

IEEE Guide for Rail Transit Traction Power Systems Modeling

IEEE Vehicular Technology Society

Developed by the
Rail Transportation Standards Committee

IEEE Std 1653.3™-2021
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Developed by the

Rail Transportation Standards Committee
of the
IEEE Vehicular Technology Society

Approved 25 March 2021

IEEE SA Standards Board

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Abstract: A description of the data, techniques, and procedures typically used in modeling and analysis of traction power systems is provided in this guide.

Keywords: analysis, IEEE 1653.3™, modeling, traction power

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Introduction

This introduction is not part of IEEE Std 1653.3–2021, IEEE Guide for Rail Transit Traction Power Systems Modeling.

During development and updating of various IEEE standards and recommended practices related to rail transit traction power, the Rail Transportation Standards Committee of the Vehicular Technology Society recognized a need for a published document to describe the process of traction power system modeling. This guide provides an introduction to the terminology and methodology of rail transit traction power systems modeling.

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IEEE Guide for Rail Transit Traction

Power Systems Modeling

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1. Overview

1.1 Scope

This guide provides a description of the data, techniques, and procedures used in modeling and analysis of rail transit traction power systems.

1.2 Purpose

This guide provides methods and terminology for rail transit traction power system modeling.

1.2.1 Applicability

This guide is intended for application by engineers involved in the design and specification of new traction power systems, as well as ~~and~~ the technical evaluation of existing traction power systems in response to re-definition of operating parameters (e.g., increase in service).

1.2.2 DC versus ac traction power systems

This guide is intended to apply primarily to dc traction power systems. However, many of the techniques can be applied to ac traction power system analysis.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{1,2}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

1.4 Limitations

While this guide establishes a methodology for determination of various parameters that may be of value to designers of individual traction power system components (e.g., switchgear, transformers, rectifiers, and cable), it does not address the detailed design process for those components.

¹The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

²The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

Where analysis described in this guide is similar to analyses described in IEEE Std 399TM [B29 B26],³ this document does not repeat the information in IEEE Std 399-[B26], but instead [it](#) highlights how the IEEE Std 399-[B26] recommendations should be tailored to the specific requirements of a traction power system. This document also describes certain studies that may be of value as part of traction power system design, but are not usually part of commercial and industrial design.

2. Definitions, acronyms, and abbreviations

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause. ⁴

2.1 Definitions

ac traction power system: A transit system in which power is delivered from wayside to on-board vehicular systems via alternating current, at nominally constant (or not deliberately varied) frequency, at the vehicle/_wayside interface.

auxiliary power (hotel power): Those systems, other than propulsion of the vehicle/consist that draw electrical energy. Examples include lighting, heating and air conditioning, [and](#) air compressors, ~~etc.~~

~~**AW0:** The ready-to-run vehicle, without crew or passengers.~~

~~**AW1:** AW0 + crew + every seat occupied by a passenger. For U.S. transit properties, a commonly accepted weight per passenger for this purpose is 70.3 kg (155 lb).~~

~~**AW2:** AW1 load + weight of standees at 0.251m² (2.7 ft²) of suitable standing space per standee.~~

³[The numbers in brackets correspond to those of the bibliography in Annex H.](#)

⁴[IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.](#)

¹~~IEEE Standards Dictionary Online subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.~~

bunching: Deviation of individual headways (between adjacent trains) compared to nominal or average [headways, which results in more trains in the power zone than a nominal headway would indicate.](#)

contact conductor: The part of the distribution system, other than the track rails, that is in immediate electric contact with current collectors of the cars or locomotives. ⁵²

current limit: [Some trains are equipped with a current limiting function. This limits the total current \(auxiliary and traction\) into the train to this value and is not voltage dependent. This is different from forced performance reduction.](#)

dc traction power system: A transit system in which power is delivered from wayside to on-board vehicular systems via direct current at the vehicle/wayside interface.

design criteria: A description of required system performance. This may establish different requirements depending on [the](#) status of the wayside traction power system (e.g., single contingency outage conditions [versus](#) ~~vs.~~ operation with all equipment in service).

diode grounded: [A type of traction power system where each TPSS is equipped with a diode connected between the negative busbar and ground that allows current to flow from ground to the negative busbar but not in the reverse direction. The running rails remain electrically isolated from ground throughout their length.](#)

dwelt time: The period of time measured from the instant a train stops at its berth at a passenger station until the instant it resumes motion.

electrically floating: [A type of traction power system where there are no deliberate connections between the running rails or the TPSS negative busbar and ground.](#)

⁵² The contact conductor is usually either a contact rail (sometimes known as a third rail), or the contact wire of an overhead contact system.

forced performance reduction: Almost all modern trains are equipped with variable voltage variable frequency inverters driving three-phase ac asynchronous motors. The programming for the inverters will vary the available torque from the motors (and hence the tractive effort at the wheels) automatically depending on the line voltage. This helps ensure that as the line voltage reduces so does train performance, which reduces the current demand by the train, and prevents a voltage collapse by excessive current demand.

headway: The time separation between two trains both traveling in the same direction on the same track. It is measured from the time the head-end of the leading train passes a given reference point to the time the head-end of the following train passes the same reference point. Nominal headway is sometimes used to apply to design headway for a system, or average headway of a group of trains.

negative grounding device: A device that monitors the potential difference between running rail (negative return) and earth ground. When the potential difference reaches a predetermined value, the device temporarily shunts the running rail to earth ground to reduce the rail voltage to safe limits. Some negative grounding devices can regulate the voltage in both positive and negative directions. This is also known as a voltage limiting device.

normal conditions: When the traction power system configuration is not impaired by an outage to a substation or a feeder segment.

track stationing: The agreed-upon measuring of distance and location identification along the railroad.

track-to-ground (rail-to-ground) voltage: The potential difference between track and earth at a given location.

train consist: Quantity of cars in an operating train. This is typically a design constraint (e.g., operation with a six-car train consist). When this term is applied in connection with simulation and modeling, it may also be appropriate to establish the types of cars in an operating train (e.g., operation with a train consisting ~~consist~~ of six Type A cars plus two Type B cars).

transit property: The organization that operates the traction power system and trains.

validation: The process to confirm that the underlying formulas in the load flow analysis software being used and the solving algorithms are accurate and can be relied on. This would be achieved by comparing simulated results with field results and should be documented in a validation report for the software. The software only needs to be validated once unless there are fundamental changes to its solving algorithms; at which point, it should be validated again.

vehicle/wayside interface: The point(s) at which electrical power is transferred between the wayside electrical distribution network and vehicles. ⁶³ These interface points are the location where vehicle contact shoes or pantographs are in touch with contact conductors and the rail/wheel contact points.

vehicle weight: Several vehicle weights are of interest for different purposes⁷ and are often called out as follows:

- AW0: The ready-to-run vehicle, without crew or passengers
- AW1: AW0 + crew + every seat occupied by a passenger. For US transit properties, a commonly accepted weight per passenger for this purpose is 70.3 kg (155 lb)
- AW2: AW1 load + weight of standees at 0.251 m² (2.7 ft²) of suitable standing space per standee
- AW3: AW1 load + weight of standees at 0.167 m² (1.8 ft²) of suitable standing space per standee
- AW4: AW1 load + weight of standees at 0.125 m² (1.35 ft²) of suitable standing space per standee

verification: The process to check the data entered into a particular load flow analysis is correct.

⁶³ The direction of power flow is usually from the wayside system to the vehicle(s) but can be from the vehicle(s) to the wayside power distribution system, during regenerative braking.

2.2 Acronyms and abbreviations

[AW](#) added weight

NGD negative grounding device

OCS overhead contact system

rms root mean square (see 3.2.8.1)

[TPSS](#) traction power substation

3. Modeling and validation

3.1 Introduction

Different model(s) will typically be required during system design, each one developed and tailored to specific issues and needs, [as follows](#):

- During initial design, and prior to commencement of construction for a new transit system, analysis can establish preliminary locations for substations and can confirm the feasibility of proposed system characteristics [(e.g., overhead contact system (OCS) conductor types/sizes, nominal and minimum system voltages, [and](#) substation ratings], ~~etc.~~.
- As [the](#) design is finalized, modeling is of value to confirm and finalize system and equipment characteristics, and to develop engineering estimates of relevant system performance characteristics (e.g., energy consumption, ~~and~~ [and](#) vehicle run times).
- For evaluation of existing systems in response to changes in operations levels or deployment of new vehicles with new performance characteristics, modeling serves to identify areas of the traction power system that may require capacity upgrade.
- Modeling can be performed at any time to evaluate new or previously unforeseen changes in operations levels or outages or reconfiguration of the wayside traction power distribution system.

- Modeling can provide a valuable tool to quantify [the](#) performance characteristics of new technology systems.

3.1.1 Purpose of modeling

Modeling is generally performed with the intent of assessing traction power system performance and reliability. Some of the issues that can be addressed via modeling are described [as follows](#) ~~below~~.

3.1.1.1 Quality of power delivered to trainsets

Modeling can provide some indication of the range of voltages that will be delivered to trains during operations. Comparison of these voltage ranges can be made against train voltage limits (high, intermediate, or low). Low-voltage criteria must be met to [help](#) ensure continuous operation of trains. Operation of trains at voltages in the intermediate-to-low voltage range can result in reduced vehicle performance (i.e., reduction in available acceleration and/or top speed).

3.1.1.2 Overloading assessment of wayside equipment and feeders

Modeling can provide assessment of expected loading (long time, short time, and instantaneous) on wayside equipment, which can be compared against withstand ratings of equipment, short-term or instantaneous ratings of equipment, and relay settings.

3.1.1.3 Establishment of operational restrictions

Modeling can be used to evaluate proposed operational restrictions in situations where the traction power system is operating in a reduced capacity (e.g., under selected equipment outages). If analysis of a minor reduction in system performance (e.g., a reduction in speed in the vicinity of an impaired substation) indicates that system operations can be maintained, but that system operations cannot be maintained without the performance reduction, then the operations restriction might be considered as a viable option when compared against capital upgrades of the wayside system that would otherwise be required to maintain full performance.

3.1.1.4 Energy management

Modeling can be used to evaluate or compare the energy consumption of different technologies, system configurations, and operating strategies/policies.

3.1.2 Baseline criteria

Baseline criteria should be established and verified prior to modeling. Examples of baseline criteria to be considered may include the following; these should be collectively established by the transit property and the modelers:

- Applicable criteria or requirements of the user/owner (e.g., desired train service levels, acceptable train voltage ranges, and specific outage conditions to be evaluated)
- Maximum allowable temperature limits of equipment
- Temperature ratings (short term and continuous) for insulation systems
- Environmental conditions for analysis (e.g., ambient temperature and climate)
- Vehicular performance capabilities and limitations, including performance limitations that may result at low train voltages
- Wayside civil alignment information
- Electrical distribution network characteristics
- Operations levels
- Contingency failure/outage conditions
- Maximum ceiling voltage for regeneration (if regeneration is to be evaluated as part of the simulation process)
- Other minimum or maximum voltage levels (associated with reduced vehicle performance, ~~or~~ minimum vehicle cutout voltage, or otherwise established as design criteria limits)

3.1.3 Validation of software

Any software used for the undertaking of load flow analysis should be validated. The validation exercise only needs to be undertaken once to prove the underlying algorithms in the software are correct. Validation against field recorded data is preferred, but validating it against another validated software or hand calculations is acceptable where this is not possible. The validation of the software would only need to be redone if there is a fundamental change to the solving algorithms.

Validation is best undertaken using simple scenarios to reduce uncertainties and unknown variables. Ideally, validation would be undertaken during maintenance hours with limited trains on the system where train movements can be known exactly and mimicked in the simulation ~~of the modeling process is desirable~~. A suggested validation process is described in Annex A.

Validation of the software does not need to be undertaken for every project the load flow analysis software used and would add unnecessary cost to a project if this was required. However, agencies may have specific reasons for requiring a full validation exercise to be done for a new model, despite using software that has previously been validated.

Comparing the output of the load flow study to actual operations is difficult. In operations, railroad service is subject to constant variations in station dwell, vehicle load, wind affecting the power drawn by the trains, weather and passenger loads affecting auxiliary power supply loading, rail adhesion conditions, and utility voltages which are impossible to address in modeling. However, one must allow for these unknowns. At present, no analytical basis for recommending a tolerance is known. It is the judgment of the working group of this guide that a 10% discrepancy between the following quantities is to be expected and should be allowed for:

- Worst-case instantaneous train voltage (modeled versus observed in operation)
- Energy drawn by a train in the course of a single trip over the railroad
- Station-to-station run times and/or end-to-end run time

3.1.4 Verification of data

Verification differs from validation as verification is about checking the data that have been inputted into a simulation, not about specifically confirming the accuracy of the underlying algorithms of the software. No matter how accurate or validated the software is, if the incorrect data are entered into the model, the results of that model will be wrong.

Verification would cover the calculating of numerical values from information provided as well as where those values are used and that the values have been correctly inputted into the simulation model. Verification would normally be covered by a company's quality assurance procedure that would require the simulation model to be checked by an engineer prior to use.

3.1.5 Commonalities between models

The modeling techniques addressed in this guide generally require preparation of electrical network model(s) to describe the system and to facilitate analysis. The electrical network(s) require information to describe individual components of the distribution system, including feeders and equipment (e.g., transformers and, rectifiers). Power sources (generally utility sources, but also possibly regenerating vehicles) must be included in the model. It may be necessary to model vehicles as nonlinear loads for load flow analysis of the distribution system. When conducting short-circuit analyses, faults may be modeled as nodes in the system, or possibly as low-impedance connections.

3.2 Train operations and wayside network modeling

3.2.1 Purpose

Train operations and wayside network modeling is performed to determine the relevant performance parameters of a wayside electrical distribution system when providing power to trains. These parameters can then be compared to equipment and criteria ratings to determine whether if the wayside system provides an acceptable quality of power and reliability, as well as and other purposes. For a typical report of train operations and wayside network modeling, see Annex B.

3.2.2 Background and legacy modeling approaches

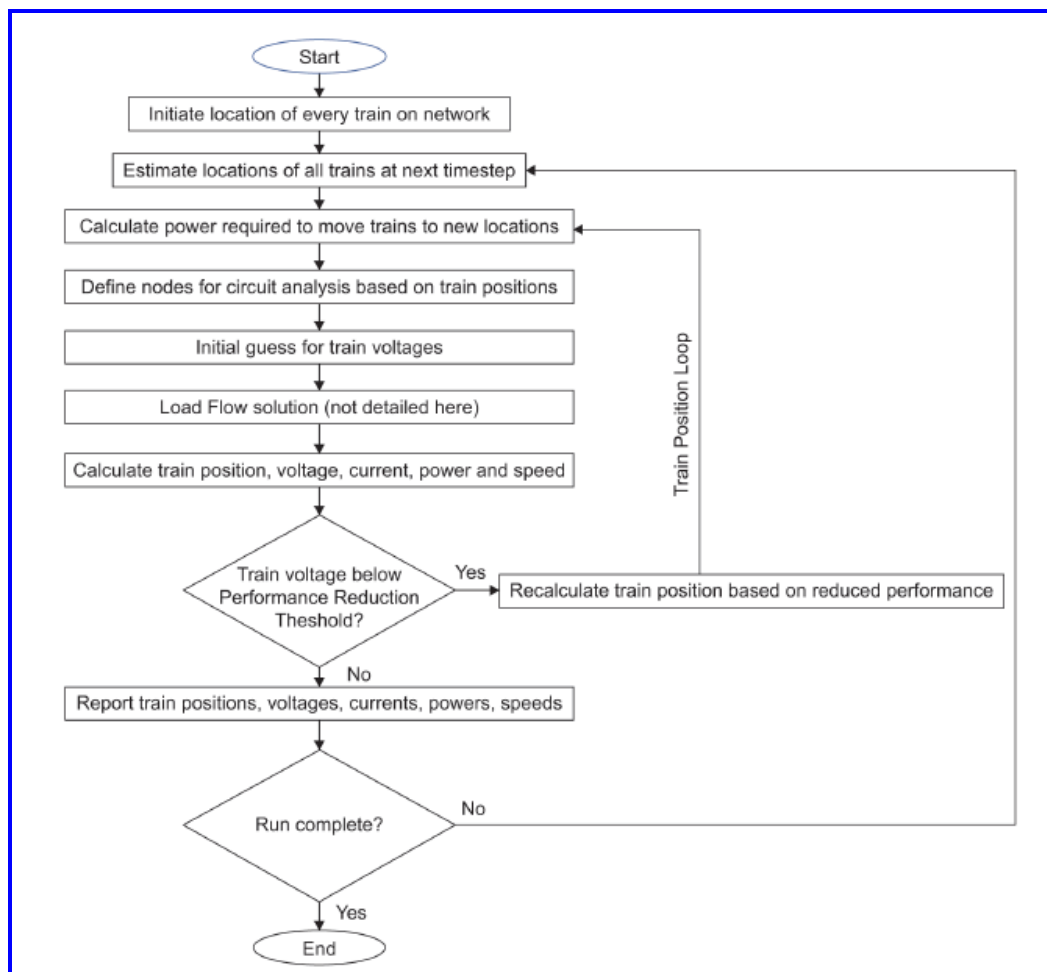
Calculations of current flow in and voltage at the load ~~are~~ **is** fundamental to the design of traction power systems, from the earliest use of electric traction. These calculations are straightforward to perform for simple radial fed loads. For small networked loads and generators, various manual techniques were developed to simplify the arithmetic. As these networks became larger, these techniques became laborious and calculation approximations were made as described by De Koranyi [B11]. In many cases, these approximations were acceptable because the input data and load data were of limited accuracy.

~~Analog~~ **Analogue** models were developed, and these proved to be very powerful and were used until computer programs started to become available. Even so, these ~~analog~~ **analogue** models also used approximations to limit the physical size of the model and the amount of work to set up the model. These models could even perform transient analysis. The accuracy was again only as good as the input data on the line impedances, loads, generators, and motor starting current. Despite these apparent limitations, robust networks were regularly designed.

Digital computer-based models can perform complex calculations quickly and accurately and in very large quantities. All these calculations can be very useful, but just like earlier modeling techniques, they are still only as accurate as the input data.

When a train is in motoring mode and its voltage falls below a certain specified level, the power drawn by the train will be reduced; when this voltage reaches the minimum system voltage level, the motoring power is automatically reduced by the train to a selected value (forced performance reduction). Similarly, when a train is in regenerative braking mode and its voltage is above a certain specified level, its output power to the traction power system will be reduced; when this voltage reaches the maximum specified voltage level, the regenerative braking feedback to the traction power system will be reduced to zero (diversion of regenerated power to onboard resistors, where installed, or utilization of friction braking where no onboard resistor is installed). The simulation software should accurately model these interactions.

The reduced available power to a train may reduce the acceleration of the train (e.g., when going up a gradient) and have an impact on the train's run time. This will most likely happen during severe contingency scenarios when an entire substation is out of service or a feeder is out of service (single-end feeding). The impact will be localized. Ideally the modeling software should link the train movement simulation to the traction power simulation. Such a feedback loop (shown as the "train position loop" in Figure 1) is useful in assessing the impact of the traction power system on the real operational performance of train movements. To achieve this objective, the train movement simulation should also accurately reflect the state of train control systems, which govern the interactions between trains. For the evaluation of the traction system performance, the simulation can be performed with or without the train position loop.



(New)

Figure 1—Traction power load flow flowchart

A load flow program used for the analysis of a traction power system differs from what is used for industrial or utility purposes because the loads (the trains) move. The nodes, and the impedances between nodes, have to be redetermined with every timestep. The software used for railroad load flow purposes therefore may use several loops, as follows:

- a) Determine train position.
- b) Determine power required by train.
- c) Determine voltage at train.
- d) If the voltage is low enough to affect the tractive effort of the train, redetermine power.
- e) If the voltage is low enough to affect the tractive effort of the train, redetermine train position.

The engineer should choose the software that has the capability to provide the required accuracy as recommended in this guide while meeting the design requirements of the project.

3.2.3 Process

Train operations and wayside network modeling ~~are~~ **is** typically performed according to the following sequence:

- a) *Vehicle data collection and model development:* Available tractive effort ~~versus~~ **vs.** speed for tractive vehicle(s) is determined. This data might also include variations in tractive effort as a function of voltage at the vehicle/wayside interface. Subsequently, this data can be used to develop a performance profile (speed ~~versus~~ **vs.** time, and acceleration ~~versus~~ **vs.** time, for acceleration from a stationary position to maximum speed) for operation of a multicar train consist on level tangent (straight) track. This would be established for a fixed loaded train weight (and, if necessary, at different voltages at the vehicle/_wayside interface). Typical equations and procedures applicable to this process can be found in *Railroad Engineering* [B18], ~~2nd Edition~~ [B16]. Collection of data regarding vehicles should also include data describing auxiliary power requirements.

In some cases, the acceleration (or speed) ~~versus vs.~~ time performance profile may already be established (for a given load or train weight) on level tangent track. This may allow for determination of the available tractive effort ~~versus vs.~~ speed.

The criteria for analysis should include definition of the vehicle passenger loading (passenger weight) to be applied during analysis. Vehicle weight AW2 ~~or AW3~~ is commonly used for traction power modeling, although the loaded vehicle weight(s) to be utilized in modeling should be established early in the modeling process by the transit ~~agency property~~. If ~~these~~ ~~this~~ criteria ~~are is~~ based on loaded vehicle/train weights ~~that which~~ are different from the loaded weight applicable to the initial data described ~~earlier above~~, then the data (tractive effort ~~versus vs.~~ speed, speed versus time, and/or acceleration versus time) must be adapted or revised to reflect the actual weight that is to be modeled.

- b) *Modeling of operation according to specific civil alignment/route characteristics:* Data ~~are is~~ collected describing the civil track plan and profile for the actual rail system that is to be analyzed. This would include data such as grades, curves, alignment, station stops, and speed limits. Physical performance (speed/location ~~versus vs.~~ time) for operation of trains on the transit system can then be determined based on headways and/or train schedules.

Train control methodology must also be considered in developing the model. Different methodologies such as automatic train operation (ATO), coasting, speed stepping, or braking methods will generate different results.

- c) *Electrical network model development and analysis:* An electrical model of the wayside traction power system is then developed, including utility source impedances and characteristics. In conjunction with train locations and loads as described above, corresponding train power consumption (including power consumption associated with propulsion₇ and with auxiliary on-board vehicle loads) can then be determined. Network analysis can also determine currents and voltages (as time-varying functions) in the wayside system.

If necessary, interactions between train performance and system voltages (e.g., dependencies between tractive effort and train voltage) can be determined by simultaneous or iterative calculations that consider these parameters.

Computer modeling of a rail transit system in this manner generally requires specialized software, and different software packages may be suitable for analysis of some transit systems but not others. ^{Z4} The user of software should be sufficiently knowledgeable of the software performance to describe in detail the algorithms and calculations performed by the software, so that suitability for use on a particular transit system can be assessed. In addition, the software should have capabilities for detailed data printout at intermediate stages of calculations so that the correctness of the algorithms and processes can be evaluated. Additional verification/validation against measured data can also be performed, as described in Annex A.

3.2.4 Regenerative braking

Regenerative braking is generally provided ~~typically implemented~~ on the modern transit systems as a standard feature. It provides ~~to provide~~ some degree of energy conservation by regenerating kinetic energy from braking trains, and distribution of this power to other loads (hotel load of the train, other trains on the system that are consuming power or energy storage system). With the correct equipment the energy can be provided to ~~, and/or~~ a receptive utility or transit property distribution network. When trains are operating with regenerative braking, this could ~~, or to energy storage systems. However, regeneration may not always~~ be considered as part of a system model modeling effort for the following reasons:

- Although regenerative braking may be inhibited on one train due to maintenance, regenerative braking would not, at an undetermined date in the future, need to be switched off across the entire fleet of trains. Modeling the system with regenerative braking switched off on all trains as the default scenario is, in effect, modeling a failure scenario as the usual scenario. See the following paragraph for further considerations.

^{Z4}For example, some software packages provide for analysis of dc traction power systems only, or of ac traction power systems only, as the detailed modeling processes can be considerably different.

- Regenerative braking can provide up to 25% or higher⁸ of the total system energy, although this depends on a number of factors, including:
 - 1) The ratio of the maximum regen over voltage to substation light load voltage.
 - 2) The headway between trains.
 - 3) The number of train brakes and accelerations per mile.
 - 4) The gradient profile.
- Ignoring regenerative braking may lead to the requirement of more TPSS and/or higher utility services into the TPSS that will unnecessarily lead to overdesign and increased project costs.
- Where some railway equipment cannot be properly modeled or sized without regenerative braking enabled, for example, Wayside Energy Storage Systems or TPSS inverters.
- Regenerative braking can raise rail potential due to the different current flow in the running rails.
- Regenerative braking will lead to higher rms currents in some wayside feeders.⁹

⁸Refer to the following references: Bae et al. [B11], Mariscotti and Pozzobon [B44], Hellmund [B23], and Lu et al. [B43].

⁹This occurs as regenerated current travels back up the wayside feeder, through the dc busbar, and then down another wayside feeder to a train on the adjacent track. The first wayside feeder is now being heated by currents traveling in the reverse direction. Although this does not occur on all track feeders, some track feeders will inevitably see an increase in rms current load.

Although a simulation may be undertaken with regenerative braking switched on, there could be cases where it is preferred to run the simulation with regenerative braking switched off. This would be evaluated on a case- by-case basis. One example where it could be beneficial to switch off regenerative braking is where there is a “high” headway between trains (e.g., greater than 10 min) and not wanting to “mask” a potential low voltage due to the happenstance of a train braking into a station just as the train on the other track accelerates from the station. Then the agency or engineer may consider completely ignoring the benefits of regenerative braking. However, the interconnection of various lines on a nonlinear rail network may still mean that regenerative braking should be considered where individual headways are “high” but the combined headways result in a more frequent service. As an alternative, the agency may consider specifying a simulation is undertaken with regenerative braking switched off, but all substations remaining operational, as one of the contingency simulations.

It should be appreciated that if the “normal” case modeled depends on trains using regenerative braking, then that implies that the operator will maintain regenerative braking capacity on substantially all of the trains.

- ~~— A network model that considers regeneration may be more complex than a model that ignores regeneration and therefore may not be available for analysis~~
- ~~— Accurate modeling of regeneration requires additional data to properly describe the performance of the regenerating trains during braking and the characteristics of the receptive load(s)~~
- ~~— The benefit of regeneration might be intentionally ignored during design to provide a more robust system because loads on wayside system components are generally greater when the effects of regeneration are ignored⁵~~

Where ~~If~~ the primary goal during modeling is to develop an estimate of overall system energy consumption, then the impact of regenerative braking needs to ~~should~~ be included when trains are operating with regenerative braking.

⁵~~Where a receptive utility or transit property distribution network is present, it is possible that consideration of regeneration actually results in computation of higher load on wayside feeder(s), but this situation is not commonly encountered.~~