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IVIsion and IVInet – tool chain for the electrification of city bus routes

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Abstract

The Fraunhofer Institute for Transportation and Infrastructure (IVI) developed a method and matching tools (IVI*sion* and IVI*net*) that analyzes and evaluates individual bus routes or entire bus route networks regarding their suitability for electric buses.
IVI*net* analyses the vehicle rostering plan and the route network. The software is designed especially for the development of suitable solutions in the transfer from diesel-powered bus networks to electric buses. Based on generalized values for traction energy demands and simplified assumptions regarding the energy demand of auxiliaries, heating, and cooling, the state of charge of the energy storage is analysed for the vehicle circulation under consideration of a boost charging strategy. With an optimization method the optimal number of charging infrastructure will be find under given conditions.
IVI*sion* is an in-house development that comprises several program modules for data processing, for the calculation of driving systems, and for evaluating the calculation results. At least it contains more than 200 preconfigured drive trains for conventional, parallel, and serial hybrid as well as purely electrical driving systems. IVI*sion* offers opportunity for detailed calculations that take into account models for auxiliary units, the wiring system, drive train cooling, and passenger compartment air conditioning. All powertrain components, auxiliary components and their respective intelligent control strategies are part of the tool. The usage of the tool chain is explained in an application example.

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1. Motivation

The German Federal Government has defined the goal to reduce CO2 emissions by at least 40 percent by 2020 and by 80 to 90 percent by 2050 compared to values recorded in 1990. To reach this goal, so-called renewable energies shall be further expanded and developed, and energy efficiency shall be increased. This process is supported by numerous laws, such as the Renewable Energies Act (EEG), as well as measures and initiatives, such as funding programs for renewable energies or funding for hybrid buses. Hybrid buses are generally regarded as an interim stage on the way to fully electric city buses. Many transport companies are currently testing battery buses. Their wide and general usage is still opposed by the low energy content of the energy storages as well as the missing charging infrastructure. This fact considerably limits the range and flexibility of battery buses in route planning compared to diesel buses.

The current development stage of electric buses and their charging infrastructure features numerous concepts and approaches. The broad agreement is that electric buses should always be regarded in relation to a suitable charging infrastructure and a matching route planning. Transport companies are facing the task of making indicatory decisions for their further development in the future. These decisions will not only affect cost planning and the necessary financial resources for procurement of technology, but they will also deeply interfere with the existing processes and structures of those companies.

In order to reduce the technical and financial risks, a strategy for the stepwise migration from diesel-powered city buses to electric city buses must be defined. This strategy must take into consideration technical and planning aspects such as the analyses of the route network, the vehicle rostering plan as well as the technical equipment of electric buses and their charging infrastructure.

Nomenclature

EDDA Bus	electric bus with fast charging system
IVIsion	simulation tool for longitudinal vehicle dynamic
IVInet	simulation tool for investigation of electric bus operation and planning of charging points
SOC	state of charge

2. Typical approach

The Fraunhofer IVI developed a method and matching tools that analyzes and evaluates individual routes or entire route networks regarding their suitability for electric buses. The general approach and the use of these tools will be described below.

The developed method includes five tasks:

- Analysis of the route network
- Analysis of vehicle rostering plan (vehicle rotation)
- Definition of technical and economic boundary conditions
- Generalized calculation (coarse screening) and evaluation using IVI*net*
- Detailed calculation using IVI*sion*

2.1. Analysis of the route network and rostering plan

The first development step analyzes the route network and the scheduling of the city buses. Each city and each transport company have their typical characteristics requiring an individual analysis. Over the years, route networks and schedules have been optimized with regard to customer orientation and adapted to local conditions. This includes for example passenger volume, regional topography, integration into transport associations, design of the route network, ramification of routes as well as the influence of the traffic volume on the schedule as it varies throughout the day. All these criteria are reflected in the vehicle rostering plan.

The analysis of the route networks and the vehicle rostering plan determines the following values and parameters:

- Number of routes serviced per daily duty
- Number of termini serviced per route and duty
- Duration of stay at termini
- Topographical characteristics of routes serviced
- Ridership according to daytime
- Types of buses used (vehicle passenger capacity, equipment)
- Route schedule
- Type and location of central nodes in the route network
- Frequency of servicing bus stops
- Number of routes servicing a terminus
- Number of vehicles at a terminus at the same time

These values and parameters are the basis for defining input values for later calculations.

2.2. Definition of technical and economic boundary conditions

The increasing number of concepts requires a selection before calculations can begin. Selecting one concept may be associated with advantages and disadvantages and may influence the future compatibility with other technical solutions. In cooperation with the transport company, core parameters for the analyses are specified. Table 1 shows a selection of current charging concepts.

Table 1. Charging concepts.

Charging concept	Description and comments
stationary charging with low transmission power; overnight charging	suitable for energy storages with low permissible load; energy storages with high energy content (>250 kWh), resulting in high investment costs and high vehicle mass; vehicle round trip limited due to energy content; central position of charging station in bus depot; no visible integration necessary in the city
fast charging with conductive transmission (high transmission power)	demonstration project „EDDA Bus“, Fraunhofer IVI; energy storages with low to medium energy content (100-150 kWh); decentralized position of charging stations; high charging power (up to 300 kW); larger number of charging stations (e. g. placed at terminal stations); integration into cityscape necessary;
inductive charging during waiting time at terminus	demonstration project Braunschweig high expense in infrastructure (installation of induction loop into the road infrastructure); energy storages with low to medium energy content (100-150 kWh); limited charging power, requiring longer standing times during round trip; additional mass due to „pick-up“ power transmitters;
charging during vehicle travelling using a pantograph	installation of catenary segments necessary; high investment costs; use of existing infrastructure possible (e. g. substations of trams); energy storages with low to medium energy content (100-150 kWh); cityscape affected by visible catenary; fixed routes

In addition to the charging concepts, several types of electric energy storages are available. Electrostatic energy storages (capacitors) are used for electric buses only in combination with energy storages with low permissible charging currents. This is caused by the low specific energy content. The characteristics of the electrochemical energy storages depend on cellular chemistry. Advantages and disadvantages of types of energy storages can be found in the relevant literature.

Factors influencing the acceptance of public transport include the travel comfort of the vehicles used. In many regions, especially in the South, air-conditioning in the passenger compartment and at the driver's workplace are standard features. Both the air conditioning in the summer and the heating in the winter require additional energy input. Especially in the wintertime, the energy demand for the heating might be as high as for driving, resulting in a very limited range of the vehicle. As an alternative, oil heating (similar to diesel-powered city buses) may be used instead of electric heating (direct power or heat pump).

The following technical boundary conditions are defined in accordance with the transport company:

- Type of vehicle and passenger capacity
- Type of heating and air conditioning
- Boost charging concept and charging power of infrastructure
- Options for positioning the charging infrastructure
- Prioritization of an energy storage concept (e. g. li-ion batteries)
- Prioritization of routes and tours for electric buses
- Surrounding conditions for specification of heating and air conditioning

These definitions may vary depending on the manufacturer as well as available technical systems.

3. Functions and application of the tools IVI*net* and IVI*sion*

The Fraunhofer IVI recently developed the tools IVI*net* and IVI*sion* – both software programs created in Matlab/Simulink.

IVI*net* analyzes the vehicle rostering plan and the route network. The software is designed especially for the development of suitable solutions in the transfer from diesel-powered networks to electric buses. Based on generalized values for traction energy demands and simplified assumptions regarding the energy demand of auxiliaries, heating, and cooling, the state of charge of the energy storage is analyzed for the vehicle circulation under consideration of a boost charging strategy. As a result, circulation and routes are defined for three categories that are:

- directly suitable for the deployment of electric busses
- suitable for the deployment of electric busses under certain conditions
- currently not suitable for the deployment of electric busses

Routes and schedules of the second category will be analyzed in detail using the working tool IVI*sion*. It contains among other things a comprehensive modeling of the vehicles and the vehicle components. It allows analyzing the energy demand under various climate conditions and takes the topology of the route into account.

3.1. Working tool IVInet

The program is primarily operated via a graphic interface. IVI*net* uses separate program routines to perform repeated calculations with changed input data in order to conduct comprehensive variant analyses. Due to specific features of every city and its bus operation plan, there is no special algorithm for this procedure. Instead, an adapted source code is applied and will be modified if necessary.

IVI*net* can depict two radically diverse energy supply systems – energy supply at determined charging points or section-wise energy supply. The first one refers to charging infrastructure where the vehicle has to come to a hold during the recharging process. This kind of energy supply can refer to both charging stations with conductive contact systems or to inductive loading systems. In case of section-wise energy supply, the vehicle moves along the loading infrastructure that typically consists of conductive systems (overhead cable, conductor rails) or inductive, linear systems for energy transmission. A specific coupling and uncoupling duration as well as a specific charging performance characterize both energy supply systems during standstill. Additionally, in the case of section-wise energy supply, information on the charging performance during the vehicle motion can be given.

The basic procedure of a manual calculation consists of the following steps:

- preparing the town-specific rosters
- choosing and allocating vehicle types to the rosters
- compiling and loading of the input value table
- defining the environmental conditions
- identifying the topology of the routes (optional)
- selecting vehicle types from a database
- allocating a vehicle type to vehicle kind
- manually selecting stops that shall be fitted with loading infrastructure (point by point energy supply)
- defining the parameters of the loading infrastructure
- manually selecting the sections that shall be fitted with loading infrastructure (section by section energy supply)
- starting the calculation
- evaluating the calculation manually and partly automatized
- automatized report creating
- manually evaluating the results and if necessary, iterating the process

Vehicle types refer to specific vehicles from different manufacturers. Vehicle kind refers vehicles from a transportation company that have been standardized and classified by certain distinctive features, for example 12m bus with air conditioning, 12m bus without air conditioning or 18m articulated bus.

Typically, the working procedure is an iterative process. The high degree of town-specific characteristics and the individual requirements by each transportation company constantly demand that an experienced user manually evaluates the results. Several illustrations (diagrams, numerical values, reports) support the user in his or her target-oriented quest for suitable solutions.

Typical tasks that can be conducted using IVI*net* are:

- determining the average energy demand with regard to routes and rosters
- determining the recharging potential with regard to routes and rosters
- selecting suitable ending points for the recharging
- determining parameters for evaluating the suitability of a route, of parts of the network or of the entire network for using electro-buses
- determining environmental conditions that have a long-lasting influence on the future operation of the vehicles

The crux of the calculus algorithm are energy footprints of the vehicle types. Calculations based on simplified assumptions guarantee a quick flow path of extensive data sets, while dispensing with a detailed analysis of varying speed profiles. The quick flow path of an individual calculation is an important precondition for elaborating optimal solutions by varying input parameters in automatized calculation processes.

3.2. Working tool IVIsion

IVI*sion* is an in-house development of the Fraunhofer IVI. It comprises several program modules for data processing, for the calculation of driving systems, and for evaluating the calculation results. The calculation module of IVI*sion* will be introduced in detail below.

IVI*sion* contains more than 200 preconfigured drive trains for conventional, parallel, and serial hybrid as well as purely electrical driving systems. At present, vehicles can be modeled that consist of up to three vehicle sections and have up to five axes. This allows modeling almost all currently known vehicle kinds, such as passenger car, truck, or multi-section city buses including the AutoTram® Extra Grand. The program library contains all essential drive train components as well as a large selection of auxiliary units and components. Several strategies as well as the control of all components are included and can be configured according to specific applications. The main application of IVI*sion* is the calculation of the longitudinal dynamics of the vehicle and the creation of energy and performance balances. IVI*sion* is suitable for both the calculation of road and rail vehicles.

In principle, the application fields of IVI*sion* can be divided into two segments – conceptual evaluations and detailed calculations. Conceptual evaluations are simplified design calculations that refer to pre-configured drive trains and operational strategies. By simply selecting several basic parameters, the module allows to quickly compare concepts using the same database. Besides merely calculating the longitudinal dynamics, IVI*sion* offers to perform detailed calculations that take into account models for analyzing auxiliary units, the wiring system, drive train cooling, and passenger compartment air conditioning. The same applies to the simulation procedure. All auxiliary components and their respective intelligent control strategies are part of the component models and content of IVI*sion*.

A detailed observation demands real-life component-related parameters that further increase the accuracy of the calculation results. The detailed calculations provide a basis for analyzing the energy management, for comparison and for optimizing operational strategies.

Figure 1 presents the basic scheme of the IVI*sion* program. It can be divided into four relevant blocks: driver model, operation strategy, vehicle, and environment and traffic.

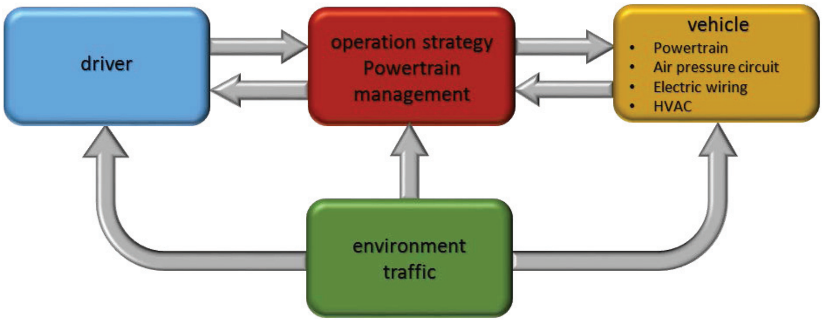

Fig. 1. Basic scheme of the simulation program IVI*sion.*

The “driver” model compares the current position and speed of the vehicle with the driving cycle specifications and generates accelerator and brake pedal values. The model allows accurate conducting of the driving cycles with regard to time and position. To be able to manage the vehicle depending on its position is of particular importance for vehicles with a drastically changing total weight (e.g. an 18m city bus: empty weight/additional load: 55 %/45 %) and relatively low driving power (about 8-10 kW/t). Heavily laden, such vehicles are not able to follow measured speed procedures that have been measured when the vehicle was only half-laden or even empty.

If speed requests are generated purely depending on time control, the vehicle will progressively stay behind the predefined route of the driving cycle. This will cause a change in the elevation profile in relation to the speed profile and stops. Moreover, stationary loading stations will no longer be targeted precisely. The necessary traction performance, the door open time (important for air conditioning), passenger exchange, and stationary recharging will not be correctly simulated.

If the driving demands are generated accurately with regard to the vehicle position, the vehicle will arrive correctly at all stops and recharging stations. Then, just as in real operation, a time delay arises. That is why intelligent target speed parameters and a driver model that is accurate with regard to both time and speed are indispensable.

The target speed will be provided by the module “Environment and traffic”. Target speed can be based on real-life measurements, on standardized driving cycles such as the New European Driving Cycle (NEDC), or they can be freely configured. Another task of the module is to provide an elevation profile for the route travelled. Further input parameters are the ambient temperature, sun radiation, and cloudiness, which affect the energy demands of heating and cooling systems. Moreover, time- or distance-depending additional loads can be defined. The definition of distance-depending additional loads is a pre-requirement for modeling vehicles with varying passenger volumes in public transportation.

The block “vehicle” contains all component models for the drive train, the vehicle section, the passenger compartment, the electrical energy supply (low- and high-voltage networks), the pneumatic network as well as heating and air conditioning. Each component model can be chosen individually.

The following vehicle model is stored in the program:

- conventional, parallel and serial hybrid as well as electric drive trains
- multiple unit vehicles with up to three segments and up to five axes
- combustion engine, electrical machine and gearbox models that are based on component characteristics
- power electronics based on characteristic curves
- energy storage (accumulator, condensator)
- wiring system (high-voltage and low-voltage)
- component cooling
- compressed air system
- passenger compartment air conditioning
- contact models for the systems “wheel-road” and “steel wheel- track”

The task of the module “operation strategy/powertrain management” is to monitor the performance limits of all drive train components as well as the technical and physical limits of force and power transfer. In contrast to many torque value based drive train controls, the operation strategy used in IVI*sion* is performance-based. Performance-based drive train control consists of several cascaded control circuits. Depending on the chosen propulsion system, the top-level contains the power distribution for conventional, hybrid or electrical propulsion. The necessary component controls are displayed below. All parameters of the operation strategy are summarized for each specific component analogically to the vehicle parameterization. This way, the impact of individual components and their respective intelligent control, e.g. the charging strategy or the start/stop of the combustion engines, can be quickly quantified and easily combined in varying drive trains.

In order to control diverse drive trains, the following operation strategy functions are available:

- Predictive operation strategies for optimizing the energy demand or the driving performance
- Strategies depending on the driver profile for a detailed and flexible vehicle characterization of passenger car hybrid vehicles (economic, comfort, sports)
- Self-learning SOC-control (state of charge) of the traction storage
- Recharging strategies for partial energy supply along the route

A graphic interface (figure 2) has been developed for IVI*sion* in order to provide user-friendly operability. In this interface, several tabs are available with selection fields for preparing the parameterization of the calculation model. The selection fields will be blended in depending on the chosen drive train and the optionally activated component models.

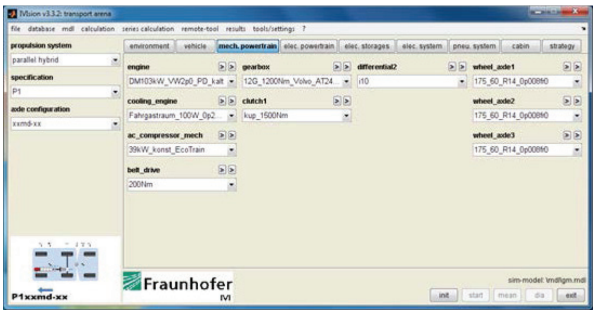

Fig. 2. Graphical user interface of IVI*sion.*

By contrast with the energy demand simulation of passenger cars in the standardized driving cycles NEDC, US-City etc., the same simulation for public mass transport vehicles on routes has to take into account additional framework conditions:

- drastically changing load with considerable impact on the driving performance demand
- frequent deviances from measured target speeds due to insufficient driving power in simulations for high passenger volume
- high accuracy with regard to the route when arriving at stops or external recharging stations
- high energy demand of auxiliary units and considerable impact on the available traction capacity
- relatively low traction storage capacity of hybrid vehicles when put in relation to the vehicle mass
- long phases of acceleration and deceleration
- high frequency of route iterations

4. Application example

At present, in Germany, against the background of the so-called “Energiewende” (a national policy demanding the shift from conventional resources for energy generation to sustainable ones), several public transport companies are discussing scenarios for converting diesel-engine city bus transport systems to electrically driven transport systems. During a research project in several cities in Thuringia, the Fraunhofer IVI conducted studies on the transition to electric buses with a partial contact line operation. These studies aimed at evaluating the technical and operational limiting conditions for establishing a contact line network, the design of the necessary drive train, and the dimensioning of the energy accumulators of the vehicles. In order to reduce the technical effort as well as the costs, the contact lines have to be installed without any crossings or track switches. The contact line sections shall be kept as short as possible and the system shall be operated by 18m articulated buses. The ambient conditions have been defined as 40 °C in summer and -20 °C in winter. Even at these extreme temperatures, the unrestricted operation of the vehicle has to be guaranteed.

Below the study for the city Gotha shall be exemplified. Gotha has about 50,000 inhabitants. Besides diesel engine city buses, trams operate in Gotha. Therefore, the necessary substations for the energy supply of contact lines already exist. Figure 3 shows the city map of Gotha and the position of the substations.

Fig. 3. City map of Gotha and position of substations.

Figure 4 presents the scheme of the chosen line on Gotha. The roster of the line stipulates the service of four terminal stops. Terminal stop 1 and 2 are located in the city area. In the outskirts, the line branches and the terminal stops 3 and 4 are serviced in turns. The routes have a distance of 12 and 24 km. The trip takes 24 to 30 minutes.

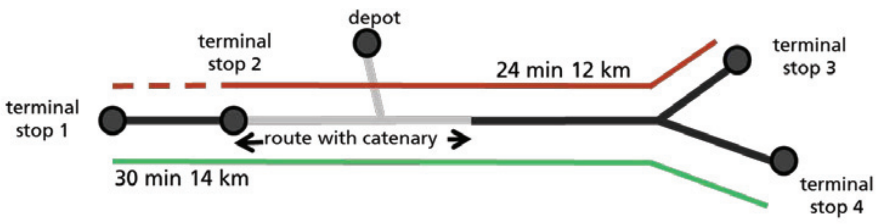

Fig. 4. Scheme of the line in Gotha.

As a first step, it was investigated if stationary charging stations at the terminal stops could provide sufficient energy to the vehicles. The costs for this would have been relatively low. However, due to the very short turning time, this was not possible. The energy accumulators would therefore discharge during the day and an unrestricted operation of the vehicle could not be guaranteed. As a solution approach it was examined if a partial contact line could be applied.

The energy accumulators were designed and dimensioned considering the study results for other cities in Thuringia. These study results implied an energy content of 210 kWh. The design of the vehicle in Gotha is based on these results in order to make sure that a similar drive train can be used in all Thuringian cities. This might allow the cities to jointly purchase the vehicles and prevents the necessity of individual and customized solutions for each city.

Under consideration of the above- mentioned conditions, in the next step, the maximum length of the contact line was identified. The result was 3.5 km. In figure 5 the blue curve illustrates the course of the energy content. When the energy needed for the traction task as well as for heating or air conditioning is taken from the storage, the energy content decreases. When operating below the contact line, the charging level of the energy accumulator rises. During the course of one day, the energy content (indicated by the state of charge SOC) never falls below 0.7

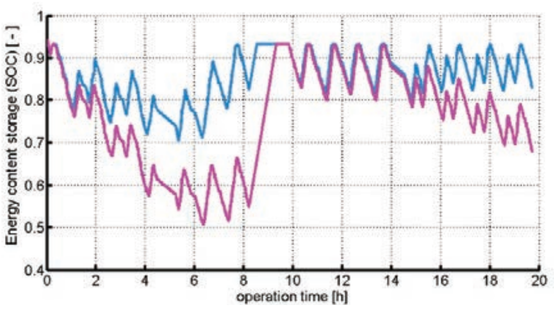

Fig. 5. Charging level of the energy accumulator during the course of one day.

That is why a shortening of the contact lines has been investigated. In an iterative process, the result for the minimal length was identified as 2.5 km. The pink curve illustrates the course of the energy content of the storage for this scenario. During the day, the SOC reaches a minimal value of 0.5. At the end of the day, the value is 0.7. It has to be noted that these calculations have been performed under the assumption of extremely low temperatures of -20 °C in winter. Such temperatures are only reached on a few days a year. The reduction of the contact line could reduce the investment effort by 700.000 Euro.

5. Outlook

The application of the working tools is not limited to an individual line. At present, the Fraunhofer IVI is developing a changeover scenario for a big German city for the step-by-step transition of the entire transport network to electric buses.

This transition shall start in 2020 and end in 2025. The city's public transport company has a fleet of more than 800 buses that operate about 130 lines. The bus rostering plan covers nearly 1300 duties, summarized for weekdays and weekends. The main challenge is to secure the transport coverage by using as few stationary charging stations as possible. For this purpose, new solution approaches and optimizations routines are developed so that the application fields of the working tools of Fraunhofer IVI are constantly extended.

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