A Review of How Game Theory is applied in Transportation Analysis

Yiting Li*

School of Economics, University of Edinburgh, Edinburgh, United Kingdom

Postcode of University: EH8 9LJ

*Corresponding author: s1799147@ed.ac.uk

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Abstract: With the development and application of game theory, it is widely used in various fields. As the importance of traffic problems has gradually increased in recent years, many scattered articles are studying the issue. Therefore, this paper will analyze the impact of game theory on transport systems. This paper will collect and summarise many previous studies from both macro and micro perspectives and conclude with a research methodology. Finally, it also mentions the drawbacks of game theory and suggests possible solutions for the future. This paper believes that this article will help future researchers in this field to understand the current state of research and problems quickly.

1. Introduction

It has been almost 100 years since the origins of game theory in 1928. Due to technical advancements, the application and development of game theory have mostly solved different traffic problems during the previous 20 years. Figure 1 illustrates the congestion state in America's cities, that congestion has increased significantly in the previous 20 years. This proves that traffic congestion is a problem that needs to be addressed urgently. Many transportation academics have created a range of models to help minimize or avoid traffic congestion. However, because related research is often dispersed, and people can't observe the impact of game theory on the entire transportation system at a glance, it's critical to organize and classify this type of study to get a complete overview. This paper collects a large body of literature. The authors are committed to using game theory to solve traffic problems. Most of the studies are about traffic congestion. Therefore, this paper has categorized the past literature from both macro and micro perspectives to summarise and analyze previous research more clearly. At the same time, the drawbacks of game theory should be identified, and people should take some steps to address them, so this paper has proposed some possible solutions which may be of interest to future research scholars. At the moment, the future of game theory in the field of transportation is clear. Although the practical use is relatively small, this paper believes that with the development of technology, soon these studies can be used in real life.

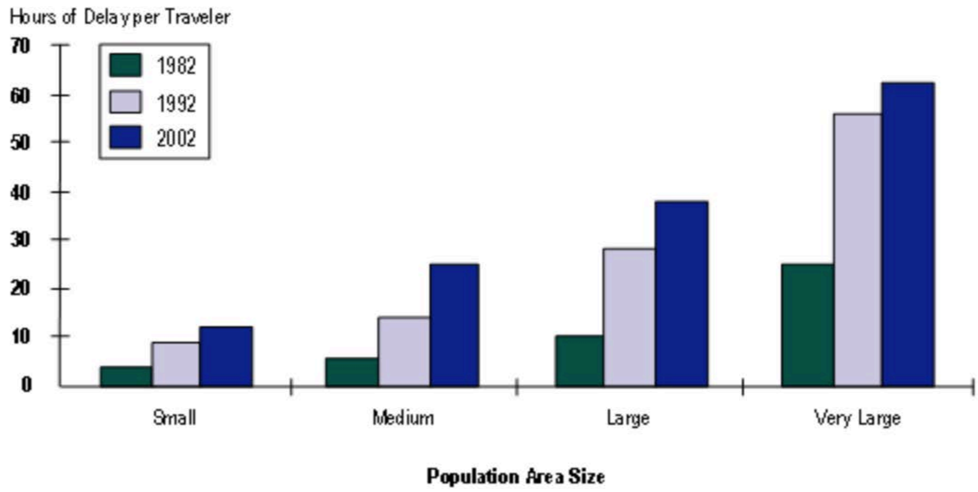

Figure 1. Congestion Has Grown Substantially in U.S. Cities Over the Past 20 Years [1]

This paper will take you through four aspects to make a comprehensive analysis. Firstly, it will introduce the history and development of game theory. Then, it divides all the studies into macro and micro parts and presents the research results within 20 years. Subsequently, this paper will summarize previous studies' general research methodology in this field. Finally, it is a conclusion of the whole piece of the review.

2. Background of game theory

2.1 History and Development of game theory

The origin of game theory was in 1928. The famous mathematician John von Neumann proposed and proved a non-cooperative zero-sum game of two people in a published paper, which is now the basic principle of game theory in economics [2]. In 1944, the Theory of Games and Economic Behavior published, this book significantly accelerated the development of game theory [3]. In the 1950s, John introduced the concept of Nash equilibrium. Until the 21st century, game theory has reached a mature stage of development in economics and has applications in biology, science, transportation, and other fields [4].

2.2 Common models of game theory used for the analysis of transportation system

2.2.1 Non-cooperative model

In general, it is a game played by single players, and all the players act independently in this situation. It emphasizes that a single player makes autonomous decisions and that other players do not influence any action [5].

2.2.2 Nash equilibrium model

In this game, no change in one player's strategy (no change in the other player's strategy) will increase his payoff [6]. The model's qualities are also its strengths and shortcomings in this model. The gain is that each side's approach is determined by the other, and each side reaps the maximum profit; however, the drawback is that each side is unlikely to modify its strategy if it is dictated by the other.

2.2.3 Cournot model

The Cournot model, which was proposed by French economist Gounod in 1838, is a model in which just two enterprises compete in a market [7]. It is the basic foundation for the application of Nash equilibrium. The model shows how competing but uncoordinated players' output decisions combine to produce an outcome halfway between a competitive and monopolistic compensation. The Gounod model posits that there are only two sellers in a product market, that there is no cooperation between them, that each knows how the other will act, and that each chooses the best output to maximize profits [8]. The model is commonly used to analyze games with three or more players. Multi-player games are standard in the transport sector, so the model is widely used.

2.2.4 Stackelberg model

This model has two roles: leader and follower, and the outcomes are usually dictated by players' actions at differing stages. The hierarchical structure in social, economic, and management systems is clearly represented in this system [9]. The model is mainly used to analyze monopolies in oligopolistic markets. It is also covered in this topic, and this paper focuses on the characteristics of this model having asymmetric competition.

2.2.5 Bounded rationality model

Herbert Simon provided a more realistic model, indicating that it is frequently feasible to realize a more satisfactory solution than the ideal one [10]. In this topic, there are various players in-game analysis in transportation. But not all of them are rational in real life, so many scholars choose this model to reduce analytical errors.

2.2.6 Repeated model

A repeated game is when the same structure is repeated multiple times with the effects of the number of repetitions on the outcome getting observed [11]. The model is characterized by the presence of long-term benefits that are taken into account. When a single game is converted to a repeated game, players may change their strategy because of long-term interests. This is particularly true in the field of transport, where many transport problems end up being solved in the long term, thus getting to the root of the problem.

3. Categorisation of game theory applications in transportation analysis and a general research process

3.1 Categorisation of game theory applications in transportation analysis

This paper divided relevant studies into two categories by looking at them over 20 years: macro and micro. Macro analysis is concerned with the broader issue, which frequently involves many players. On the other hand, micro-analysis focuses on evaluating specific scenarios in which just a few people are engaged in a limited region.

3.1.1 Analysis based on macro perspective

Firstly, transportation participants can be divided into two groups: organizers (government and associated transportation service industry entities) and users (users of transportation systems).

A) Games between organisers and users

A game analysis can be used to analyze governments and travelers to tackle the problem of traffic congestion. Commuter behavior was tested in 2012 when the government imposed a congestion charge, a bus subsidy, or both [12]. The government's economic approach to easing traffic congestion encouraged people to convert from private automobiles to public transportation. Several trials and comparisons show that implementing both a congestion tax and subsidies is more effective, albeit the congestion tax should be kept within an acceptable range. This indicates that the research is intricately tied to economics knowledge, significantly as both subsidies and taxes influence demand and supply curves to some extent, affecting externalities.

In 2018, relevant academics investigated the interactions between policymakers and commuters to assess the creation of public transportation policies and strategies to improve the appropriate policy mix. The initial stage was to create a Stackelberg game model to represent the dynamic interaction between the government, transportation providers, and passengers, and then to recommend the best policy mix and resource allocation to reduce the system's total cost [13]. This implies that because it considers the decisions of three or more players, this form of the model is complicated to set up and run. Because many of the processes in the model entail policy changes, it's also challenging to test the model in a real-world setting. However, it is expected that as technology advances, this problem will be overcome by other means in the future.

In 2018, a scholar modeled and evaluated a generic car-sharing system using game theory [14]. With the success of bike-sharing, it is expected that car-sharing will follow suit soon. As a result, it is vital to investigate this subject, which will also assist future system researchers in developing better systems. The entire process of obtaining Nash equilibrium via pure and mixed strategy components can be examined further.

Related researchers used MAS to build a traffic signal controller for several junctions in 2020, illustrating how game theory can be used for MAS decision making (determining how agents can cooperatively manage traffic signals at multiple crossings) [15]. A dual-mode agent architecture that uses both independent and cooperative processes can be developed to regulate traffic congestion successfully. According to the results of the experiments, the proposed technique may successfully reduce the average delay time under varied traffic demand scenarios.

B) Games between organizers

In order to model the evolution of traffic networks, a simple game theory model was proposed by researchers in 2007. Three participants are identified in the development of the network, including the passengers, BRT firms, and government transportation agencies [16]. As a result of maximizing their profits, each manipulator plans to develop transportation networks. The simulation results are remarkably similar to the empirical findings. It is impossible to disregard the possibility that more participants will appear in the future, allowing the model to be enhanced further.

In 2007, it was also claimed that developing cooperative urban freight systems would significantly reduce road congestion. Unified game theory is primarily used to investigate cooperation and decision-making among members of truck-based logistics alliances [17]. This emphasizes the importance of collaboration, implying that expenses, time costs, and negative externalities can all be significantly reduced when such research is used in practice.

Researchers postulated in 2012 that a network of independent standard supply networks may be built by combining multiple independent supply chains [18]. Cooperative game theory can be used as a suitable mechanism for horizontal aggregation. The ultimate goal is to reduce traffic congestion, transportation costs, and CO2 emissions as much as possible. However, the system's weaknesses should be recognized as well. System operational failures can occur, and this should not be overlooked. The entire supply chain network could be paralyzed in the case of a system breakdown, causing massive societal concerns.

In 2012, an academic investigated how three operators make the optimal operational decisions in a highly competitive environment. A two-level programming operations model is presented to describe the decision-making behavior of urban passenger transport operators, which assesses the behavioral conjectures amongst three actors (managers, operators, and users) [19]. Both are multi-level game models. This model is analogous to the Stackelberg model. The Logit model is proposed in this study to examine passenger mode choice behavior in terms of trip utility maximization, which considers total commuting time, waiting time, and overall trip cost for each model.

C) Games between users

In 2009, it was suggested that when each individual's optimal strategy differs from the group's ideal approach, traffic participants as a single rational subject are prone to confusion. The collective is more likely to participate in illegal traffic behavior [20]. As a result, management measures are required to regulate traffic participants' optimal strategies. This means that management strategies could include providing suitable courses, conducting training, etc. Even while it will increase expenditures, it will improve the traffic system's efficiency over time.

In 2012, a heuristic optimization strategy for autonomous vehicles at uncontrolled crossings was suggested based on a game-theoretic model [21]. In their proposed approach, autonomous vehicles are shown as reactive agents who communicate and work with the intersection controller to reduce total delay. This demonstrates that, as technology progresses, the technique is efficient. Once it is implemented in real life, this technology could be a tremendous answer to traffic congestion, accidents, and other issues with more risk and error avoidance.

Intelligent Transportation Systems (ITS) are a hot topic among researchers in 2019. A new model based on the Stackelberg cybersecurity game is proposed [22]. This song model can be used to characterize critical cyber threats and, as a result, increase detection efficiency. Artificial intelligence is likely to be used in cyber defense research in the future to reduce false positives and increase detection times and rates.

3.1.2 Analysis based on micro perspective

A) Games between organizers and users

Due to the lack of non-cooperative tactics for induced games, it was proposed in 2006 to describe signalized crossings as Markov chains with finite control for traffic congestion problems [23]. Intersections are a non-cooperative game in which each player tries to reduce their queue as much as possible, and Nash equilibrium is the best option. Game theory and linear programming are principally employed in this work to address the traffic light control problem for urban traffic, and the model's employment has proven to be beneficial. The importance of studying traffic light junctions is argued in this work. As the first researcher to look into the subject, they must look into it from the participants' perspective because the only way to address the traffic congestion problem is to look into what the participants think.

In 2010, Nash and Stackelberg equilibria were examined as the key answer for generating non-cooperative games. The proposed modeling signal intersections as finite-control Markov chains [24]. This paper and earlier research have some similarities. Each intersection is viewed as a non-cooperative game in which each player tries to lower their waiting time, resulting in a model that significantly reduces traffic congestion.

In 2015, the researchers presented a system to ease traffic congestion that would use the capabilities of future autonomous/self-driving vehicles to replace intersections such as signals and traffic signs. The Nash equilibrium model was utilized to analyze the entire project [25] . This paper argues that research is intimately tied to technological advancements and that more innovations and analyses can be developed soon as a result of this research. However, according to this report, this system has some flaws, such as unexpected crashes or programming problems, which future researchers should consider.

A game was developed in 2015 to solve the difficulty of coordinating different traffic signal management systems. The conclusions of this study are based on Nash equilibrium, and they are proved using a triangular junction as an example [26]. The intersection's goal is to reduce queue times, whereas the signal controller's task is to figure out the optimal signal timing approach. As a gamer, the signal controller is regarded. The goal is to determine the green time at each intersection such that signal and queueing delays are minimized. This problem has its own set of inherent bounds. A leader-follower (Stackelberg) game model can be used since roadways with larger traffic volumes demand longer green light times.

A game-theoretic optimization approach offered a one-of-a-kind solution to segregated traffic light regulation in 2016. The algorithm for modelling a signal intersection consists of four steps, each of which is represented as a player in a game in which the players come to an agreement [27]. Variables like stage order and freecycle length can also be accounted for using the Nash game. To evaluate its effectiveness under various degrees of traffic demand, the proposed Nash bargaining method is compared to the optimal fixed-time planning and execution control algorithm. Finally, simulation results reveal that in all traffic scenarios, the proposed Nash bargaining control algorithm outperforms the fixed time and execution control technique. The adjustments improved stopping times, queue lengths, travel times, average vehicle speeds, system throughput, fuel consumption, and emission levels.

B) Games between organizers

A study was conducted in 2016 in response to air traffic management tactics to allow airlines to make trade-offs between different performance criteria [28]. Firstly, many approaches for systematically collecting airline inputs and incorporating them into effective air traffic management initiatives can be presented. Secondly, a game theory technique is used to analyze the possibilities of strategic airline activities. A ground delay scenario for two New York area airports is simulated to demonstrate how these tactics operate in an existing system. Also, based on the findings, a scoring system can be used to evaluate (including airline profitability, system optimization, and fairness) and incentivize airline preferences. Finally, central authorities can design air traffic management initiatives that significantly improve system performance while respecting airline goals.

C) Games between users

Some scientists put their micro-level, congestion theory, and congestion pricing theory in 2005 due to two or more cars [29]. Using a two-player game proved that the growth of congestion depends on the hurry with which individuals reach their destination (a relative evaluation of early arrival, late arrival, and journey delays). Congestion pricing can be a collaborative tool to lower total transportation costs (if returned to the participants). The experiment is then extended to a three-person game to demonstrate that congestion is an adverse mitigating scenario for the player who does not cause congestion.

Researchers determined in 2015 that probabilistic prediction is an efficient way for characterizing conflict resolution to produce an advantage and improve the overall efficiency and safety of the air transportation system [30]. It is possible to present a cooperative game model with a prioritization system that allocates players to different states while considering the preferences of others. The game conflict resolution is then described using a probabilistic prediction model. Players will choose a conflict-free approach due to the nature of cooperation, guaranteeing that the system as a whole can reach a socially consistent solution that settles conflicts while satisfying individual preferences. Finally, related challenges, both conceptually and quantitatively, demonstrate the correctness of the proposed approach.

A study for the aviation industry was completed in 2020, and it decided that there could not be any overlap between the protected regions of the two planes. According to earlier research, they frequently prefer to alter the aircraft's speed or inclination themselves. The authors present a method for changing the aircraft's rate and the angle simultaneously using a linear programming approach. They also provide links to back up their statements [31]. Conclusion this paper considers there seems to be relatively little research into aviation at the moment, so their study might give some inspiration to future generations. But usually, with this area of research, people should be more cautious because, in aviation, the margin for error is minimal. If a bit of bit goes wrong, the results are often horrible. So, it is shown that there could be some system or regulation to bind or prioritization to be rated in advance so that problems can be solved quickly in times of emergency. It is also essential to have a plan B, like a parachute for skydivers.

3.2 A general research process

Through much research and analysis, people can learn that studying transportation systems with game models can be divided into four steps. The process is shown in figure 2 below.

By analyzing the current situation and the problems occurring at the moment, it is reasoning to develop a suitable model, apply the model and observe the changes, and verify the model's feasibility with confirmed cases.

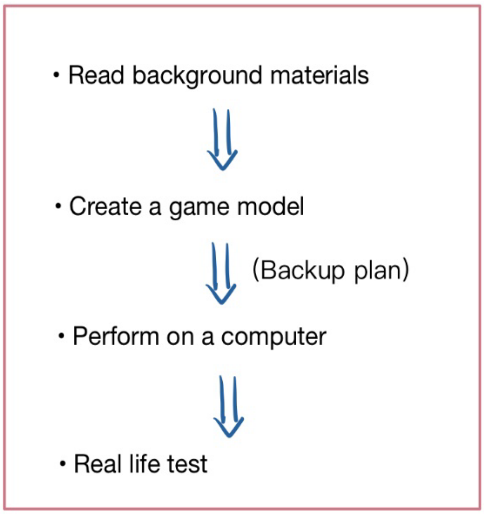

Figure 2. The process of general research

The first stage is to read a lot of background material about the analysis's target and learn everything there is to know about it. The next step is to identify existing issues and create a model (each problem should have a corresponding solution). In this section, a few researchers also provide a backup plan in case the modeling fails during the process. In the third step, the whole model is performed on a computer, and the model is advanced using mathematical and statistical methods. Finally, the model must be tested in real life to demonstrate its viability.

4. Conclusion

As the use of game theory to transportation grows in popularity, this study classifies previous research to build a more thorough review, allowing future actors to grasp better the context, classification, and limitations of this research analysis.

4.1 Key findings

This paper has been inspired by reading the recent literature on game theory analysis in transport systems. In this research, it has become clear that research on traffic congestion is becoming increasingly important and that the growing problem of traffic congestion has led to increased caution and attention being paid to this issue. This study shows that taxes and subsidies on transport significantly impact people's behavioral patterns. At the same time, the possibility of traffic accidents and congestion can be reduced with the introduction of high-tech inventions such as autonomous driving systems and automated systems for intersection signaling. Furthermore, by analyzing the behavioral patterns of people with different identities, the most efficient equilibrium can be obtained with the help of the Nash equilibrium theory, non-cooperative games, and cooperative games.

4.2 Research significance

This review has organized and categorized the current research results. A comparative analysis of transport systems has indicated the directions in which future researchers can make more breakthroughs. On the one hand, at the level of technological development, there may be more complex and sophisticated systems in the future. On the other hand, there is relatively little research in some niche directions, such as the aviation field, which will inevitably lead to significant breakthroughs in the future when more researchers take notice of them.

4.3 Limitations and future studies

Although game theory has helped solve many difficulties in transportation, much research still reveals significant flaws.

The concept of "absolute rationality" is perhaps the most notable. It is shown that in game theory, people analyze a problem based on the rationality of all parties, but "absolute rationality" does not exist in real life, leading to the analysis of specific models that do not fit into certain scenarios in reality.

Simultaneously, in many models, the number of participants is excessive, resulting in delayed and error-prone progress. Next, many of the models are so complex that most of them require the help of a computer to proceed. It can be inferred from this that future models will become more and more difficult.

This paper proposes the following recommendations for the above issues that future researchers can use.

Firstly, bounded-rationality game models can solve the first problem very well, and this review suggests using this model to analyze the actual situation. Secondly, people can group the participants and use statistics to select samples to do the analysis. The conclusion usually does not have a lot of bias. This paper believes that a more accurate system can be developed to improve the current errors with the advancement of technology.

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