

Towards an approach to road cargo system-of-systems modelling

Per-Olof H. Sturesson^{1,2*} and Ciarán J. O'Reilly^{1,2}

¹ *KTH Royal Institute of Technology, Teknikringen 8, 100 44 Stockholm, Sweden*

² *The Centre for ECO² Vehicle Design, Teknikringen 8, 100 44 Stockholm, Sweden*

*Corresponding author. perploff@kth.se

ABSTRACT

The transition from internal combustion engines to electric propulsion for road-cargo systems is on-going and faces multiple challenges for the involved actors and affected stakeholders. The product development of, for example, future battery electric heavy trucks for long distance hauling requires new perspectives on concept evaluation and selection due to high data uncertainty. These new perspectives are needed to satisfy the business objectives of both OEMs and transport providers, while also fulfilling an overall set of requirements, including environment-related ones. From a society point of view, public investments in electric power generation and distribution grids will be needed as use of electric energy will increase. These public investments need to be balanced and prioritized with other expenses. The investments in new technology in terms of battery electric haulers made by the transport providers need to be profitable and competitive with respect to utilization rate and cargo transport efficiency. The time duration of the mentioned activities is significantly different, which adds more complexity. The complexity of the road cargo system as a whole can be modelled as a system-of-systems, as the constituent systems like truck, transport and energy providers as well as energy and road infrastructure are independent managerially and/or operationally systems themselves. This paper describes the state and outlook of the conceptual modelling of key components in a general road cargo system of systems framework.

1. INTRODUCTION

The ongoing global climate change driven by greenhouse gas emissions from fossil fuels, where the ground transportations, i.e. road transportation, accounts for 16% of the total CO₂ emissions, is a challenge to mitigate (Ritchie, 2020, IEA, 2022). Road transportation accounts for three-quarters of the transport emissions, where most of this originates from passenger transportation, around 45% while 30% is from road cargo transports. Reduction of greenhouse gas emission may be undertaken through a combination of reducing emissions at the vehicle source, change in fleet configuration and the total transportation demand. The demand for ground transportation is however increasing due to an increase in regional and global economic growth and trade. This implies that CO₂ emission reduction is a multi-objective problem, consideration to both environment and economics are needed when countermeasures are to be researched, developed and implemented.

The efforts to reduce CO₂ emissions at the source focus on optimization of the internal combustion engine, transition to other energy sources like hydrogen or electricity as well as minimizing road load, i.e. mainly aerodynamic drag and rolling resistance. The former efforts are likely to result in marginal improvements in efficiency compared to the emission reduction needed and the fact that the internal combustion engine has been available on the market for more than a century while transition to hydrogen and electricity yields in larger emission reduction possibilities. Using well-to-wheel perspective it is evident that transition to either hydrogen or electricity also requires focus on emission reduction on the energy production system.

The transition to electric as well as hydrogen propulsion systems for road cargo system is evolving. Standard purpose zero-emission heavy trucks, which mainly have a battery-electric propulsion system, have been on sale on the Chinese and European markets for more than half a decade. The sales numbers in Europe at present are small, the market share is less than 2% indicating that a possible major market break through still lies in the future (ICCT, 2025a). The sales of zero-emission heavy truck by configuration are different, more evenly distributed between tractor-semitrailers (long haulers) and rigid trucks compared to conventional heavy trucks, where tractor-semitrailers hold slightly more than half of share. On the Chinese market the sales of zero-emission heavy trucks reached a share of slightly less than 21% by the end of year 2024 (ICCT, 2025b). The overall share for whole year 2024 were 13%, indicating a market break through. Battery swapping techniques, allowing for smaller batteries in terms of energy storage, mass and vehicle

investments, together with national subsidies have paved the way for the increase in sales.

Traditionally, the product development in the heavy truck industry as well as in the automotive industry is by its nature evolutionary, innovative in small increments while minimizing development risk. The introduction of new innovative technologies such as electrification of the propulsion system is challenging as a high degree of uncertainty is present in the concept phase, where the vehicle architecture is defined. The decisions concerning definition of product capabilities balanced to product cost and investments to meet requirements from stakeholders and customers are strongly affected. Reuse of system and system elements as well as investments, i.e. legacy, minimizes product development risk but may be a constraint for innovation. Dependency and effects of capabilities and business objectives may be complex but are important to consider. As an example, the energy storage concept, e.g. type, sizing and packaging constraints, relation to payload penalty may affect the contribution margin for transport mission, which may be offset by lower cost of energy. The truck, abstracted as a system, has interfaces to other systems, see Figure 1, which need to be considered in the management of the product life cycles (Walden et al, 2023). The increasing complexity with respect to endo- and exogenous system and system elements including interfaces over the whole product life together with sustainability regulations yields in additional challenges during the concept definition and selection phase. As an example, the infrastructure investments in energy distribution to a network of point-based charging stations or semi-continuous charging while driving may also be needed. The product life and residual value are also important factors to consider. The time lag and inertia of infrastructure investments differs geographically and feature differences to product development rate in the heavy truck industry. This means that the conceptual sweet spot for a single global configuration for e.g. long hauling may be difficult to find. Modelling and analysis of system interactions to support decision making in the conceptual phase may be a key factor to minimize risk.

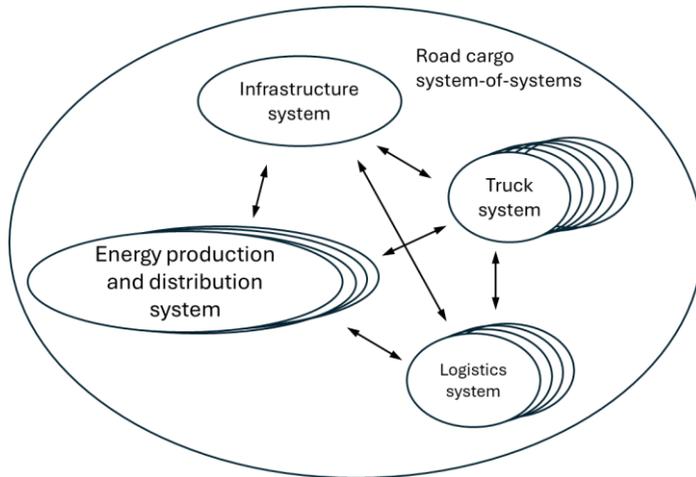


Figure 1: Modelling approach of road cargo system-of-systems.

Systems Dynamics methodology offers opportunities to model and analyse complex systems using a trade-off between simplicity/high abstraction level versus complexity/high detail fidelity and has been applied to transport system for several decades (Shepherd, 2014). The advantage with System Dynamics approach is that both qualitative and quantitative entities may be included using, for example, a causal loop diagram but a too complex model can be difficult to understand and lack rigour. For decision making quantitative metrics may be requested resulting in a need of mathematical representation of the system input and output relationships build on empirical and/or physical relations including feedback loops with time lag and gain.

Application of System Dynamics to model and analyse transportation systems is often limited in consideration to one of the systems shown in Figure 1 and sometimes only statically in the meaning that the critical dynamic interaction or feedback between systems and system elements are not included (Ghandriz, 2018). When optimisation of vehicle concepts with respect to mainly total cost of ownership have been done considering interaction to road infrastructure for different propulsion concepts and truck configurations the problem quickly gets very large as the number of vehicle configurations is substantial (Ghandriz, 2018). Finding the global optimality may then be hard.

In (Raoufi et al, 2024), key entities are identified together with their interactions using reinforcing or balancing loop. Grouping of entities to facilitate system dynamics is found to be useful. In (Andruetto, 2024) a System Dynamics approach to model and analyse different policy scenarios for the road

cargo transport has been conducted starting with the establishment of causal loop diagrams. The model has been decomposed into different sectors where stock and flow equations have been formulated. Metrics for emissions and a proposed transport efficiency metric have been evaluated. Consideration to charging of electric trucks and infrastructure has been included by means of different policies. In (Fehler! Verweisquelle konnte nicht gefunden werden.r, 2023) a system-of-systems modelling approach have been applied to study different scenarios for infrastructure in the Netherlands considering passenger transportation by road and rail as well as cargo transport on rail, road and seaways. Interaction for demand and choice of transportation mode (e.g. rail or road) has been modelled.

Within the Centre for ECO² Vehicle Design at KTH Royal Institute of Technology a general framework for modelling road cargo systems featuring interactions to be modelled using system dynamics approach has been developed with purpose to support conceptual decision making (Fehler! Verweisquelle konnte nicht gefunden werden.et al, 2021). The framework includes system context, characteristics and performance for each constituent system. A step-by-step development of configurable vehicle models or agents balancing accuracy of underlying physics to computational effort has been done (Fehler! Verweisquelle konnte nicht gefunden werden.2022, Wu, 2023) to support the modelling and analysis of road cargo system-of-systems.

The overall research questions for the ongoing project are:

1. How to model the system-of-systems that make up road-cargo transport considering its constituent systems and technologies and their relevant interdependencies and dynamics for a class of transport missions and conditions?
2. What are the relevant category elements (e.g. society and planning, infrastructure and energy provision, haulage operators, vehicle manufacturers, etc.) and their interdependencies?
3. What are the emergent phenomena and behaviours that characterise the constituent systems at different scales (e.g. coarse and fine) and what are the underlying mechanisms, variables and connections to be included in a valid model?
4. How can the scale resolution be extended from early coarse indicative simulations to more advanced resolution while retaining category element interfaces, handling increased uncertainties, and maintaining verification and validation capabilities?

5. Strategies for systems of system model verification and validation and critical metric development and cascading to constituent systems.

This paper focusses on describing the architecture, the early phase of definition, abstraction and partly the implementation of some key system elements of the road cargo system-of-systems.

2. METHODS

While Systems Engineering is traditionally focused on the development and life management of monolithic systems with well-defined boundaries System-of-Systems Engineering is focused on the assembly of a mix of possibly already existing and new systems into a new whole where the capability is greater of its constituent parts (DeLaurentis et al, 2023). In Systems Engineering the basic assumption is that a given set of requirements based on input from customers and stakeholders yield into that the system can be built to meet those requirements. This assumption does not hold if the boundaries interfaces are open or ill-defined resulting in unpredictable behaviour of system elements and unclearly defined requirements, which make the verification and validation challenging.

The term system is old and may be attributed all the way back to Aristotle: “The whole is more than the sum of its parts. The part is more than a fraction of the whole.” This abstraction is called systems thinking defining a system as an integrated set of elements, subsystems, or assemblies that accomplish a defined objective (Walden et al, 2023). The term system-of-systems is defined as a set of systems or system elements that interact to provide a unique capability that none of the constituent systems can accomplish on its own (ISO 2019). Classification is applied in both Systems and System-of-Systems Engineering. The term complex system is defined as a system composed of multiple interacting elements, which collective behaviour does not yield trivially from the behaviour of individual elements (DeLaurentis et al, 2023). Classification may also be based on the level of control authority (DeLaurentis et al, 2023). A system-of-systems where the participation is voluntary and feature no central objective, management, authority or funding is denoted collaborative system-of-systems. This means that the constituent systems have a high degree of autonomy in its operation. The road cargo system clearly fulfils these two definitions and can be defined as a complex, collaborative system-of-systems.

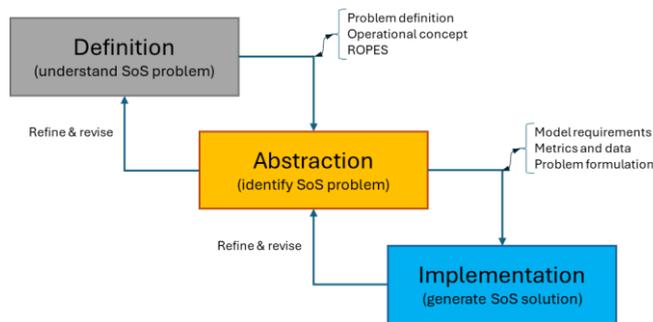


Figure 2: Overview of the Definition, Abstraction and Implementation (DAI) process after (DeLaurentis et al, 2023).

System-of-Systems Engineering is a relatively young discipline and therefore not as advanced and standardized as Systems Engineering (DeLaurentis et al, 2023). Framework and formal structured process for modelling and analysis of systems-of-systems regardless of size and operational context is available and consist of three phases (DeLaurentis et al, 2023): Definition, Abstraction and Implementation (DAI), see Figure 2.

The Definition phase focusses on understanding the system-of-systems in terms of operational context, timescale, objectives etc. The Abstraction phase bridges the Definition towards the Implementation phase, where modelling and analysis is the emphasis, and focusses on using the outputs from the Definition phase to build relationships by describing networks between entities, preferably by visualising.

During the Definition phase it is useful to use a lexicon or ontology that features the representation of system-of-systems into multiple levels, each with constituent elements and their interactions. Depending on the modelling objective (qualitative or quantitative) the requirements on the applied lexicon may differ and different ways of categorization may be applied (DeLaurentis et al, 2023). The categorization of the system-of-systems into the qualitative and quantitative elements is more effective compared to mass brainstorming (DeLaurentis et al, 2023). In System-of-Systems Engineering the categories Resources, Operations, Policies and Economics form the acronym ROPE and may be used to categorize the constituent elements in a system-of-systems. There are no limitations to adding more categories that seem useful for a problem at hand. Any category extension may also be performed iteratively during the DAI process. Resources include physical and non-physical elements as trucks, energy distribution, roads and routing software in a road cargo system-of-systems. In contrast to systems engineering, where humans usually are

assumed to be users or operators, system-of-systems engineering often exhibits its modelling challenges of humans due to their socio-technical character. Operations are the processes and procedures that contribute to the dynamics of the system-of-systems like a transport mission or a charging operation. Policies are the regulations and rules that govern management and operations like truck driver working hours or emission taxation and regulations. Finally, the Economics are e.g. revenue, interests, investments, operational cost and taxes for the different stakeholders. Introducing hierarchy levels as the second dimension of system-of-system categorization yields in sorting of elements with interdependence and autonomy where lowest level, the α -level, manifests in no further decomposition and may be thought as building blocks (DeLaurentis et al, 2023). The next levels, β , γ and so on, are the collections of elements from the immediate lower level. Depending on the size and complexity of the system-of-systems the number of hierarchy levels may vary. In Figure 3 a system-of-systems a generic model abstraction using ROPE categories and hierarchy levels is shown.

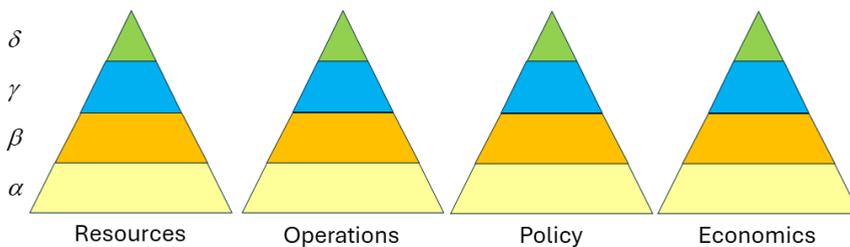


Figure 3: The ROPE categories and levels of hierarchy after (DeLaurentis et al, 2023).

The Abstraction phase focusses on the defining the actors, effectors, disturbances and the interdependency networks using e.g. the categorized entities from e.g. a table shown in Figure 3. The big picture dynamics is encapsulated. The outcome of the abstraction are the modelling variables as inputs, outputs and metrics at each level of the system-of-systems (DeLaurentis et al, 2023). The emphasis is on building the highest possible level of abstraction, to move away from details. Three classes of design variables in the abstraction process are in focus: composition (which systems, functions and resources), configuration (which operational interdependencies and constraints) and control (what autonomy, which incentives). Composition relates to topics like which systems are present, the interface requirements, cost and risk while configuration relates to topology of the system-of-systems and which information is

passed on the links and control address how and who controls the effectors. In a product development context consideration to time scale for the system-of systems is also carried out. Finally, identification of stakeholders and their needs, the tangible systems of resources, the drivers, which are the forcing functions that drive the stakeholder network, the disrupters, which are the exogenous entities that affect the network and the network itself are done.

3. RESULTS

An initial road cargo system-of-systems model has been developed where the Definition, Abstraction and partly the Implementation phases have been performed. Results from the Definition phase in terms of ROPE-table as shown in Table 1. Quantitative characteristics can then be identified and assigned to the resources and economic categories in the ROPE table at α -level for modelling purpose in the Implementation phase. The dynamics of the operations with exciters, both exo- or endogenous, and constraints may then also be formulated by means the operations and policy categories in ROPE table during the Abstraction phase. Model requirements and simplification criteria and the impact on modelling and accuracy of analysis results are also important outcome, see Figure 4. Objective data (Transport Analysis, 2024) has been input to simplifications done, which are valid for a Swedish transport system context and obviously the simplifications may be different for another context yielding in different simulation outcome.

Table 1: ROPE table for road cargo system-of-systems.

	Resource	Operations	Policy	Economics
α	Vehicle, road, energy production unit, energy distribution hub, logistic hub,	Vehicle operation, road infrastructure operations, energy production unit operation, energy distribution hub operation, logistic hub operation	Vehicle policies Road policies, Working hour regulations, Energy production regulations and policies Energy distribution regulation and policies logistics hub policies,	Vehicle operating costs, road operating costs, energy production unit operating costs, energy distribution operating costs, logistics hub operating costs
β	Transport provider vehicle fleet, energy production plant, energy distribution network, B2B logistic provider network	Transport provider operations, road network operations Energy production plant operations, energy distribution operations, logistics provider operations,	Policies concerning network operation	Operating cost for a resource network
γ	Collection of national resources in a road transportation system	Collection of national operations in a road transportation system	Policies for national road transportation system	Forecast of national road transportation market

During the Implementation phase modelling and analysis take place generating data for model verification and validation as well as project decision

making. Depending on complexity of the system-of-systems of interest it may be useful to make a graphical representation of the implementation to visualise the interactions by the different systems. In Figure 5 a conceptual representation using a causal loop diagram of the road cargo system-of-systems is shown in where equations of motions for vehicle system are incorporated in order to derive metrics like energy consumption and CO₂ emissions (Hayes et al, 2018, Wu, 2022, Rill et al , 2020, Wu, 2023). Complexity may be added gradually by means of iterations of model abstraction, simplification and re-modelling depending on outcome of model verification and validation tasks.

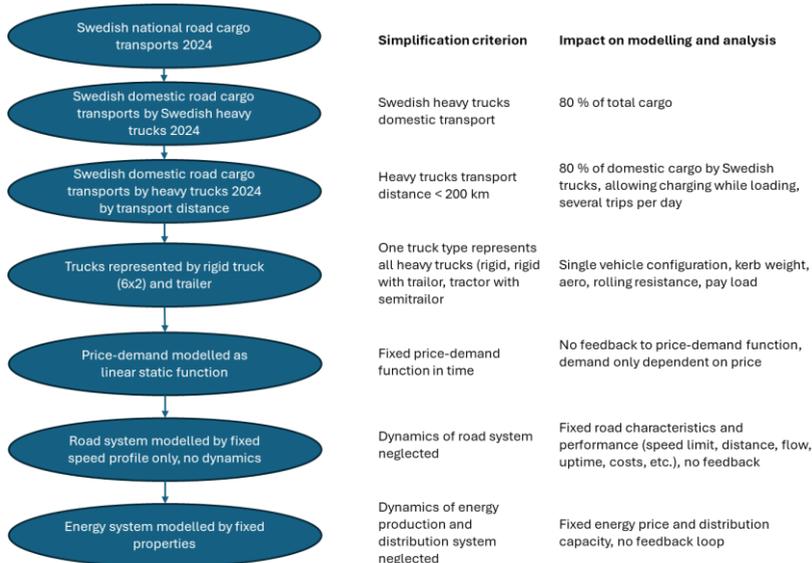


Figure 4: Model abstraction for road cargo system-of-systems.

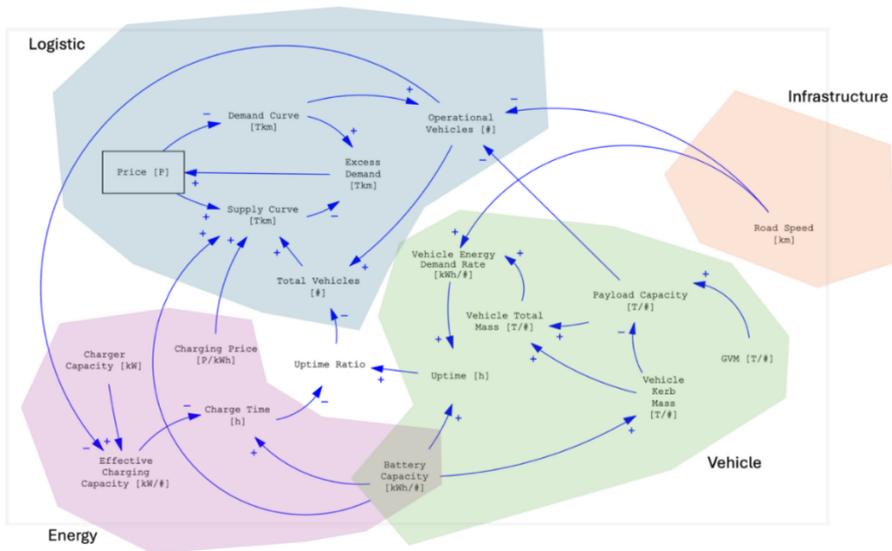


Figure 5: Conceptual representation of the system-of-systems model.

4. DISCUSSION

An initial conceptual road cargo system-of-systems model for a Swedish context has been developed using System-of-Systems Engineering approach. By means of categorisation of the constituent systems and their elements and model simplification the system dynamics of conceptual model could be established. The simplifications applied will influence simulation outcome, other contexts require other simplifications. The underlying fundamental equations for different metrics like energy consumption and CO₂ emissions have been implemented separately and will be integrated in model in the future. Policies can be implemented as model constraints or exogenous excitors. The next steps focus on model verification and validation followed by remodelling iterations where increasing modelling complexity may be a key until sufficient accuracy is achieved. The famous quote by G.E.P Box “All models are wrong, but some are still useful” may be used as guideline in the verification and validation task emphasising on a “useful” model as end outcome. Inclusion of the dynamics of energy production and distribution system and road system may be studied in future work and also more complex modelling such as socio-technical parameters and parameter sensitivity and uncertainty propagation to model response. Interactions with additional systems like

macro-economics to study and understand balancing economic and ecological performance are also planned.

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