Towards Impact Assessment of Cooperative Routing on Traffic Efficiency: A System Dynamics Approach

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Abstract: The proliferation of connected vehicles and Cooperative Intelligent Transport Systems (C-ITS) introduces novel opportunities for enhancing various aspects in traffic (e.g., efficiency, sustainability, safety). As C-ITS gains prominence, evaluating its impact requires comprehensive impact assessment studies. While microscopic simulators and Agent-based Models (ABM) dominate C-ITS evaluations, this paper adopts an alternative approach, utilizing System Dynamics (SD) to assess the impact of Cooperative Routing (CR) on traffic efficiency. Thereby a Stock-Flow Model (SFM) is developed, considering parameters such as equipment rates, delay thresholds, and route update intervals. Results indicate that even a low equipment rate (25%) significantly improves traffic efficiency. However, high equipment rates with prolonged route update intervals introduce challenges, causing route overloads and increased delays. These effects are consistent with the current literature on CR using ABM. Furthermore, this study suggests possibilities for model extensions, including predictive rerouting, alternative rerouting criteria, and consideration of sustainability impacts. Overall, these findings contribute to further development in the direction of cooperative connected and automated mobility.

1 INTRODUCTION

In recent years, the automotive landscape has witnessed a surge in the integration of sensors and communication technology capabilities in vehicles, facilitating data collection and inter-vehicle communication (Lu et al., 2014). With more than 100 million connected vehicles expected to be on the road, an opportunity arises to address traffic-related challenges and enhance overall traffic efficiency (Statista, 2023; European Commission, 2016). The potential for inter-vehicle communication creates opportunities for the development of innovative services designed to enhance traffic conditions. These services are referred to as Cooperative Intelligent Transport Systems (C-ITS). One such service, Cooperative Routing (CR), enables vehicles to share trip information, allowing others to optimize routes based on predefined criteria.

Impact assessments of C-ITS frequently employ microscopic traffic simulators and agent-based modeling (ABM) to evaluate traffic efficiency, sustainability or safety (Pribyl et al., 2020; Soon et al., 2019; Wu et al., 2019; Agriesti et al., 2020). A literature review by Walch et al. (2025) highlights the dominance of these methods in C-ITS studies. While ABM is well-suited for evaluations of vehicle interactions and traffic dynamics, it may not always be necessary to simulate traffic at such granularity. A viable alternative are System Dynamics (SD) models, offering a higher level of abstraction and proving useful in capturing feedback effects, a critical aspect for C-ITS. Additionally SD facilitates scenario testing as it is less resource intensive than ABM. This allows for the rapid and flexible assessment of parameter configurations and the evaluation of their impact on multiple impact categories. Therefore, this work introduces a SD approach utilizing Stock-Flow Models (SFM) as a tool to assess the impact of a simple CR application across different scenarios, with a focus on traffic efficiency.

This paper is structured as follows: Section 2 explains the methodology applied. Section 2.1 outlines the model concept, followed by the development of a SFM and its rerouting logic in Section 2.2. Section 3 defines scenarios with varying parameters and compares simulation outcomes, including findings from recent ABM studies. The paper concludes with key insights, limitations, and future research directions for using SD in C-ITS impact assessments.

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2 METHODOLOGY

System Dynamics (SD) is an interdisciplinary approach to modeling the dynamic behavior of complex systems over time, focusing on feedback loops and interdependencies rather than isolated variable relationships (Forrester, 1969). It starts with qualitative Causal Loop Diagrams (CLDs) to visualise variable interactions and progresses to quantitative SFMs by classifying variables as stocks (levels), flows (rates), auxiliaries and parameters, and incorporating the causal links identified from the CLDs (Breitenecker et al., 2008).

In this paper the principle of SD is applied to the context of Intelligent Transport Systems. A C-ITS service known as Cooperative Routing (CR) will be modelled using a SD approach to test the impacts of different parameter configurations on traffic efficiency. To this end, a model concept was first developed, which was used to create a quantitative SFM based on a qualitative CLD. The modelling process for developing the simulation model is described in more detail in the following sections.

2.1 Model Concept

CR is a C-ITS service enabling vehicles to dynamically adjust routes using real-time traffic data shared between vehicles and infrastructure. This service optimizes routing recommendations based on criteria such as minimizing delays or travel times, thereby approaching a system optimal equilibrium state (Wardrop, 1952). In this study, CR is applied to a simple scenario where vehicles travel from a source to a target area, choosing among three route options (Figure 1).

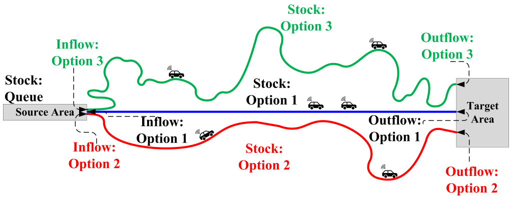

Figure 1: Model Concept – Cooperative Routing.

In the Base Scenario (without CR), vehicles follow a predefined route based on individual preferences or typical traffic patterns. The baseline daily traffic volumes for these routes reflect real-world data from EVIS.AT (2024). CR introduces the ability for equipped vehicles to reroute dynamically when delays are detected, improving traffic distribution and reducing congestion. The model incorporates the concept of an equipment rate, representing the proportion of vehicles equipped with C-ITS technology and therefore capable of utilizing CR. Equipped vehicles adjust their routes in real time according to the rerouting logic, while unequipped vehicles continue along their initially selected paths, unaffected by rerouting recommendations.

In order to avoid excessive complexity in the model and to be able to transfer the concept to a system dynamics model, the following simplifying assumptions were made:

- **Perfect Information:** Assumes accurate real-time traffic information with no errors, outliers, or communication delays, and therefore accurate rerouting recommendations.
- **100% Compliance Rate:** Assumes all vehicles follow rerouting recommendations.
- **No Additional Flows:** Assumes routes have no additional in- and outflows, except for the source and target areas.
- **No Subsequent Route Changes:** Assumes once a vehicle selects a route, it cannot be altered along the way.

2.2 Development of the Stock-Flow Model (SFM)

The model development began with a CLD based by the research of Walch et al. (2024), which examined impact propagation and rebound effects across various impact categories of C-ITS services. A modified and condensed version of the CLD from Walch et al. (2024) was then converted into a SFM using VENSIM. A universal structure for vehicle flow and Key Performance Indicator (KPI) calculation was designed to apply to all three route options. The model was further enhanced with a rerouting logic based on computed KPI values, specifically using the delay rerouting criterion. The finalized, comprehensive model is detailed in the Annex (see Figure 8).

2.2.1 Basic Structure – Route Options

The SFM, shown in Figure 2 for Route Option 1, provides a standardized structure applicable to all route options. Vehicles enter the queue based on *Input Data* derived from daily traffic volume measurements, with inflow calculated using both input data and traffic volume exceeding route capacity.

Vehicles in the queue make route decisions based on a rerouting criterion, and the respective number of vehicles depending on the *C-ITS EQUIPMENT RATE* will be rerouted. Route departure from the queue is

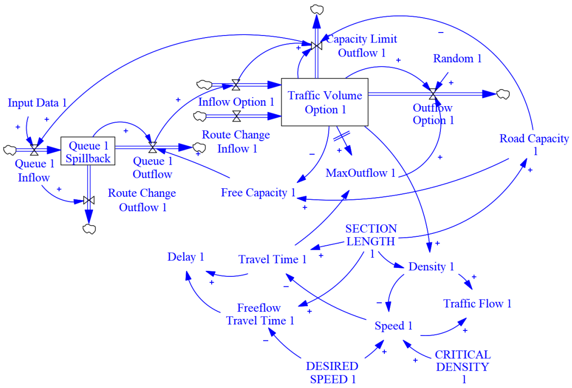

Figure 2: Basic Stock-Flow Model - Route Variants.

determined by the outflow equation of *Queue 1 Outflow*, ensuring it aligns with available road capacity on the intended route based on the traffic volume in the queue. The stock *Traffic Volume* represents vehicles actively traveling, with outflows accounting for destinations reached or capacity constraints. Traffic efficiency Key Performance Indicators (KPIs) are calculated using *Traffic Volume* and fundamental diagram equations. *Density* is derived from *Traffic Volume* and *SECTION LENGTH*, while traffic *Speed* is calculated using *Density*, *DESIRED SPEED*, and *CRITICAL DENSITY* via Drake's equation (Drake et al., 1966). *Traffic Flow* is computed as the product of *Speed* and *Density*, while *Travel Time* incorporates *SECTION LENGTH* and *Speed*. To prevent infinite travel times, a minimum speed threshold of 0.83 m/s (3 km/h) is applied. *Delay*, calculated by subtracting *Freeflow Travel Time* from *Travel Time*, serves as input for the routing logic.

The SFM applies uniformly across all routes, with default parameter values outlined in Table 1. These defaults allow for dynamic parameter adjustment during simulations, enabling sensitivity analysis and scenario testing.

Table 1: Default Values - Basic Structure Parameters.

Parameter	Route Option 1	Route Option 2	Route Option 3
SECTION LENGTH [m]	4,000	6,000	8,000
DESIRED SPEED [m/s]	27.78	27.78	27.78
CRITICAL DENSITY [veh/m]	0.035[1]	0.035[1]	0.035[1]

[1] Parameter value was selected, to set the maximum traffic flow to 2,100 veh/h (Rodrigue, 2020).

2.2.2 Rerouting Logic

The rerouting logic of the SFM, depicted in Figure 3, builds on the structure outlined in Figure 2. For clarity, the SFM structures for each route option are abbreviated, with each rectangle labeled "route option" representing a complete SFM as shown in Figure 2, highlighting only the most important in- and outflows.

The logic compares *Delays* between route options to select the one with the lowest delay (*Route Choice*). A *DELAY THRESHOLD* is incorporated to prevent rerouting for minor *Delays*, ensuring rerouting occurs only when the threshold is exceeded. To stabilize frequent route fluctuations, a cyclic update mechanism, represented by the stock *Route Choice Cyclic Update*, enforces a fixed interval (*UPDATE INTERVAL*) during which the selected route remains constant.

Rerouting calculations consider the proportion of vehicles equipped with C-ITS (*C-ITS EQUIPMENT RATE*) and are based on the route determined by the cyclic update mechanism. Vehicles are rerouted only from routes not selected by the *Route Choice* calculations. For example, if option 1 is selected, C-ITS-equipped vehicles originally destined for options 2 and 3 are redirected to option 1, while vehicles already assigned to option 1 remain. The aggregated result, representing all vehicles to be rerouted, is stored in the variable *Route Changers*.

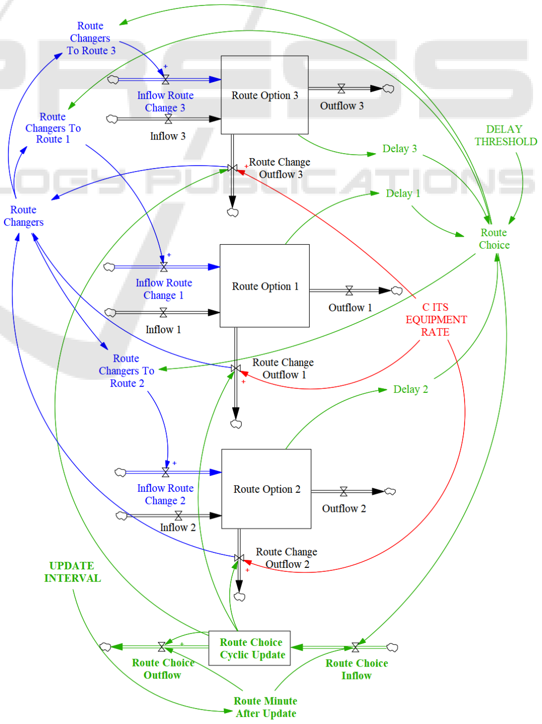

Figure 3: Rerouting Logic - Simplified View.

Default values for the parameters (*C-ITS EQUIPMENT RATE*, *Delay Threshold*, *Update Interval*) are set to 0 but can be dynamically modified during simulations. Combining the basic SFM for each route

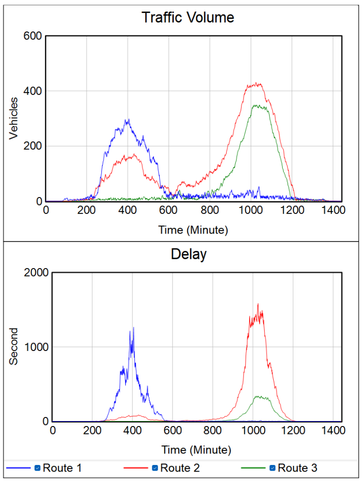

Figure 4: Results - Base Scenario.

option (Figure 2) with the rerouting logic (Figure 3) results in the complete SFM for CR (compare Figure 8 in the Annex).

3 RESULTS

The described SFM was implemented in VENSIM and served as the basis for assessing the impact of CR. A series of scenarios, each with unique parameter configurations, were systematically defined, tested, and analyzed. The results from these tests are detailed and compared in the subsequent subsections.

3.1 Base Scenario

The simulation results for the Base Scenario, where no rerouting occurs and vehicles follow their assigned routes, are summarized in Figure 4. Default parameters were applied, with the simulation covering one full day (1,440 minutes). The figure highlights traffic efficiency KPIs, including *Traffic Volume* and *Delay*.

The traffic patterns reveal notable peaks: route option 1 experiences a morning surge in *Traffic Volume*, while route option 3 has an evening peak. Route option 2 shows a smaller morning peak but a significant evening increase. Based on calculations using the fundamental diagram, it can be inferred that these peaks correspond to reduced *Speeds*, resulting in increased *Travel Times* and significant *Delays*. For instance, *Delays* exceed 1,000 seconds (16.6 minutes) on route option 1 in the morning and 1,400 seconds (23.3 minutes) on route option 2 in the evening.

Overall, the results depict high *Traffic Volumes* experienced by each route at specific simulation intervals, suggesting potential traffic efficiency improvements through strategic rerouting. Subsequent sections delve into scenarios featuring different parameter settings designed to explore rerouting effects.

3.2 Scenario I

In Scenario I, a *C-ITS EQUIPMENT RATE* of 25% was applied, meaning a quarter of all vehicles on all routes were rerouted to the route with the lowest delay (*Route Choice Cyclic Update*). The following parameters were used:

- *C-ITS EQUIPMENT RATE:* 25%
- *DELAY THRESHOLD:* 0 seconds
- *UPDATE INTERVAL:* 0 minutes

The results, depicted in Figure 5, demonstrate significant improvements in traffic efficiency. *Traffic Volume* was distributed more evenly across all three route options, with only one peak in the evening. As a result, *Delays* saw substantial reductions compared to the Base Scenario. Morning peak *Delays* were nearly eliminated, dropping to under 15 seconds, while evening peak *Delays* for all routes were reduced to less than 105 seconds (1.75 minutes), compared to 23.3 minutes in the Base Scenario.

The route change graphs highlight dynamic alternations in route choices, driven by the redistribution of *Traffic Volumes*. Early in the simulation, route option 1 was selected continuously for approximately 70 minutes, but thereafter frequent alternations occurred, ensuring balanced *Delays*. When vehicles rerouted to a specific route increased its *Traffic Volume* and *Density*, leading to higher *Travel Times* and *Delays*, another route was selected in the subsequent time step. Rerouting was performed every minute, even when *Delays* were minimal, as shown in the *Delay* and *Route Changers* graphs for the first 800 minutes. In summary, it is observed that a relatively low *C-ITS EQUIPMENT RATE* of 25% already leads to significant improvements in traffic efficiency. However, as will be discussed in Section 3.4, further increases in the *C-ITS EQUIPMENT RATE* do not necessarily correspond to improvements in traffic efficiency.

3.3 Scenario II

Scenario II builds on the setup of Scenario I with a *C-ITS EQUIPMENT RATE* of 25%, but introduces additional conditions: a *DELAY THRESHOLD* of 60 seconds, ensuring rerouting only occurs when the *Delay* on an unchosen route exceeds this threshold, and an *UPDATE INTERVAL* of 5 minutes, where *Route Choice Cyclic Update* is updated only at these intervals. The applied parameters are:

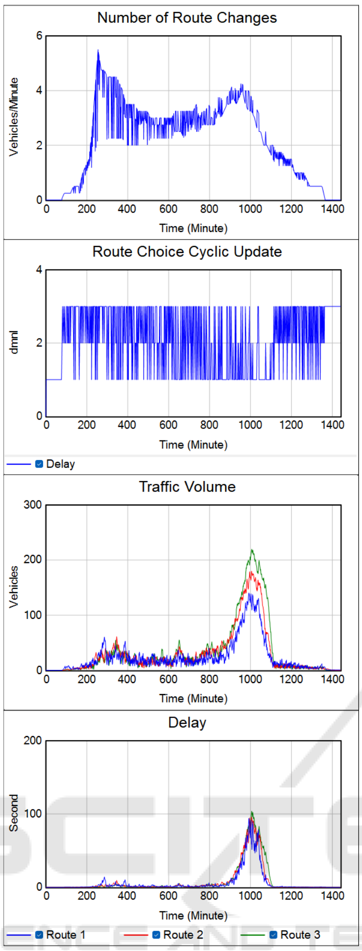

Figure 5: Results - Scenario I.

- *C-ITS EQUIPMENT RATE:* 25%
- *DELAY THRESHOLD:* 60 seconds
- *UPDATE INTERVAL:* 5 minutes

The results (see Figure 6) reveal key differences from Scenario I. Rerouting does not occur continuously but starts at minute 276, redirecting vehicles to route option 3. After this, rerouting is absent for several hours until the evening.

Unlike Scenario I, the *Route Choice Cyclic Update* exhibits fewer alternations due to the 5-minute update interval. This results in less balanced *Traffic Volumes* among the three routes. In terms of *Delay*, Scenario II shows increased peaks compared to Scenario I. Morning *Delay* for route option 1 reaches 100 seconds (1.67 minutes), while evening peak *Delays* for all routes range between 180 and 190 seconds (3 to 3.17 minutes). Despite these increases compared to Scenario I, Scenario II still achieves significant traffic efficiency improvements over the Base Scenario.

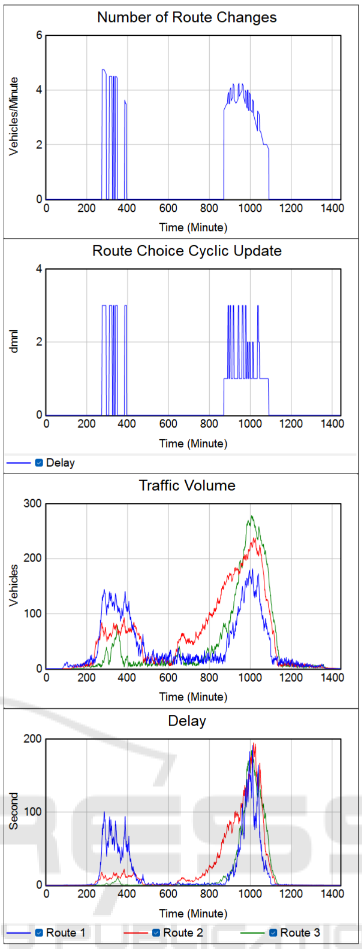

Figure 6: Results - Scenario II.

3.4 Scenario III

Scenario III applies a *C-ITS EQUIPMENT RATE* of 100%, where all vehicles are rerouted to the current *Route Choice Cyclic Update*. The *DELAY THRESHOLD* and *UPDATE INTERVAL* remain similar to Scenario II. The parameters used are:

- *C-ITS EQUIPMENT RATE:* 100%
- *DELAY THRESHOLD:* 60 seconds
- *UPDATE INTERVAL:* 5 minutes

The results (see Figure 7) demonstrate that while Scenario III achieves improvements compared to the Base Scenario, it performs worse than Scenarios I and II. A detailed analysis reveals fluctuations in *Traffic Volume* and *Delay*. This decline in efficiency arises from the high *C-ITS EQUIPMENT RATE*, which results in all vehicles being rerouted to the route with the lowest *Delay*. Although this temporarily alleviates congestion on high-delay routes, it risks overloading the selected route, leading to inefficiencies.

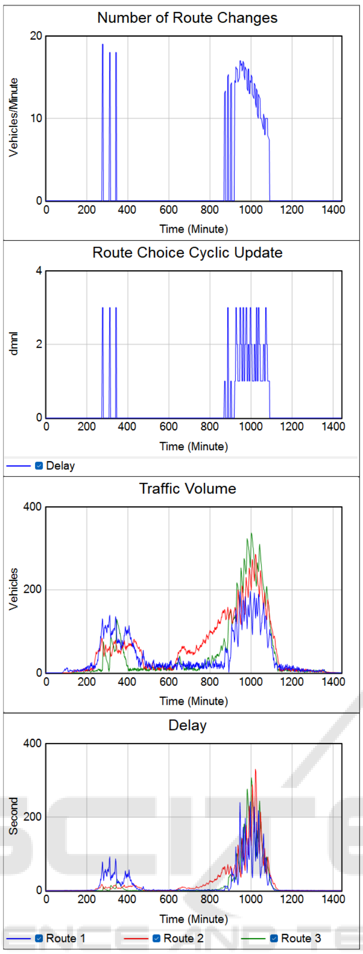

Figure 7: Results - Scenario III.

The combination of a 100% *C-ITS EQUIPMENT RATE* with an *UPDATE INTERVAL* reinforces this effect. For 5 consecutive minutes, all vehicles from two routes are rerouted to the currently selected route, causing rapid increases in *Traffic Volume* and *Delays*. Once the interval elapses, vehicles are rerouted again, resulting in similar effects on the newly selected route. This cyclic pattern disrupts traffic distribution, causing uneven *Traffic Volume* and higher *Delay*. The morning *Delay* for route option 1 reaches up to 90 seconds (1.5 minutes). During the evening peak, *Delays* for route options 1, 2, and 3 reach 240 seconds, 330 seconds, and 310 seconds, respectively.

4 SYSTEM DYNAMICS VS. AGENT-BASED MODELS

Comparing the findings from this SD-based study to existing literature using ABM reveals consistency in results, despite differences in methodology.

For instance, Kim et al. (2020) explored CR for enhancing traffic flow via ABM with SUMO and OMNET++ simulators on a Manhattan grid network. Their findings showed that CR significantly increased average speed and reduced travel time. However, for equipment rates near 100%, benefits began to diminish. Improvements were substantial up to a 20% rate, with continued, albeit reduced, efficiency gains between 20% and 60%. Beyond 60%, high volumes of rerouted vehicles caused congestion on alternative routes, mirroring the trends identified in the SD model. Similarly, Wedel et al. (2009) investigated CR using SUMO and VSimRTI simulations in Cologne. Their results demonstrated significant travel time reductions (up to 50%) for both cooperative and conventional vehicles at 80% equipment. Cooperative vehicles showed benefits even at a 20% rate, while conventional vehicles required at least 60% to see improvements. At approximately 75% equipment, regular vehicles outperformed cooperative ones due to remaining on main routes, avoiding congested alternative paths. Katsaros et al. (2011) analyzed CR based on congestion levels using SUMO and JiST/SWANS. Their work revealed that travel times decreased significantly up to an equipment rate of 60%. However, equipment rates exceeding 80% led to adverse effects, as collective rerouting congested alternative routes. They proposed improving rerouting algorithms to prevent simultaneous diversion of all equipped vehicles. The results obtained from the SD approach are consistent with ABM findings in terms of trends in travel time and speed improvements across varying equipment rates. Notably, both approaches identify diminishing returns or even adverse effects at high equipment rates due to overloading of alternative routes.

The SD approach offers a macroscopic traffic simulation model, in contrast to ABM's microscopic approach, which requires detailed agent behavior calibration. This reduces modeling effort in C-ITS impact assessment, as the SD model does not require such detailed implementation. Additionally, the SD model explicitly encodes interrelationships and feedback loops between different impact categories, enhancing interpretability. In contrast, ABM implicitly captures these effects in the results analysis. The SD framework supports rapid scenario testing and sensitivity analysis, enabling quick exploration of parameter variations, while ABMs require extensive computational resources and time for multiple simulations and post-simulation analysis. Therefore, while both models produce comparable results, the SD approach offers advantages in terms of modeling efficiency, explainability, and immediate scenario testing, making it a valuable tool for assessing C-ITS impacts.

5 CONCLUSION

This work applies the SD modeling technique to assess the impact of the C-ITS service CR on traffic efficiency. By using the developed SFM, multiple scenarios were defined to test different parameter combinations and compare the results. The findings highlight the influence of the *C-ITS EQUIPMENT RATE*, *DELAY THRESHOLD*, and *UPDATE INTERVAL* on results, with all scenarios showing improvements over the Base Scenario to varying degrees.

Key findings indicate that low *C-ITS EQUIPMENT RATEs* yield significant traffic efficiency improvements. However, rerouting all C-ITS equipped vehicles (100% *C-ITS EQUIPMENT RATE*) to the route with the lowest *Delay* can cause overloads, particularly with long *UPDATE INTERVALs*, leading to *Delays*. Introducing a *DELAY THRESHOLD* helps avoid rerouting for minimal *Delays*, though this reduces overall efficiency as it takes some *Delay* to initiate rerouting. High *UPDATE INTERVALs* in combination with a high *C-ITS EQUIPMENT RATE* lead to route overloads. A more selective rerouting strategy, where only a portion of equipped vehicles are rerouted for optimal performance, is recommended.

Future extensions of the model could include predictive rerouting based on anticipated outcomes, integration of different rerouting criteria such as *Free Capacity* or *Travel Time*, and the inclusion of stochastic elements to account for compliance probabilities. Additionally, the model could be expanded to assess other impact categories such as sustainability, considering factors like CO_2 emissions and noise levels, allowing for rerouting criteria that balance both traffic efficiency and sustainability.

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APPENDIX

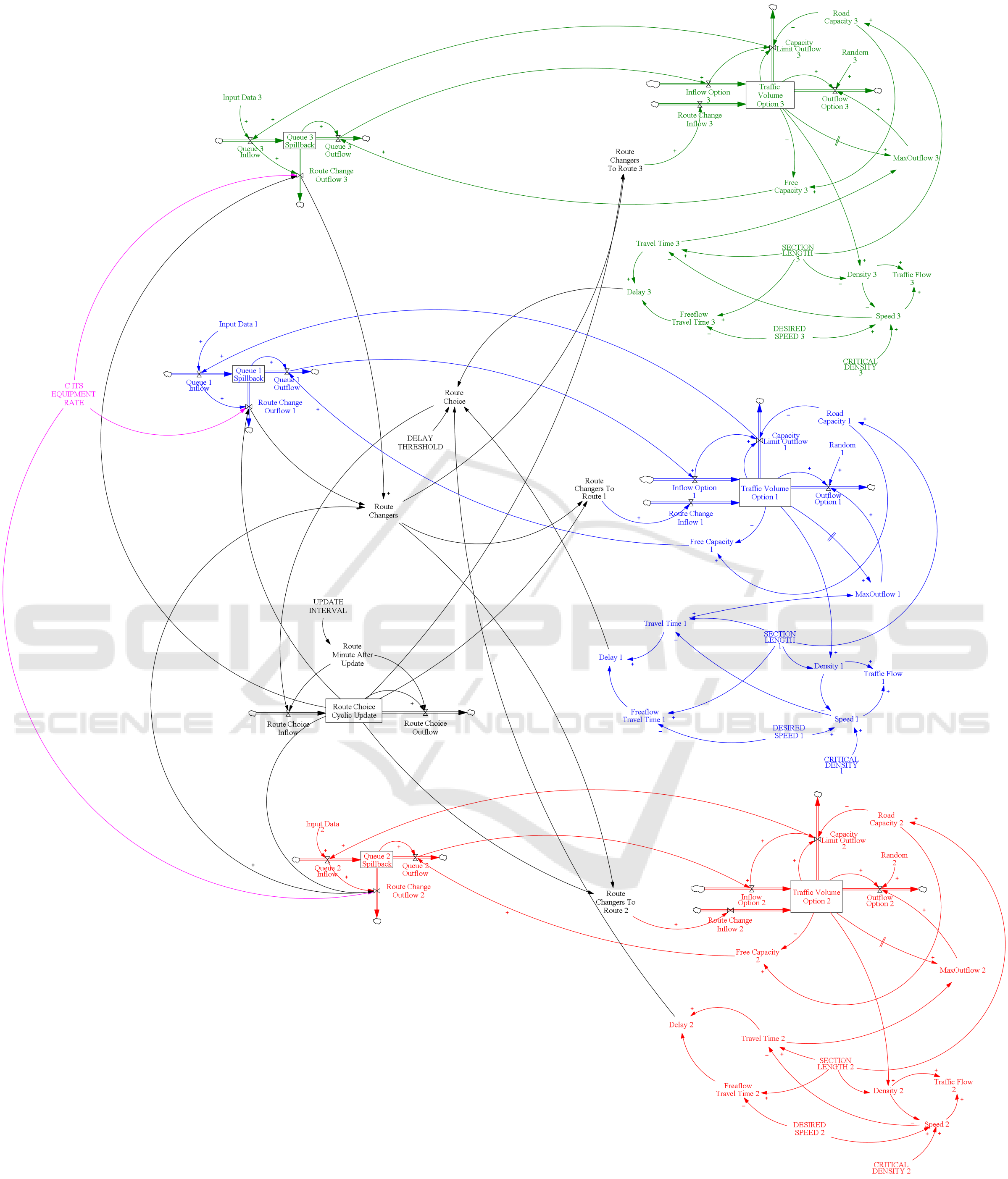

Figure 8: Complete Stock-Flow Model.