31st Annual INCOSE international symposium
Honolulu, HI, USA
July 17 - 22, 2021

Using Models and simulation for concept analysis of Electric Roads

Lars-Olof Kihlström
Syntell AB
PO Box 10022, SE-10055 Stockholm, Sweden
+46 706661978
lars-olof.kihlstrom@syntell.se

Matthew Hause
Systems Solutions Inc (SSI)
3208 Misty Oaks Way, Round Rock, Texas, USA
+1 917 514 7581
mhause@systemxi.com

Andreas Kihlström
BRP systems AB
Diskettgatan 4, SE-583 35 Linkoping, Sweden
+46 761641978
andreas.kihlstrom@brpsystems.se

Ida Karlsson
Syntell AB
PO Box 10022, SE-10055 Stockholm, Sweden
+46 761681703
ida.karlsson@syntell.se

Bilin Chen
Syntell AB
PO Box 10022, SE-10055 Stockholm, Sweden
+46 736571556
bilin.chen@syntell.se

Abstract. Using electricity to directly power moving vehicles has been used for a long time as evidenced by trains, trams, and electrical buses. Providing electricity to move heavy transport trucks on roads Therefore does not represent a huge innovation. Since heavy haulage traffic on roads represents a significant part of carbon dioxide emissions, electric roads (ERs) that can provide engine power to heavy road haulage is seen as significant by the Swedish government (Bateman et al, 2018SP04EN). Several Swedish government authorities as well as private companies are actively testing equipment both for trucks as well as roads. Once they have been deployed, ERs will also provide benefits as regards air quality and traffic noise. This paper describes a concept analysis project that uses models and simulation to analyze electric road scenarios. Electric road enabled trucks of different types run along an electric road and are subjected to different road conditions, speed restrictions as well as queues over a defined amount of time. The ability to analyze both management and energy consumption of an electric road is of paramount importance in determining its ability to accomplish the desired carbon-dioxide emission reductions.

Introduction

The reduction of carbon dioxide emissions is a great environmental concern and the heavy haulage traffic on roads represent a significant part of carbon dioxide emissions in Sweden (around 25%). By establishing an electric infrastructure within roads with heavy transport traffic, trucks can be powered by the electricity directly received from the road infrastructure. This can be used to significantly reduce the carbon dioxide emissions associated with heavy transports and will also provide benefits as regards air quality and traffic noise. In Sweden where this is being tested, both government authorities as well as companies capable of delivering heavy transport trucks and electricity infrastructure take this very seriously.

Currently three different technologies (Gustavsson et al, 2019) are being looked at for the infrastructure as shown in Figure 1:

- Overhead wire
- Rails in the road
- Induction coils in the road

Figure 1. Different ER technologies

There are several issues, apart from the actual technology to be used, that require consideration:

- An electric road infrastructure must be managed.
- Usage of the electricity in a road will need to be handled financially and a payment structure needs to be defined.
- Since the government desires that haulage companies as well as companies with large transport requirements make use of trucks that are electric road enabled, (i.e., contain the hardware and software to connect to an electric road), incentives will need to be defined.
- A clear understanding will also be needed concerning the electricity consumption figures that will need to be handled by the infrastructure associated with electric roads.

The stakeholders and the dependencies between them need to be considered. The following can readily be identified:

- Government (based on the need to reduce carbon dioxide emissions).
- Truck manufacturer (need to produce trucks with appropriate connectors)
- Haulage contractor (reduction of haulage costs and green image)
- Companies with large transportation needs (transportation costs and green image).
- Environmental organizations (carbon dioxide emissions)

The models defined for analysis of this system of systems make use of the Unified Architecture Framework (UAF) version 1.1 standardized by the Object Management group (OMG, 2013). UAF is a framework built on top of SysML (System modeling Language). UAF is the third version of UPDM the Unified Profile for DoDAF and MODAF (UAF, UPDM, SysML). (OMG, 2019)

Electric road concept analysis considerations

A summary of the important criteria for an electric road and its handling are shown below.

1. The electric road SoS shall allow electric road enabled vehicle speeds up to up to 90km/h.
2. The SoS shall allow billing the owner of the electric road enabled vehicle for electric road usage.
3. Electric road users shall be given access to an electric road with one of their electric road enabled vehicles that have a valid access subscription provided by the owner of the electric road.
4. An access attempt by an electric road enabled vehicle shall be prohibited if no valid subscription exists for that electric road.

Management considerations and constraints. A stretch of an electric road will need an operator to manage truck access to the road (turning segments on and off as required). There is also a need to administer the subscriptions for users, to handle usage invoicing as well as managing electricity contracts and payments towards the electricity supplier for the electric road. The operator and the owner of a road could be one and the same, but ownership and operations handling could also be split between an owner and an operator working under contract for the owner.

A set of some of the life cycle use cases is shown in Figure 2 and as a list below:

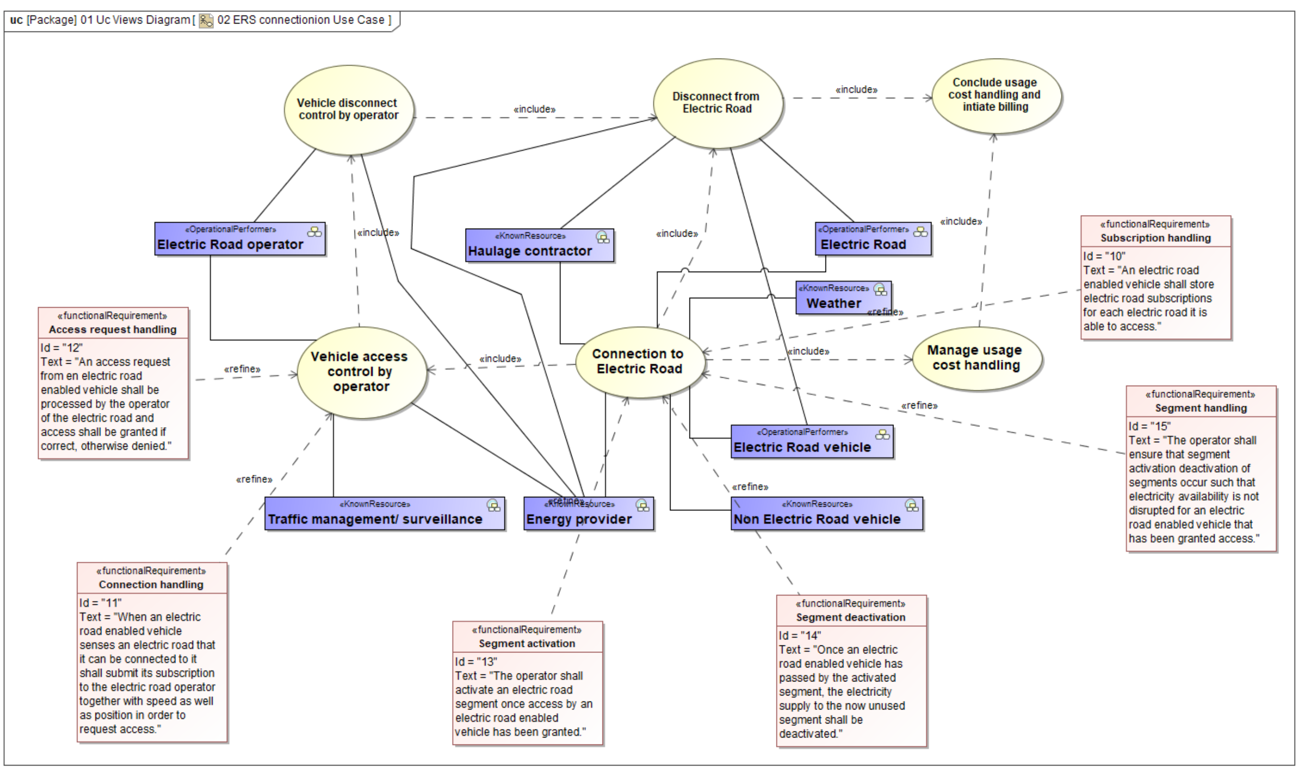

Figure 2. A use case diagram example for electric road connection and disconnection

Electric road construction	Connection to electric road	Electric road maintenance and inspection	Conclude usage cost handling and initiate billing
Vehicle access control by operator	Disconnect from electric road	Electric road owner handling	Electric road power management
Electric road accident handling	Electric road vehicle overload handling	Electric road operator handling	Electric road vehicle inspection
Electric road construction procurement	Vehicle disconnect control by operator	Electric road vehicle disconnection	Manage usage cost handling

Similar modelling approaches for large scale systems of systems analysis have been used previously (Peter Sjöberg et al, 2017).

Figure 3 is an operational architecture model and deals with connection, disconnection, subscriber management as well as energy provision. The arrows in between the elements contain flows of information required as well as items such as electricity. In Figure 4 a smaller set of the operational architecture is shown, and the flows of information required to manage subscription and access are shown. Both diagrams are UAF diagrams and correspond to SysML internal block diagrams where specific UAF elements have been used. The icons used inside elements are used to make the diagram easier to digest for non-modelers. It is important to note that the emphasis here is on the operational architecture, not on a specific implementation. The elements have an overall logical function but could be implemented in different ways.

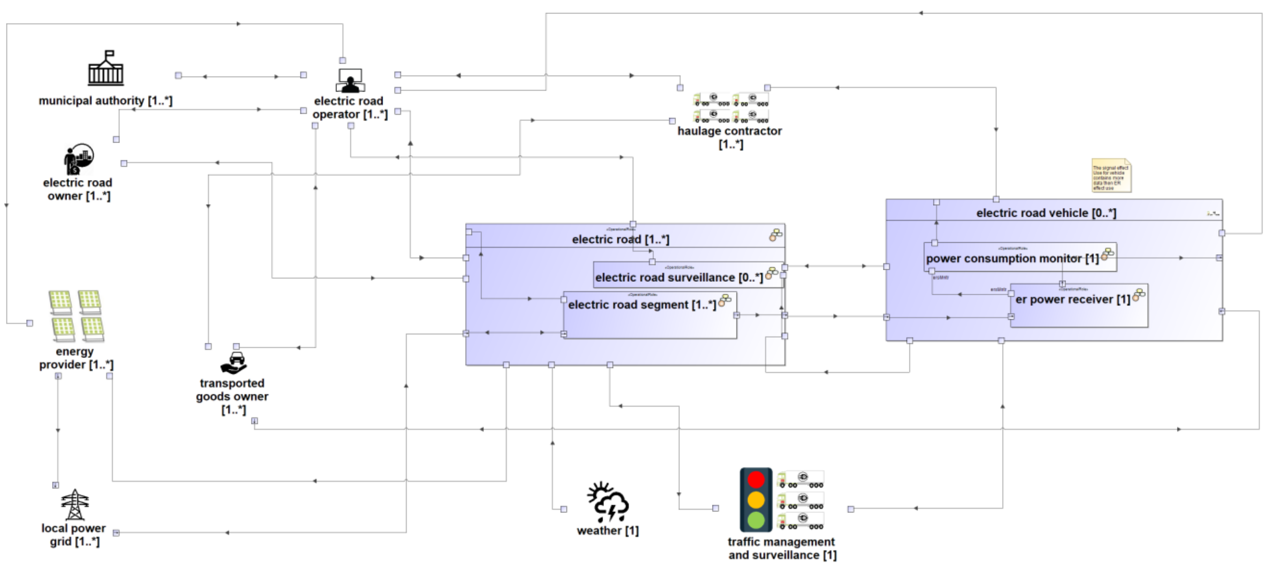

Figure 3. Operational architecture dealing with major stakeholders.

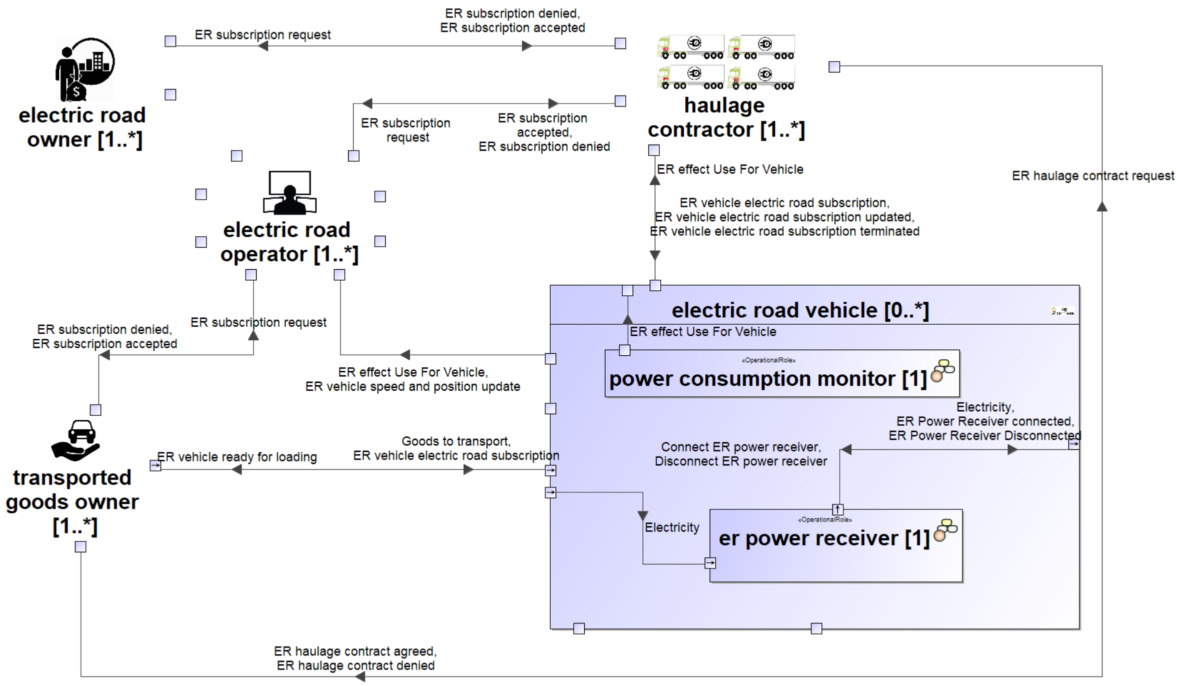

Figure 4. A portion of the operational architecture detailing access handling

A crucial point that bears consideration is whether the transported goods owner or the haulage contractor is the one that should be a subscriber. The subscriptions need to be available to the individual truck since this is the one that requests access. If the subscriber is the haulage contractor, the subscription can be made available to each truck in the fleet of the haulage contractor. If the transported goods owner is the subscriber, the subscription needs to be made available to the truck when the goods are being loaded onto the truck. The latter approach represents an additional complication, and this would therefore seem to be of interest only for goods owners with very large transport needs that will occupy a set of trucks completely on a regular basis. Obviously, an ER enabled truck needs to either be a hybrid (ER + diesel or ER + battery) to be able to operate outside of the electric road.

Infrastructure technology considerations and constraints. There are differences between the different technology choices for the infrastructure. These constraints need to be included in the modelling. All of them have different segment lengths where the segment length defines the length of the technology that can be individually turned on and off.

1. Overhead wires have an assumed segment length of 1.5 kilometers.
2. Rails have an assumed segment length of 50 meters.
3. Induction coils have an assumed length of 2 meters.

Each segment is associated with a maximum available power (Watt). Shutting the individual segments on and off is presumed to require a certain amount of time, something that for an overhead wire is probably not a concern given its length. The other two technologies need to consider this however since with a speed of 90 km/h (i.e., 25 m/s), a rail segment will be passed in 2 seconds and an induction coil in 80 milliseconds. In Figure 5, this is exemplified for a simple case. The figure shows segment activation/ deactivations where a car travelling at 25 m/s tries to connect in the middle of segment one. Here it is assumed that the segments are 10 meters in length, that the truck transmits its position to the operator every 1/5 second, i.e., every 5 meters. If it takes

0.5 seconds to turn on or off a segment the truck will get power from the road in the middle of section 2 and the operator will ensure that segments are turned on in advance of the truck to ensure that it will be able to get electricity from the road. Given these processing times, the activation brackets indicate the segments that are powered at the same time.

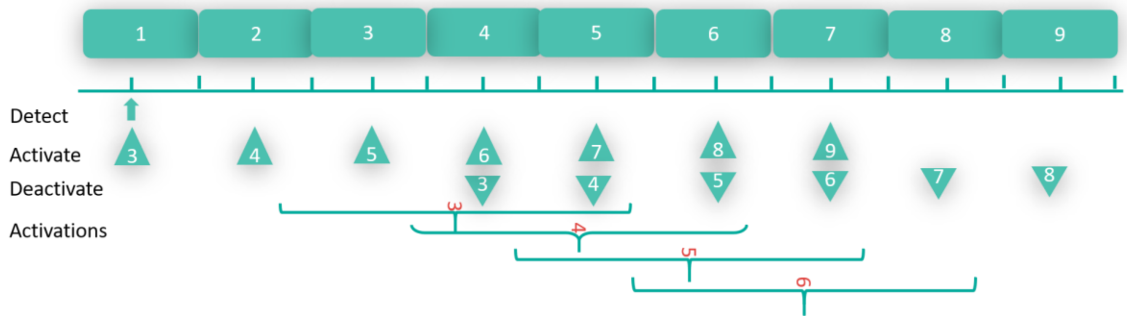

Figure 5. Possible segment activation sequence

Power requirements. If power is to be made available from the road infrastructure a clear knowledge of the power requirements needs to exist. Based on a formula that considered road gradients, friction as well as air resistance the following graphs (Figures 6 and 7) show the amount of power required for different weights and gradients (Chiara Fiori et al, 2016). As can be seen in Figure 6, maintaining a speed of 30 m/s (108 km/h) requires significant power even on a flat surface. Figure 6 shows the effect requirements for different speeds on a flat surface for trucks with the weights of 40 and 60 tons.

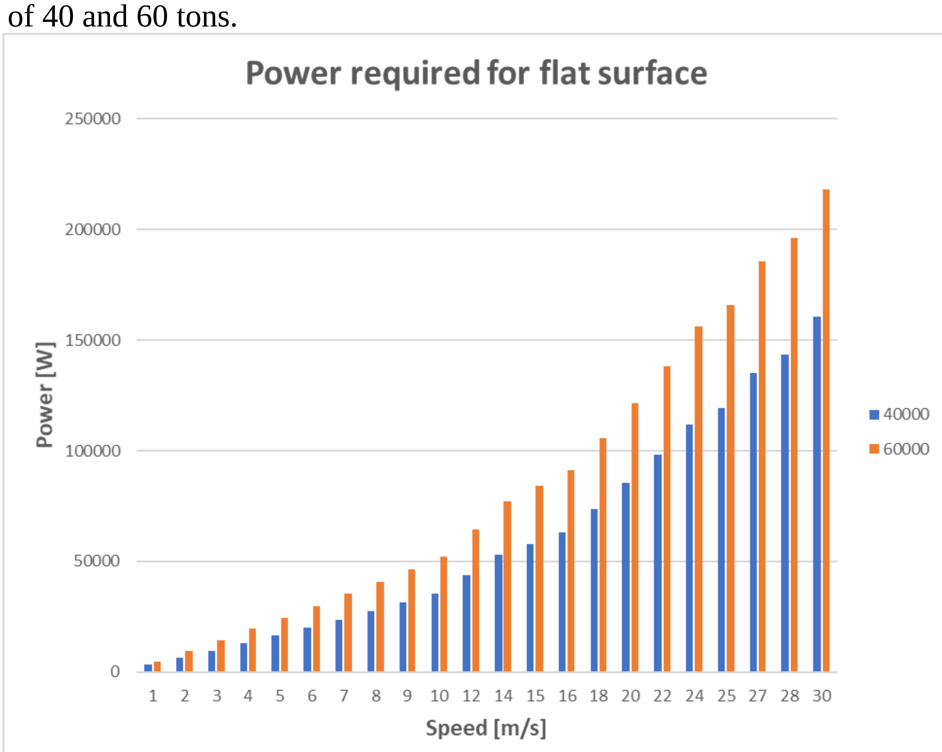

Figure 6. Power requirements example on a flat surface for 40- and 60-ton trucks

In Figure 7 the same weights are used to show the effect required for different speeds with gradients between 1 and 5 degrees. Gradients even as small as five degrees create a significant power requirement.

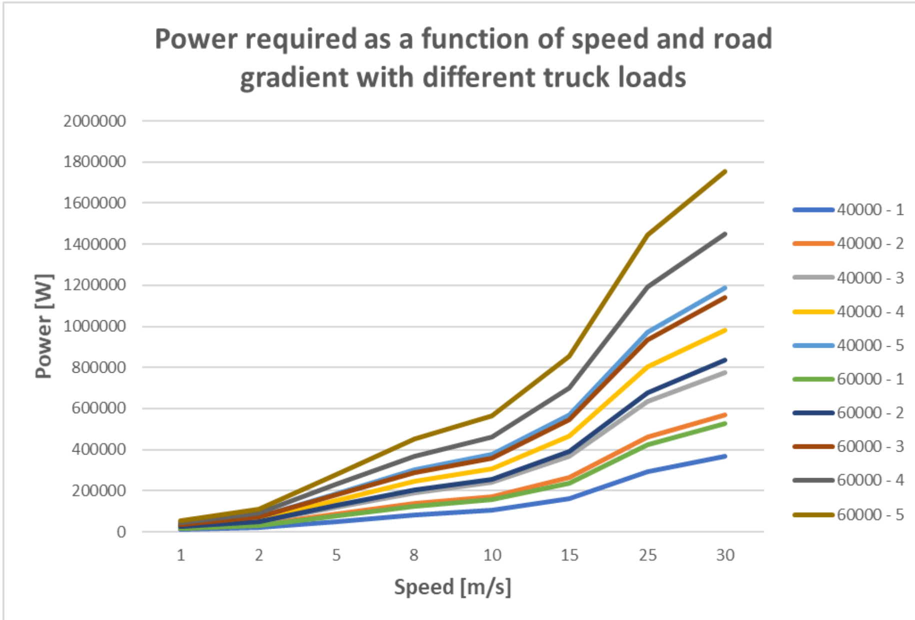

Figure 7. Power requirements example with different gradients for 40- and 60-ton trucks

Government desires and incentives for use. A primary desire of the Swedish government is that if ERs are introduced, they should result in a significant reduction of carbon dioxide emissions. An achieved reduction depends on haulage contractors as well as transported goods owners making use of electric roads and the existence of electric road enabled trucks. A government can make tax breaks available and can also attempt to make it easy for haulage contractors and transported goods owners to get the ER subscriptions they require. An approach to this could be the establishment of service providers that make it possible for haulage contractors and transported goods owners to help them select the subscriptions they need and to outsource the administration of those subscriptions to the service providers. A government could issue an RFP to get providers to respond to such a request. Figure 8 shows an example service specification and required service level.

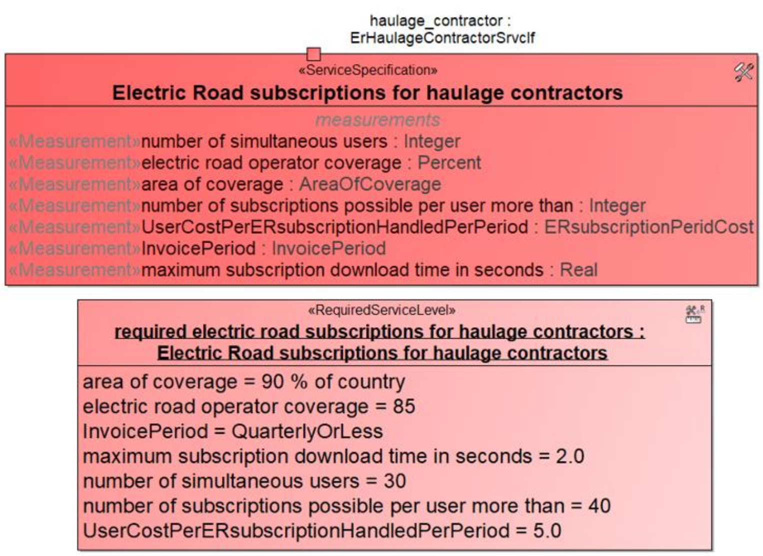

Figure 8. A specification of a service for haulage contractors enabling easy subscription access

The required service levels that a government could use within an RFP indicate what they would want a provider to be able to manage and required service levels that different providers could provide. A UAF service specification element is used, and a set of measurements defined for the specification. A required service level element is then used to define the values that the government requires a provider to meet. Figure 9 shows an example of provided service levels that could be a part of RFP responses from two different would-be service providers.

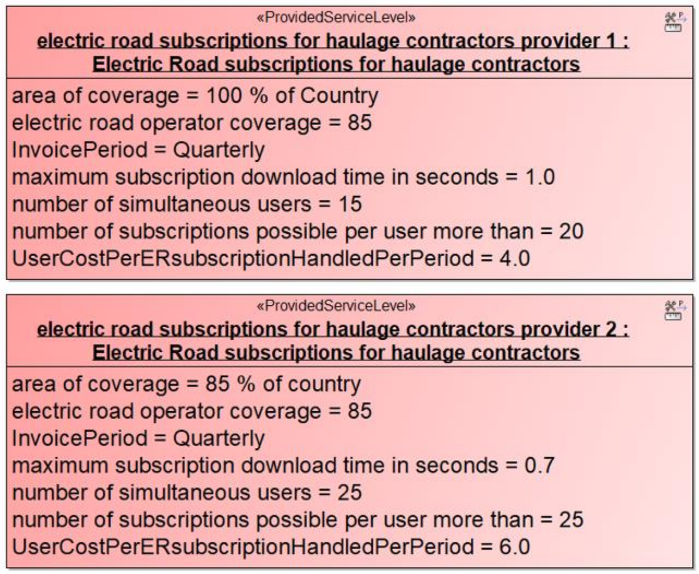

Figure 9. Possible responses to service RFP from providers

Based on these indicated responses an assessment can be made regarding suggested service provision. Naturally, the interface to the service contained in the description of the element is also important. Inside of this element the functionality that needs to be available in the service is defined from a user perspective, i.e., what a user must be able to get the service to do. The following list defines what these might be:

- Ability to download the subscriptions that need to be made available for each truck.
- Ability to request suggested ER subscriptions based on transport needs and order a selection of the ones suggested.
- Ability to renew or terminate selected subscriptions.
- Notification of changes and the ability to negotiate such changes to subscriptions.
- ER usage reports.
- Service provision invoice and payment handling.
- ER usage invoice and payment handling.

The desired effects can be stated as measurement values and once the roads are in place the values achieved can be measured. An example of this is shown in Figures 10 and 11.

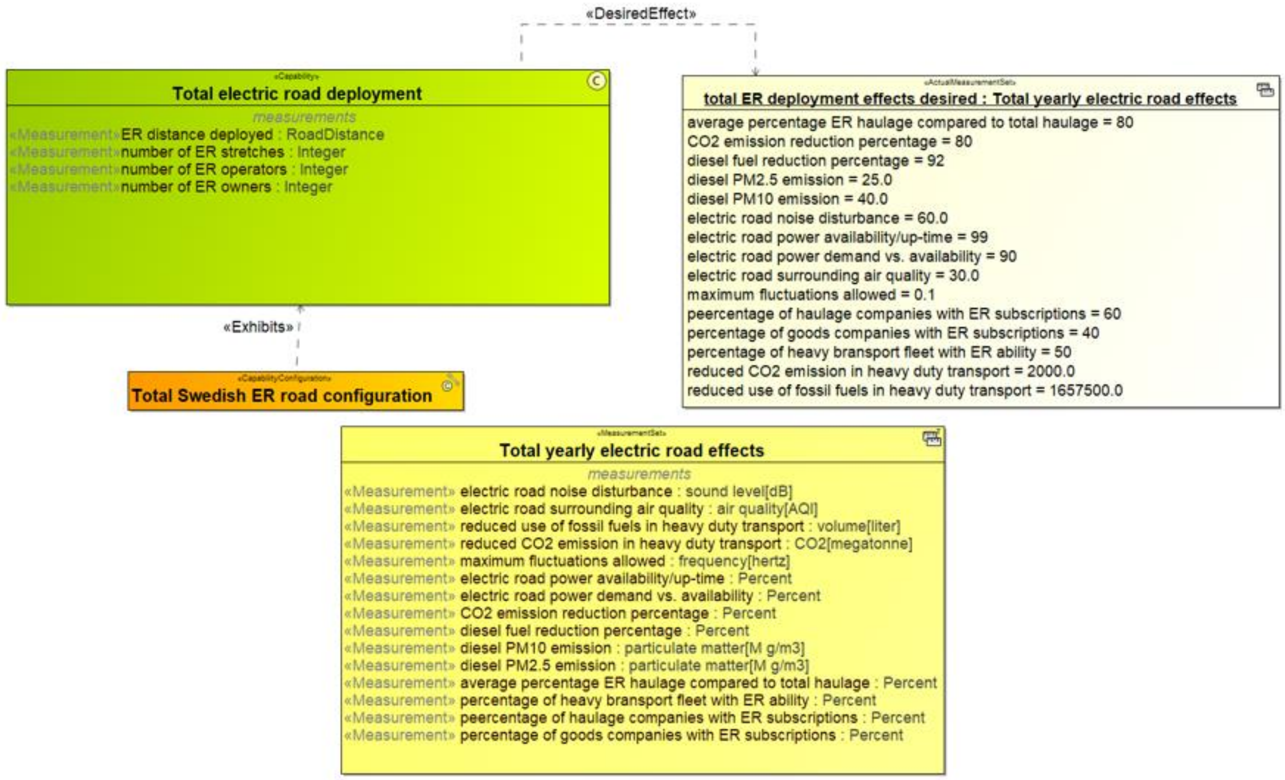

Figure 10. Desired effects definitions for complete total electric road deployment

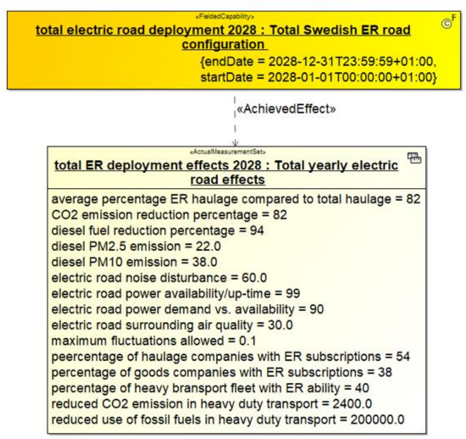

Figure 11. Possible achieved effects based on measurements for a given year

Road and traffic conditions that need to be analyzed. Power consumption on an electric road depends on realistic traffic conditions as well as the number of ER enabled trucks travelling on the road. For a stretch of road, the following conditions were considered important in order to get realistic power consumption figures:

- Different gradients on the road both uphill and downhill.
- Different speed limitations for different parts of the road.
- The appearance of queues where the speed would be different from the speed restrictions. Queues would appear at different times at different locations and last a specified time and would therefore affect the ER enabled trucks if they happen to be in the vicinity at a given time.

Model execution handling

To simulate scenarios where the traffic conditions outlined above can be tested and the power requirements analyzed the following test scenario is being used:

1. An electric road stretch of a selected number of kilometers.
2. Gradients, speed restrictions and queues defined for the road.
3. A 24-hour period of road use with specified entries and exits of ER enabled trucks during the period.
4. The scenario allows for trucks to initiate access to an electric road, get approval and use the electricity that the road segments provide (initiated by the road operator via the grid to the road. The segments are activated as required by the positions of the vehicle. The road operator activates segments through the local grid. Segment power usage is monitored as well as vehicle power usage. The haulage contractor also receives data and comparisons can be made between data from vehicle and data from segments.

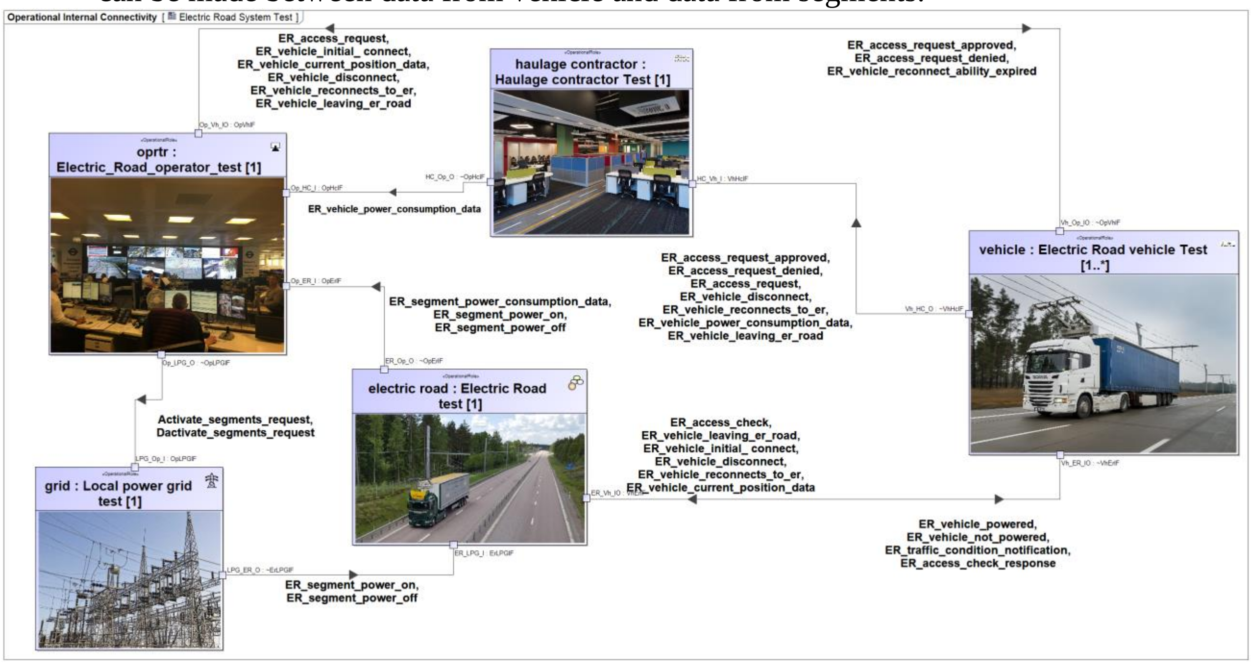

Figure 12. Simulation scenario

Certain simplifications are used in the simulation scenario shown in Figure 12 compared to a real scenario. Specifically, a real scenario would require more than one haulage contractor as well as at least one transported goods owner. It is also highly likely that more than one local power grid would be required given the length of the electric road. Figure 13 shows a fully compliant UAF based state machine diagram for one of the elements shown in figure 12 (Electric road vehicle).

Operational Performer Description Each element in the model is represented by an operational performer. Each performer contains its own state machine and can run concurrently with each other. Each state contains a series of internal transitions for signal handling, and some timer activated activities for periodic execution. An example of this would be when the vehicle needs to update its position as it drives along the road. An example of a state machine is shown in Figure 13. The figure shows the handling associated with getting access as well as what is required by the vehicle when travelling along the road. A disconnect hysteresis has been placed in the model to allow brief departures from ER connection without having to reapply for access (for example due to passing a slower vehicle or truck in the electrically enabled road lane outside of this lane).

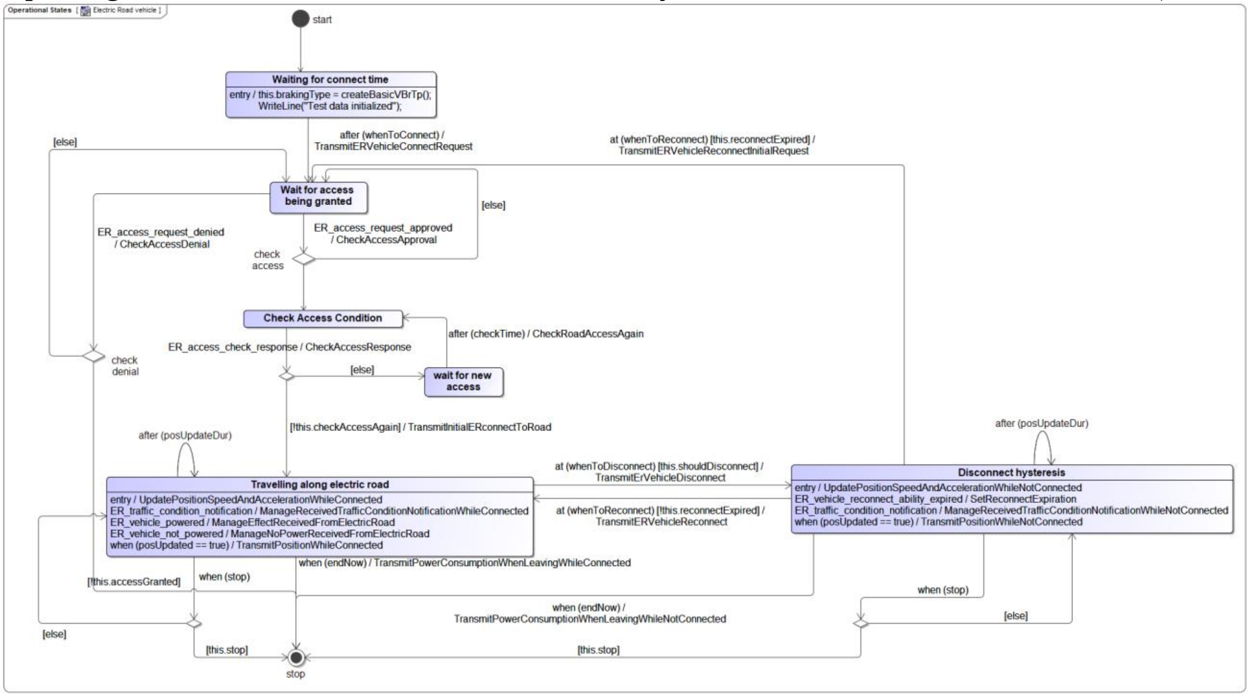

Figure 13. The ER vehicle state machine.

As the model executes, the performers will transmit signals between each other. These signals contain data that can tell the recipient what to do next. For instance, the road can receive updated position information from a vehicle. Then it needs to transmit this information to the operator to decide whether to activate new segments on the road. If new segments are to be activated, the operator transmits this information to the local power grid with another signal, who then transmits specific segment activation data back to the electric road. The model takes account of braking as well as accelerating to respond to different traffic conditions (Guangchuan Yang et al, 2016).

Implementation description. The following key implementation aspects are included in the model:

- The length of the electric road stretch is selectable as are the length of the segments that can be powered individually.
- Trucks of various weights and lengths can be introduced at different positions and at different times during the simulated interval.
- Simulated trucks will be able to accelerate and brake as traffic and speed conditions require. This implies for instance that trucks entering at a given point will need to do so when traffic conditions allow.

The behavior of the operational performers is implemented using a mixture of two methods. First is a standard implementation of SysML, using activity diagrams. These activity diagrams use a blend of standard actions, and opaque actions containing code, with JavaScript being the default language. The second method makes use of an Alf (Action Language for Foundational UML) based plugin, either inserted into existing activity diagrams or replacing them completely. (OMG, 2017)

When attempting to access any properties defined inside an operational performer, the methods differ between JavaScript and Alf. Attempting to call them by name will not work since they exist outside the context of any opaque actions and activities. Instead, the Action Language Helper (ALH) commands are used to retrieve them in JavaScript, and the “this” command is used in Alf. Any variable used outside of these two methods are either local to the activity, or a temporary variable that only exists inside the opaque action. An example of this is shown in figure 14.

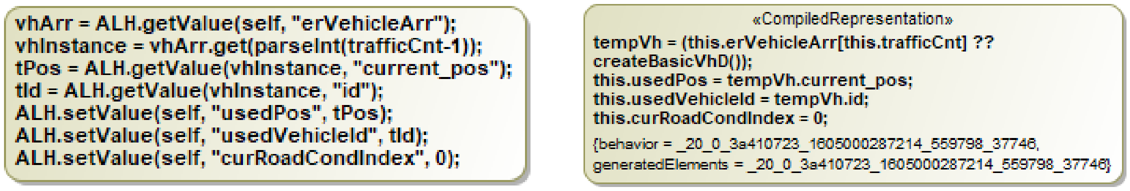

Figure 14. Comparison between default opaque (left) and Alf opaque (right) code.

Model testing description. In order to execute the model, a series of test environments have been constructed for each operational performer. The purpose of this is to be able to check the model for potential errors before executing it in its entirety, which would be both time consuming and make errors difficult to pin down between performers. There are several factors that need to be tested in each environment:

1. Signal data content, to make sure that each signal can transmit the data required between performers.
2. Signal reception activities, to make sure that incoming signal data can be correctly processed by each performer.
3. Internal activities activated periodically by timer, to make sure that internal time dependent data is updated correctly.

A testing environment consists of an operational performer, a test signal emitter, one or more signal receivers and signal interfaces between these. The signal emitter has access to a set of dummy data to transmit over to the operational performer being tested. The signals transmitted are either time based or are activated by the user during simulation. A testing architecture is shown in Figure 15.

All the incremental testing has been performed successfully for all of the elements in the model. As all the elements were placed in the complete model an integration issue was revealed that requires an update to the tool in use. The issue was related to the extensive use of Alf within the model and the fact that the model made use of a pre-pre-release of the tool. The fix needed has been identified and will be implemented thus allowing us to get the results we want from the simulation. This was however not possible prior to the finalization of this paper. We do expect however that the fix will be available such that results can be presented at the symposium.

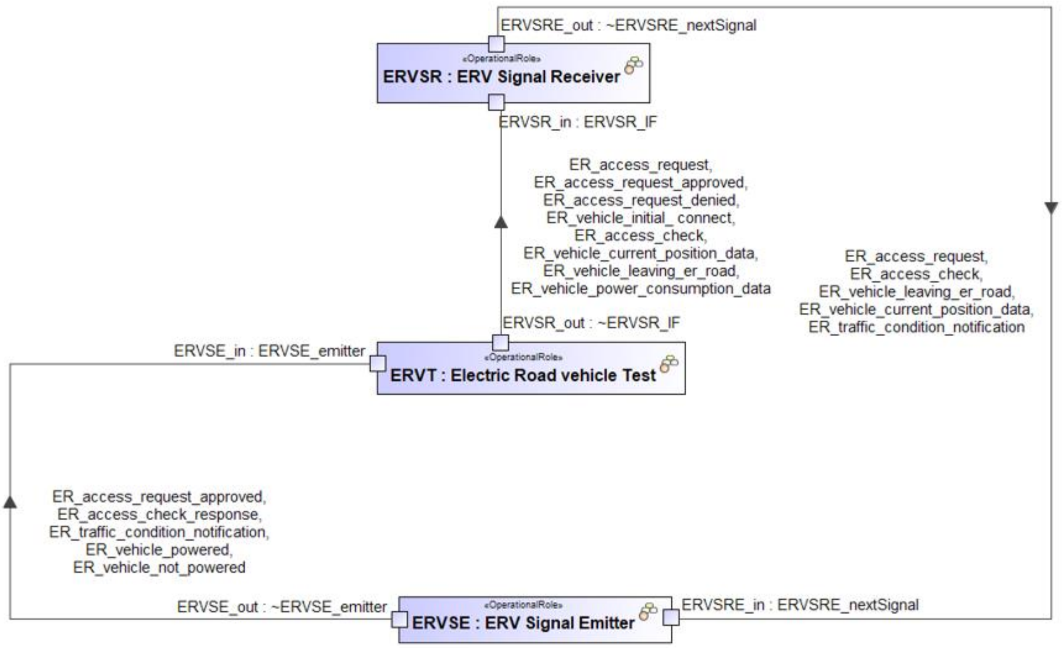

Figure 15. A testing architecture made for the Electric Vehicle operational performer.

Conclusions

As indicated above, all the incremental tests of the logic of the model have been concluded successfully. Simulation of the complete model has not been possible due to an integration issue and the fact that the project was pushing the envelope using a pre-pre-release of the tool being used. Based on the testing performed so far and previous simulation model experiences, the utility of analyzing a system of systems in this manner is however clear. It is clear based on the work performed so far that complex systems of systems yield requirements that emerge because of detailed analysis. The detailed simulations that will be performed once the model is complete will enable several different trade-off studies to be made. The model created is a logical one where the performers interact based on the logic imposed by the constraints in place. This is a key aspect of the MBSE work performed here. This means that the model is largely solution independent, i.e., several possible detailed implementation scenarios are possible. In an implementation however, the logic within the operational architecture will be highly relevant - for instance in a system at the electric road operator that monitors and manages the electric road.

Using gradient values and length for an intended stretch of ER road, power requirements for different traffic scenarios can be generated. This in turn can be used to evaluate costs for possible electric infrastructure improvements that might be needed, i.e., will the power requirements under various traffic conditions be larger than what the local electric grid structure can accommodate and what would the costs be to make such an infrastructure available. This will be valuable to government, contractors and power utilities in their planning to ensure sufficient capacity as well as to determine the financial viability of the project. The model will also allow overload handling to be tested i.e., how best to distribute power among a set of electric road enabled trucks when the power for the stretch cannot accommodate the total power required.

Management of an electric road will involve the handling of different scenarios and based on possible failures as well as being able to recognize different extreme traffic scenarios. Operational ways of dealing with such events can be analyzed based on the simulation. These areas will be further developed and analyzed as part of the model. This type of operational analysis using MBSE is becoming more common in systems engineering and helps to ensure that unviable solution configurations are not attempted. Front-loading this analysis ensures that less time is spent in the physical construction and testing of systems when it is far more expensive.

In general, the approach made use of here i.e., using models and simulations to perform concept analysis of complex system of systems is believed to have proven its value. More and more systems of systems will make an appearance as part of cities and infrastructure everywhere. Models as well as simulations based on these models can be used to aid the development as well as the handling of these systems of systems throughout their life cycles.

References

Chiara Fiori, Kyoungho Ahn, Hesham A. Rakha, 2016, Power based electric vehicle energy consumption model: Model development and validation www.elsevier.com/locate/apenergy Applied Energy 168 (2016) 257 -268

Bateman, D, 2018, Electric Road Systems: A Solution for the future 2018 SP04EN, Available at: https://www.trafikverket.se/contentassets/2d8f4da1602a497b82ab6368e93baa6a/piarc_elvag.pdf

First electric road in Sweden inaugurated https://www.trafikverket.se/en/startpage/about-us/news/2016/2016-06/first-electric-road-in-sweden-inaugurated/

Guangchuan Yang, Hao Xu, Zhongren Wang, Zong Tian: Truck acceleration behavior study and acceleration lane length recommendations for metered on-ramps International journal of transportation science and technology 5 (2016) 93-102

Gustavsson, Martin G.H, Florian Hacker, Hinrich Helms: Overview of ERS concepts and complementary technologies 2 April 2019 Swedish-German research collaboration on Electric Road Systems http://ri.diva-portal.org/smash/get/diva2:1301679/FULLTEXT01.pdf

Object Management Group (OMG). 2013. OMG2013-08-04:2013. Unified Profile for DoDAF/MODAF (UPDM) V2.1, http://www.omg.org/spec/UPDM/2.1/PDF 2012. OMG2012-06-01.OMG Systems Modeling Language (OMG SysML™), V1.3, http://www.omg.org/spec/SysML/1.3/PDF/.

Object Management Group (OMG), 2019, The Unified Architecture Framework, (UAF) Available from https://www.omg.org/spec/UAF

Object Management Group (OMG) 2017, Action Language for Foundational UML (Alf) Concrete Syntax for a UML Action Language http://www.omg.org/spec/ALF/1.1

Peter Sjöberg, Matthew Hause, Lars-Olof Kihlström, 2017, An industrial example of using Enterprise Architecture to speed up systems development, Presented at the 27:th Annual INCOSE International Symposium, Adelaide, Australia, July 15-20, 2017.

Biography

Lars-Olof Kihlström. Lars-Olof Kihlström is a principal consultant at Syntell AB where he has worked since 2013, primarily in the area of MBSE. He has been a core member of the UAF group within the OMG since its start as the UPDM group. He was involved in the development of NAF as well as MODAF. He has worked with modelling in a variety of domains such as telecommunications, automotive, defence as well as financial systems. He is specifically interested in models that can be used to analyze the behavior of system of systems.

Andreas Kihlström. Andreas Kihlström has a master's degree in Media technology and Engineering from Linkoping Institute of Technology. During his studies he worked on everything from systems modelling to AI and virtual reality. He currently works as a programmer at BRP-systems. While not directly related to the work of this paper, the experience helped with the detailed ALH and ALF implementation of the model that he is responsible for.

Matthew Hause. Matthew Hause is a principal at SSI, a member of the UAF group, and a member of the OMG SysML specification team. He has been developing multi-national complex systems for almost 40 years as a systems and software engineer. He worked in the power systems industry, command and control systems, process control, SCADA, military systems, and many other areas. His role at SSI includes consulting, mentoring, standards development, specification of the UAF profile and training.

Ida Karlsson. Ida Karlsson works as a Consultant at Syntell AB within Systems Engineering and modelling. She has a background in Vehicle Engineering from the Royal Institute of Technology (KTH) in Stockholm, Sweden and has mainly worked towards defence. The possibility to do trade-off analysis, optimize a system and identify potential bottlenecks are aspects of her work which interest her the most.

Bilin Chen. Bilin Chen is a Systems Engineer and consultant at Syntell AB in Stockholm. As a consultant he has worked with development projects, most recently characterized by electrification, and more specifically worked on the development of system architectures and requirements management with the goal of optimizing and risk mitigating at early stages. One of his personal interests right now is Machine Learning with its broad range of application and potential benefit to our society.