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# Investigating the Effects of Automated Vehicles on Large Urban Road Networks: Some Evidence from Rome

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**Abstract:** This paper explores the possibility of applying simulation models formalized in the macrosimulation approach to predict the effects from the presence of automated vehicles in our cities. It is based on the use of a robust equilibrium assignment model allowing us to obtain multiclass traffic flows, including automated vehicles (AVs) and conventional ones (CVs) on large real-sized road networks. This modelling framework has been successfully applied to the road network of the metropolitan area of Rome, allowing us to assess the effects of AVs in future traffic at increasing penetration rates and the effects of possible transport policies involving AVs.

**Keywords:** automated vehicles; multiclass assignment; assessment; simulation; Rome

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## 1. Introduction

Towards a future mobility devoted to sustainability, cars will surely be characterized by zero emission vehicles and by automated systems that represent a unique way to reduce their external costs, especially air pollution and road accidents.

To assess such future scenarios as well as to support decision makers through the modelling and simulation of the effects of future trends in the automotive and mobility fields, the study of problems related to AVs in the field of the management of supply and demand, e.g., the traffic and parking rules, the link capacity, as well as the study of effects of the reserved access to restricted areas or the reserved lanes to AVs, are some of the open issues that are assuming increasing relevance in the literature.

Aiming at real-sized network applications, this paper focuses on the possibility of applying easy-to-use and computationally fast models and methods to support the assessment of effects of the AVs' introduction on large urban networks. Therefore, the application to the road network of the city of Rome is presented and some evidence is reported to show the goodness of the proposed approach at assessing the effects of the presence of AVs at increasing penetration rates and the effects of possible transport policies involving AVs.

Aiming to support decision makers in solving technical, economic and social problems related to the planning and evaluation of transport systems, results are also presented by assessing variations in travel times and costs (user view) and transport externalities (system view) using typical Network Performance Indicators (NPIs).

The paper is structured as follows. Section 2 reports a concise literature review on models to support the assessment of the AVs' effects, while Section 3 describes the used system of models for traffic simulation. Sections 4 and 5 present the results and discussion of the case study applications. Section 6 reports conclusions and indicates future directions for the development of this research.

## 2. Literature Review

The simulation of the AVs' presence in the traffic of our cities requires changes in the transport modelling and simulation because of different vehicle spacing and interactions induced by automated system driving. It mainly impacts the traffic network dynamics of flow and density, especially when heterogeneous traffic streams (i.e., presence of mixed flow of AVs and CVs) should be considered.

Research endlessly investigates aspects of modelling and simulation to answer the questions that continuously arise for the introduction of AVs in our cities, ranging from the technological aspects (e.g., vehicle tracking) [1] to planning or simulation [2]. Specifically, many research efforts have been made to reformulate assignment models able to simulate the interaction between automated and traditional vehicles. Among proposals in this research field, Ref. [3] investigates the problem that arises in the face of AVs in traffic assignment by presenting a multiclass approach; it also includes the simulation of AV ownership demand forecast for a better estimation of the demand and of the competition of private transport with respect to public transport in the peak hours. Ref. [4] extents the traditional multi-vehicle assignment, for which [5] presents a proposal to solve the multiclass (including AVs and CVs) stochastic assignment in which AVs and other vehicle types share the urban transportation network and contribute together to congestion. The latest work of this research group is presented in [6], which explores fixed-point, deterministic and stochastic process models applied to the multi-vehicle assignment with elastic vehicle choice behavior.

In the sphere of equilibrium assignment, Ref. [7] proposes an easy-to-use multiclass assignment for the simulation of the presence of AVs, for which a robust convergence is assured by the proposal of an adjusted-BPR function. Parameters of such a function have been calibrated by using a microsimulation approach in [8].

The recalibration of the BPR function for the strategic modelling of connected and autonomous vehicles has also been faced by [9]; they tested environments at 10% increments of AV penetration rates to observe the network performance in mixed fleet environments for a better prediction of travel times.

In the class of the dynamic traffic assignment models, Ref. [10] developed a method to model the cooperative adaptive cruise control typical of AVs, while [11] explored the day-to-day dynamic in more depth. Many studies underline the need to consider changes in macroscopic fundamental diagram characteristics for a given penetration rate of AVs. Among them, the recent work [12] can be cited. Early studies focus on specific aspects of AVs in the traffic flow, whereas Ref. [13] more deeply explores some features of the AV technology, like adaptive cruise control, to set up a traffic flow model able to assess the effects of the presence of AVs. Ref. [14] develops a car-following model that also considers a cooperative platoon control in case of mixed traffic (i.e., AV presence), while the car-following model suggested by [15] adopts parameters that are validated through the fundamental diagram coherence and the analysis of stability. Ref. [16] presents a Markov chain approach to estimate the impact of AVs on the capacity, while [17] proposes a link transmission model able to capture the different route choices of AVs for a more precise dynamic traffic assignment. Ref. [18] explores the effects of AVs in travel demand by using an activity-based approach.

Among applications to support decision makers, Ref. [19] investigates the effects of AVs on the (decreasing) value of time and on the (increasing) capacity of roads by using a dynamic model. Ref. [20] examines the effects of AVs on the (increasing) accessibility as a result of the increased road capacity. Ref. [21] studies in more depth the impacts of different AV penetration rates through the analysis of transportation performances at the network aggregation level. Ref. [22] proposes a formulation of capacity in the presence of different multiclass traffic conditions; such conditions are defined by means of different AV penetration rates and different vehicle-type lane usage policies.

Because of the complexity of real urban networks, the above-mentioned literature involved a simplified approach to the problem that was initially limited to the study of small portions of the network (in some cases even few links) and simpler traffic contexts such as extraurban. For this reason, aiming at assessing the effects of both AVs and transport policies and involving them in Rome, this paper proposes to apply a robust and computationally fast demand–supply (assignment) model for the application to real urban networks, whose modelling features are provided below.

## 3. Modelling

To investigate the effects of AVs on transport networks, demand–supply interaction (assignment) models, which allow to predict path choice and flows for different vehicle types (multiclass) must be used. Specifically, the assignment model proposed in [7] is used here and recalled in terms of demand–supply interaction features and its main components related to both demand and supply.

Aiming at formalizing an easy-to-use and computationally fast model in view of the user equilibrium approach with fixed demand, let:

$\underline{f}^*$ be the vector of equilibrium link flows, which sum up flows for each vehicle type on each link;

$\underline{\Lambda}$ be the link–path incidence matrix;

$\underline{\Psi}$ be the route choice probability matrix;

$\underline{c}^*$ be the vector of equilibrium link costs, i.e., the link costs calculated at equilibrium link flows;

$\underline{d}$ be the vector of the demand, whose elements are the O/D trips per vehicle type.

$t_i$ be the travel time on link $i$, depending on the flow on link $i$, $f_i$, obtained by summing up flows for each vehicle type;

$L_i$ be the length of link $i$;

$V_{0i}$ be the "free-flow" speed on link $i$;

$R_i^2$ be the red time at the final node of link $i$;

$C_{Ni}$ be the cycle time at the final node of link $i$;

$S_{Ni}$ be the saturation flow at the final node of link $i$, function of green factor $G_i/C_{Ni}$ and capacity $S_{sat,i}$;

$\gamma$ and $\delta$ be function parameters;

The demand–supply interaction can be expressed as:

$$\underline{f}^* = \underline{\Lambda}\ \underline{\Psi}[\underline{\Lambda}^T \underline{c}^*(\underline{f}^*)]\ \underline{d} \tag{1}$$

As stated in [7], the existence and uniqueness of the assignment solution (1) is assured by using random utility-based route choice models and continuous monotone increasing cost functions like the following adjusted-BPR:

$$t_i(f_i) = \frac{L_i}{V_{0i}} + \frac{R_i^2}{2C_{Ni}}\left[1 + \gamma\left(\frac{f_i}{S_{Ni}}\right)^{\delta}\right] \tag{2}$$

The free-flow speed $V_{0i}$, the saturation flow $S_{Ni}$ as well as $\gamma$ and $\delta$ function parameters are different according to road types and intersection layouts. Ref. [8] propose different values according to the link localization (e.g., city center or suburbs), the road hierarchy (main or side street) and the vehicle type allowed (e.g., AVs and/or CVs).

The implications of AVs on equilibrium assignment models and algorithms for transport systems can be further explored in [5].

To apply such an assignment model, $\underline{d}$ represents the O/D matrices for different vehicle types, considering at least separate O/D trips for AVs and other vehicle types. It can be obtained by the application of a system of demand models incorporating explicitly the AVs in the estimation of O/D trips per demand segment as proposed in [3].

Regarding the features of the supply model, the network graph incorporates links representing conventional links (i.e., links shared by AVs and CVs) but can also include links representing AV-reserved lanes, if any, and then links to model merging zones at intersections for the above two link types. It must be able to explicitly represent supply facilities in line with the scope of the simulated scenarios.

## 4. Results

This section presents the results of a real-size application carried out on the road network of the Metropolitan Area of Rome, the capital of Italy, where more than 4 million inhabitants live.

Aiming at testing the presented easy-to-use assignment model to capture the effects and impacts of AVs on large urban networks, a system of models able to reproduce the morning peak hour of a typical workday has been implemented. It has been developed starting from the model calibrated by the Rome Transport Agency for its strategic planning studies, including those carried out during the COVID-19 pandemic [23–25]. On the demand side, the O-D matrix consists of about 352,000 trips among 499 traffic zones, in which the study area (i.e., the metropolitan area of Rome) has been divided.

On the supply side, the road graph is made of 42,969 nodes and 74,300 links representing about 7300 km of roads hierarchically divided as described in Table 1.

**Table 1.** Cost function parameters per link type.

| Road Type | Link Code | $\gamma$ | $\delta$ | $V_{0i}$ (km/h) | $S_{Ni}$ (veh/h) |
|---|---|---|---|---|---|
| Local | 1 | 1.75 | 2.40 | 47 | 1823 |
| Unclassified | 2 | 1.65 | 2.76 | 47 | 1870 |
| Residential | 3 | 1.5 | 3.00 | 55 | 1821 |
| Tertiary | 4 | 1.35 | 3.24 | 65 | 1758 |
| Secondary | 5 | 1.0 | 4.20 | 80 | 1676 |
| Primary | 6 | 1.0 | 4.20 | 88 | 1857 |
| Motorway | 7 | 0.9 | 4.80 | 124 | 2052 |
| Highway | 8 | 1.0 | 4.20 | 96 | 1854 |
| Motorway ramp | 9 | 1.0 | 4.20 | 90 | 1965 |

Table 1 also reports the main parameters associated with the cost functions per link type calibrated in [8] to simulate the network performances when the traffic incorporates AVs. The parameters of Table 1 are those adopted in our applications.

The VISUM$^{TM}$ transport modelling suite has been used to implement the assignment model of Section 3. It allows us to code the proposed modelling changes (i.e., mixed traffic flows of AVs and CVs) to the VISUM$^{TM}$ available multiclass equilibrium assignment, and to customize modelling parameters such as the value of time that influences the route choice of AVs as suggested in [19]. Of course, the reader can use any transport simulation software (e.g., Aimsun, Emme, and so on) that allows to implement a multiclass equilibrium assignment and enables to write specific custom code for the proposed changes.

As an example, Figure 1 illustrates the simulated traffic flows on the considered road network as a result of the assignment of the demand to the transport network, in which a percentage of AVs equal to the 50% is considered.

The more efficient platooning caused by the presence of AV vehicles results in higher vehicle density and speed, and thus increased road capacity. Such a capacity leap can be clearly seen in Figure 2, which illustrates this effect when a 50% AV ratio is considered.

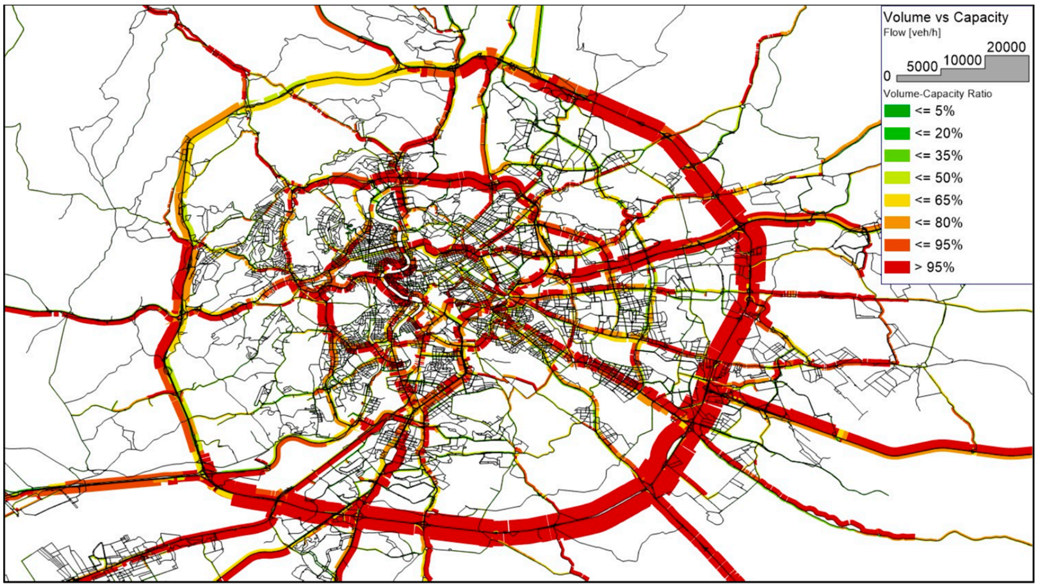


**Figure 1.** Example of assignment results: link flows and volume–capacity ratios (50% AVs).


**Figure 2.** Example of assignment results: link capacity increasing (50% AVs).

In the view of an easy-to-use approach to support decision makers and transport policy assessment for these kinds of problems, simulations have been performed by using a desktop computer equipped with an Intel Core I9-12900K processor and 32 Gb RAM running on Windows 11. By using a stop test relative gap threshold of $1 \times 10^{-5}$, the above-described simulation model takes about 4.3 min to produce the expected output, i.e., mixed traffic flows of AVs and CVs and relative network performance indicators. Figure 3 shows the convergence of the assignment to the results of Figure 1 (50% AVs).

Although a small stop value is imposed (i.e., $1 \times 10^{-5}$), convergence analysis confirms the quick achievement of the equilibrium that is typical of the robust existence and uniqueness conditions of fixed-point problems formalized in Section 3. This trend is observed in all simulations performed and is virtually independent of the percentage of AVs taken into account, which also demonstrates the easy-to-use and computationally fast features of the proposed approach even for large-scale applications.

This result, as well as all the others obtained from the simulated scenarios carried out from this study, will be discussed in the following section.

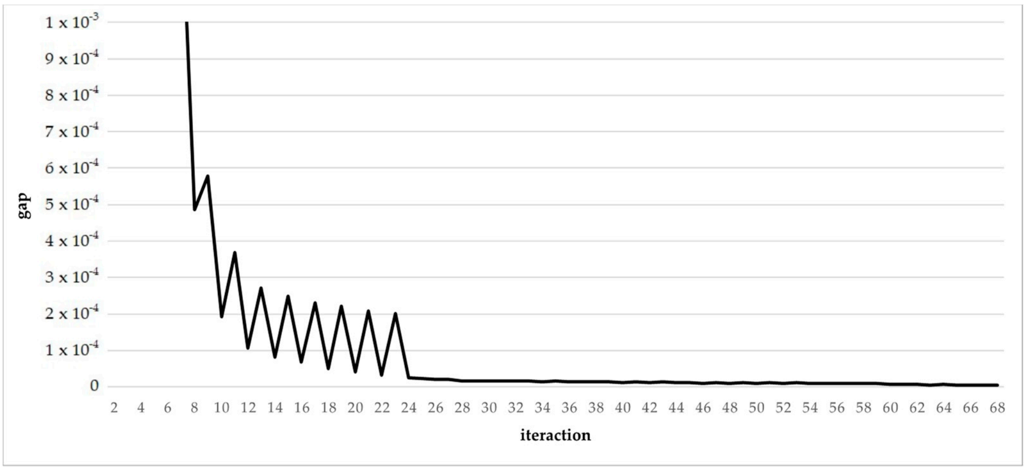


**Figure 3.** Convergence analysis (50% AVs).

## 5. Discussion

This section discusses the results obtained by the simulation of the effects of AVs in the traffic of the morning peak hour in Rome by virtually considering the increasing percentage of AVs in the mixed traffic flows up to the complete substitution (100% AVs) and comparing with the presence of all-CV vehicles (0% AVs).

The effects of the transition from the actual total absence (0% AVs) to the future all-AVs (100% AVs) are considered by simulating the different mixed cases of 12.5%, 25%, 50%, 75% and 90% of AVs in terms of O-D vehicle trips in the morning peak hour, and performing different route choices, which generate the mixed flow of AVs and CVs on the road network and influence the network performances.

Because Rome has a central Limited Traffic Zone (LTZ), a scenario where only AVs can access the LTZ has been also considered.

Specifically, Table 2 summarizes the aggregate Network Performance Indicators (NPIs) calculated to demonstrate the capability of the used assignment model to capture the effects of AVs at different penetration rates (AV%). Such indicators are the total travelled distance in kilometers, the total travelled time in hours, the average (network) saturation rate per link and the average network speed. Obtained results are discussed below.

**Table 2.** Simulated scenarios—Network Performance Indicators.

| | | AVs [%] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Indicator** | **Units** | **0** | **12.5** | **25** | **50** | **75** | **90** | **100** |
| **Total Travelled Kilometers** | km $\times 10^{-6}$ | 6.056 | 6.072 | 6.090 | 6.120 | 6.155 | 6.177 | 6.192 |
| **Total Travelled Time** | h $\times 10^{-3}$ | 105.51 | 103.70 | 102.21 | 100.39 | 98.96 | 98.35 | 98.03 |
| **Average Link Saturation Rate** | % | 93.9 | 89.8 | 86.8 | 83.1 | 81.4 | 81.2 | 81.3 |
| **Average Network Speed** | km/h | 68.3 | 68.7 | 69.1 | 69.8 | 70.4 | 70.8 | 71.1 |

Table 2 shows the increasing benefits of the introduction of automated systems up to the optimal configuration consisting of a homogeneous AVs traffic flow (100% AVs), which is characterized by greater saturation flows. Comparing with the all-CVs actual scenario (0% AVs), all the simulated scenarios with non-zero AVs present a reduction of total travelled time and average link saturation rate, as well as an increase in the total travelled distance and average network speed, as we can see from values in Table 2 that are also visualized in Figure 4.


**Figure 4.** Simulated scenarios—Network Performance Indicators.

Specifically, the 100% AVs scenario with respect to the 0% AVs performs a reduction of 7% in the total travelled time (98.03 with respect to 105.51, i.e., about 7500 h) and a reduction of 13% in the average saturation rate (81.3 with respect to 93.9), as well as an increase in the average network speed from 68.3 km/h to 71.1 km/h (+4.1%). These benefits more than compensate for the costs associated with increased externalities related to increased travel distance (+2.3%), provided that automation (which lowers road accidents) is accompanied by a transition of the vehicle fleet to a ZEV (Zero Emission Vehicles) mobility that we can now take for sure in the future.

Intermediate simulated scenarios, which are more interesting for decision makers because they have to support the transition to the future and to manage the daily traffic in our cities, show increasing benefits and costs similar to the above described, which start to be clearly seen when the ratio of AVs driving is 50% (i.e., total travel time reduction greater than 5% and average saturation rate greater than 10%). The improved performance of the network (the links of the primary network can register a capacity increase of up to 25 percent) is reflected in a change in the map of vehicle route choices, for which Figure 5 shows the differences in traffic flows (i.e., positive in red and negative in green) as result of the assignment of 50% AVs with respect to the current situation (0% AVs).

To test possible actions to foster the introduction of AVs in the city of Rome, effects have been simulated of a transport policy that allows to access the central Limited Traffic Zone (LTZ) only to AVs. Table 3 summarizes the NPIs compared with respect to the actual scenarios (0% AVs).

**Table 3.** LTZ AVs scenario—Network Performance Indicators.

| | | AVs | |
|---|---|---|---|
| **Indicator** | **Units** | **0** | **LTZ** |
| **Total Travelled Kilometers** | km $\times 10^{-6}$ | 6.056 | 6.068 |
| **Total Travelled Time** | h $\times 10^{-3}$ | 105.51 | 103.99 |
| **Average Link Saturation Rate** | % | 93.9 | 90.7 |
| **Average Network Speed** | km/h | 68.3 | 68.6 |


**Figure 5.** Comparison of link flows due to the presence of AVs (50% AVs with respect to 0% AVs).

The results in Tables 2 and 3 indicate that the policy of restricting the access of the LTZ to the AVs (i.e., 100% of AVs for trips originated and destined in the LTZ) has a lower impact than introducing 12.5% and more AVs in the whole study area. This is mainly because the rest of the network influences the route choice of LTZ trips, resulting in an average increase in time and distance.

Analyzing all the results as a whole, it is interesting to compare the LTZ AVs scenario with respect to that of including the 12.5% AVs, which has a similar number of daily trips affecting the LTZ, even if such trips have a different spatial distribution. Moreover, by focusing NPIs on the LTZ subnetwork only (see Figure 6), it obviously emerges that the impacts of the LTZ restriction to AVs in this area are better than in the 12.5% AVs scenario, but the overall network results are slightly worse. It means that the policy to encourage AVs in Rome has beneficial effects in the LTZ itself, but from an overall point of view, a widespread introduction of the same number of AVs across the entire network would be better. Such a conclusion is also supported by the fact that the total travelled distance of the LTZ-enabled vehicles represents 13.4% of the whole study area, as in the 12.5% AVs scenario. This reinforces the hypothesis that a more positive effect can be obtained if AVs are introduced with general policies and not related to focused areas such as the LTZ.

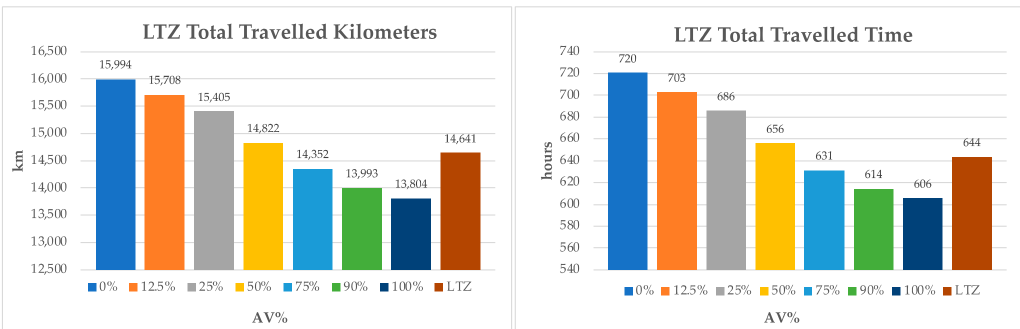


**Figure 6.** Comparison of total travelled times and distances (LTZ subnet only).

## 6. Conclusions

This paper proposed the application of an easy-to-use assignment model to simulate the effects of AVs on a large urban network. Such a model is able to reproduce route choices for different classes of vehicles (i.e., AVs and CVs) to estimate the effects of the introduction of AVs in our cities and to support decision makers in the definition of transport policies to lead the transition of today's mobility to a fully automated future.

Easy-to-use, computationally fast and commercial transportation software usage are the main features of the used modelling framework that, thanks also to a robust theoretical formalization assuring existence, uniqueness and convergence of assignment towards a solution, has been successfully applied to the complex real-size road network of Rome.

This application represents the main contribution of this work because it addresses the complexity of simulating the effects of AVs on full-size urban road networks and establishes a promising basis for the successful transferability of this research to other cities or to other areas on a different scale.

Regarding the results, simulated scenarios confirm the benefits of the AV presence in the traffic of the morning peak hour, as well as highlight the questionable benefits for the whole study area connected to allowing particular areas (e.g., central LTZ of Rome) to be accessed by AVs only. It is worth noting that approximations of such favorable values could be affected by CV human factor issues that the class of models used here does not explicitly allow for, although they are implicitly considered along with the other approximation effects of a complex system, such as road traffic in the random residual of the random utility models used in route choice.

Overall, together pushing people towards public transport and ZEV (Zero Emission Vehicles) mobility, simulated scenarios clearly suggest encouraging, as quickly as possible, the transition towards an "all-AVs" mobility. This seems to be the main way to maximize the positive effects of the introduction of AVs in our cities, especially when severe congestion in the morning peak hours occurs.

Further developments of this research are in progress. They mainly regard the use of this modelling framework to support optimal network design.

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