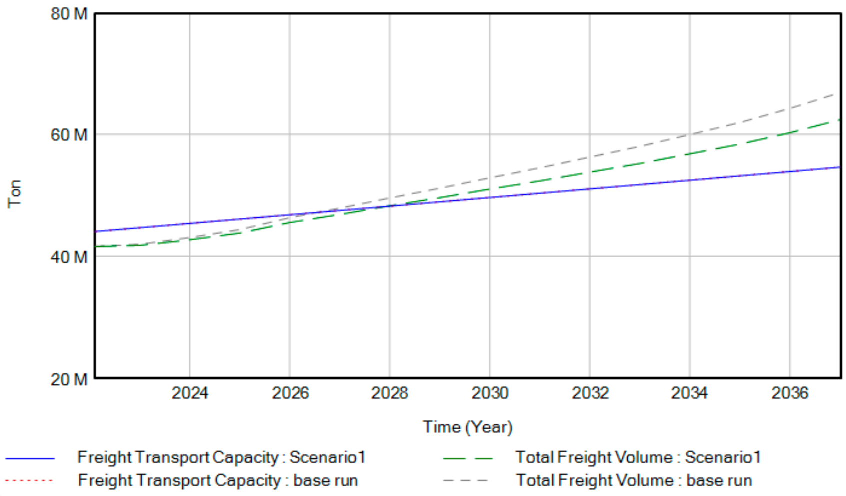

Figure 14. The effect of changing the freight-distribution coefficient on total freight demand.

4.4. Scenario 2—Changing the Travel Length of Vehicles

In order to reduce the gap between the freight-transportation capacity and the of demand for freight transportation, the influencing variables of capacity can be changed in such a way that the amount of available capacity responds to the amount of total demand for freight transportation. Base one of these influencing variable is travel length. To investigate the effect of the change in average travel length on the freight-transportation capacity, the variable amount was increased by 20% from 2027 to 2037. As a result of this increase, the total freight capacity increased in such a way that not only did the gap between total freight demand and capacity disappear, but also the system faced some excess capacity during this period. Generally, if the amount of excess capacity is too much, it causes a waste of resources. But a small amount of excess capacity seems reasonable to ensure the proper performance of the system. As can be seen in Figure 15, the freight-transportation capacity in scenario 2 increases more steeply compared to the base scenario during 2027–2037. As a result, the total freight capacity nearly matches with the freight demand. The amount of the excess capacity gap is equal to 2.6%.

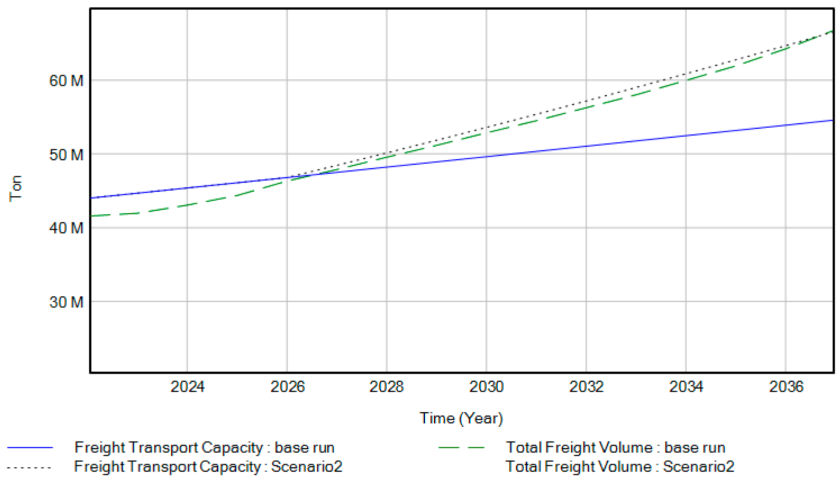

Figure 15. The effect of changing travel length on total freight capacity.

4.5. Scenario 3—Changing the Vehicle Capacity

One of the variables affecting the freight-transportation capacity is the average vehicle capacity of the freight-transportation fleet. Based on the actual data, the past behavior of this variable shows that its amount grew from 2000 to 2022 due to the change in vehicle technology. According to this, in the base run simulation, the average vehicle capacity grew according to the past trend until 2037. In the current scenario, the growth rate of this variable was 10 percent more than the growth in the base run simulation from 2027 to 2037. This amount of change caused a decrease of 45.5% in the existing gap between total freight capacity and total freight demand, but it was not sufficient to bridge the gap between freight demand and freight capacity. As shown in Figure 16, the so-called increase in the average growth rate of vehicle capacity led to an increase in the growth rate of the freight-transportation capacity during 2027–2037 (freight-transportation capacity trend line in scenario 3 compared to freight-transportation capacity trend line in the base run). Therefore, the amount of difference between freight-transportation demand and freight-transportation capacity decreased during these years. An increase in the vehicle capacity can be a result of changing vehicle technology or the adoption of policies, such as allocating government facilities on vehicles with more capacity. Considering the nature of the driving variables, a growth of more than 10% does not seem reasonable.

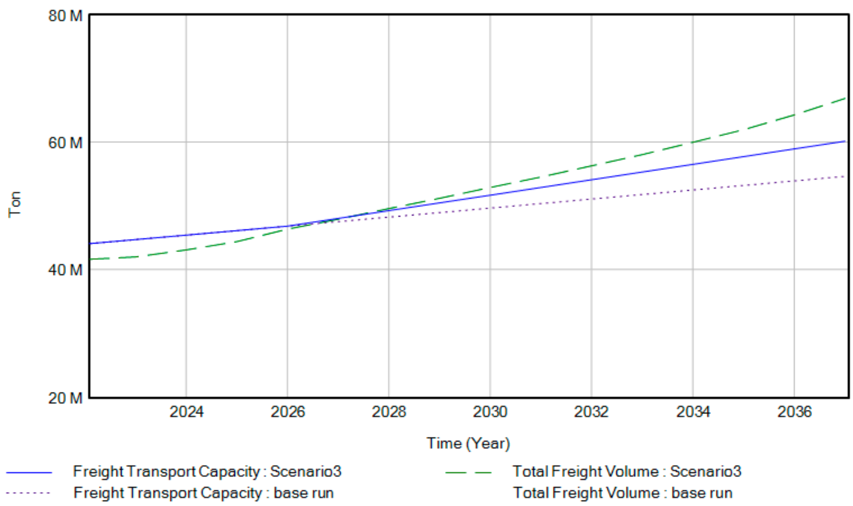

Figure 16. The effect of changing vehicle capacity on total freight capacity.

4.6. Scenario 4—Changing the Number of Vehicles

The number of freight-transportation vehicles is one of the variables affecting the total freight-transportation capacity. Variables such as private sector investment, government facilities, and depreciation rate are among the driving variables of the number of vehicles. This scenario simulates the effect of a 20% increase in the number of vehicles from 2027 to 2037 on total freight capacity. In fact, the value of this variable in 2037 grew by 20% more than the base simulation, and this growth started in 2027. The simulation results show that, similar to what happened in scenario 2, this amount of change increased the total freight capacity, and as a result, the total freight demand will be fully met by the freight-transportation capacity in the following years. As shown in Figure 17, the increasing trend line of the freight-transportation capacity in scenario 4 has a steeper slope than the trend line of the base run simulation, and this difference in slope starts from 2027, in which the number of vehicles started to change. As a result, not only will the gap between the freight demand and freight capacity be covered, but also, the system will face some excess supply in the following year. The amount of this excess supply gap will be 2.4%.

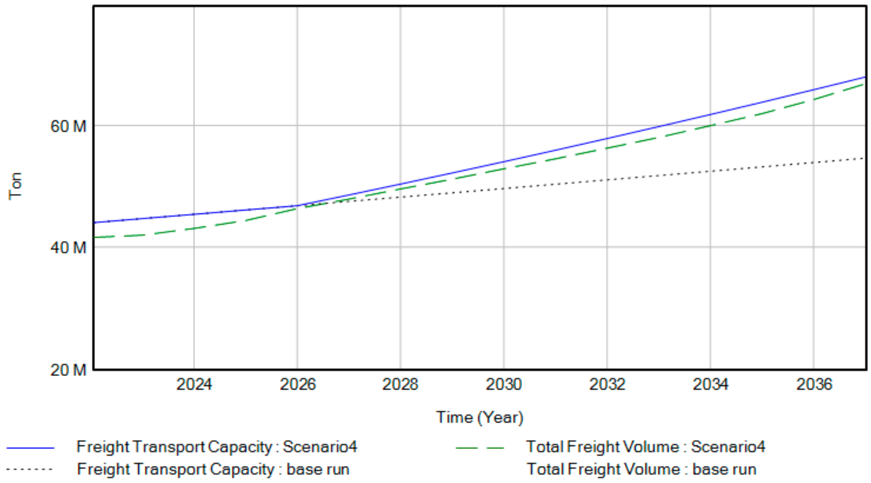

Figure 17. The effect of changing vehicle numbers on total freight capacity.

4.7. Scenario 5—Changing the Travel Length of Vehicles, Vehicle Capacity and the Number of Vehicles

Considering the different results of adopting each policy and the characteristics of the freight-transportation system of each city, it is possible to use the simultaneous adoption of several policies to change the urban freight capacity. In general, the simultaneous change in the influencing variables of the system seems to be more logical and feasible in the context of scenario planning. Also, it is more practical in order to maintain the stability of the results in the context of demand–capacity balance policymaking. In this scenario, the simultaneous effect of changing travel length (increased by 10%), vehicle capacity (increased by 5% compared to the base run), and the number of vehicles (increased by 10%) on the total freight capacity was investigated. Changing the mentioned variables, starting from 2027, and its effect on the main variables, was investigated during the period of 2027–2037. As a result, the freight-transportation capacity during this period is higher than its amount in the base run simulation (Figure 18). This variable's trend line in Scenario 5 shows that it increases more steeply from 2027 onwards compared to the base run trend line, and this will cause the available freight-transportation capacity of the system to respond to the amount of freight-transportation demand during the period of 2027–2037. The simulation results show that making these changes will completely remove the gap between total freight demand and total freight capacity. It also creates an excess supply gap equal to 1.9%.

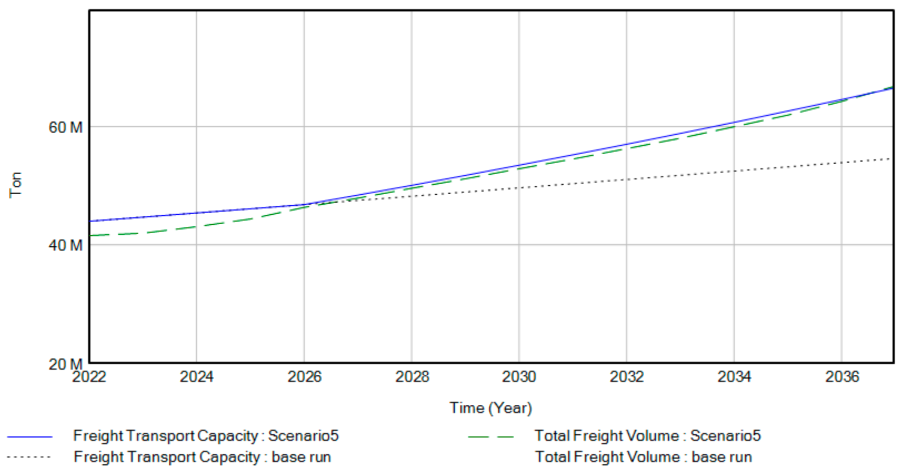

Figure 18. The effect of changing the travel length of vehicles, vehicle capacity, and the number of vehicles on total freight capacity.

Based on the results of five designed scenarios, it can be stated that the best and most practical scenario is the combined scenario. On the one hand, the results obtained from this scenario indicate the stable matching of freight-transportation demand and capacity, and on the other hand, policies that follow simultaneous change in the influencing variables is a logical approach in urban management.

5. Conclusions

Considering the effects of the urban freight-transportation system and economy on each other, one of the most important challenges of managing this system is to create a balance between freight-transportation capacity and freight-transportation demand, in order to respond to the need to transport freight despite the optimal use of resources. Considering this problem, the main goal of this article was to create a balance between freight-transportation capacity and freight-transportation demand, at an urban level, by identifying influencing variables, formulating dynamic relationships and simulating the system behavior. Considering the lack of sufficient studies in the field of macro and quantitative modeling of this system, this article modeled urban freight transportation using quantitative scenarios for the first time. The basic behavior and policy-making scenario results were simulated by a system dynamics approach. The main dynamic hypotheses of the research were developed based on the interaction of the main causal loops. It was based on the goal-seeking behavior of the freight-transportation capacity which balanced the capacity with demand through interaction loops between these two variables. By changing the control variables, the capacity will undergo changes that matches it with the demand.

The simulated model was validated using real data and the dynamic hypothesis were also verified. One of the most significant capabilities of the designed model is the possibility of adopting multiple policies in each of the existing subsystems and quantitatively evaluating the results of each of these policies. In this case, different scenarios were designed and simulated.

The simulation results show that, in order to maintain the balance between the freight-transportation capacity and freight-transportation demand, it is necessary to optimize the performance of the system in the long-term by making policies aimed at improving the main influencing variables of the system. The results show that the improvement in each of the control variables of the system leads to a reduction in the gap between freight-transportation capacity and demand. Also, the results indicate that the combination of improvement scenarios achieves the best and most practical results in terms of matching freight-transportation capacity and demand. It should be noted that the designed model has the ability to design different scenarios and can be used in line with policymaking in the general scope of urban freight system management.

Due to limitations, in order to maintain the focus of the research and the boundary of the model, some variables affecting the system were added exogenously to the model. Therefore, it is suggested to add these variables as endogenous and develop specific sub-models in future research. Generally, the designed model can be used to design different quantitative scenarios in order to optimize the freight-transportation system's performance. Therefore, defining other combined scenarios in accordance with the specific challenges of each city is suggested. This study can help policymakers to manage urban freight-transportation systems more efficiently. It is suggested that the proposed model be calibrated and used with the real data of each city.

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