NeTrainSim: A Longitudinal Freight Train Dynamics Simulator for Electric Energy Consumption

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Presentation Outline

1. Problem Statement
2. Motivation
3. Research Gap
4. Research Scope
5. NeTrainSim Description
6. Train Dynamics Formulation
7. Case Studies
8. Other Potential Utilization Areas
9. Conclusions
10. Q&A

1. Problem Statement

- Freight locomotives **efficiently move cargo** but are **carbon-intensive**.

- Class I freight locomotives consumed **3.7 billion gallons of diesel** fuel and emitted **37 million tons of CO_2** in the past year.

U.S. Energy Information Administration. Annual Energy Outlook 2022. https://www.eia.gov/outlooks/aeo/data. Accessed May 19, 2022.

2. Motivation

- To reach green environment, a simulator is required to:
  1. **Assess** freight **network performance**,
  2. **design alternative** powertrains,
  3. **Identify** necessary infrastructure **investments**,
  4. Determine energy **system response**.

3. Research Gap

- **Available** network simulators **do not track** the **second-by-second** movements and interactions of multiple trains on a **rail graph** for energy/fuel consumption calculation.
  - Tools that track second-by-second movement of trains are single train simulators or multi-train simulators on a **single track**.
  - To our best of knowledge, there are no simulators that model an **entire network graph**.

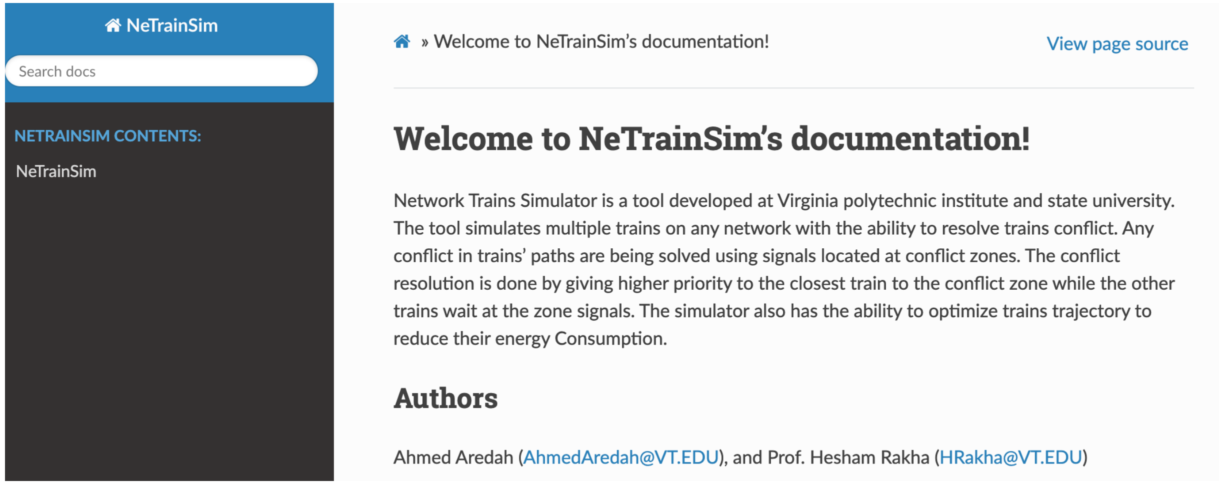
4. Research Scope

- Develop a **network simulator** that **models**:
  1. Train Interactions in **the same** direction,
  2. Train Interactions in **different** directions (resolve conflicts),
  3. Train dynamics considering each locomotive/car as a **point mass**, and
  4. Train **energy consumption** (diesel, electric, hydrogen, …).

Network map and facilities. https://www.cpr.ca/en/choose-rail/network-and-facilities. Accessed Nov 29, 2022.

5. NeTrainSim Overview

- **Network Train Simulator.**
  - Time-based network modeling of all trains
    - Track the position of each locomotive and car at user specified time steps to compute the forces on the train
    - Does not model coupler forces
  - **Open-Source** Python OOP



NeTrainSim

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NETRAINSIM CONTENTS:

NeTrainSim

» Welcome to NeTrainSim's documentation!

View page source

Welcome to NeTrainSim's documentation!

Network Trains Simulator is a tool developed at Virginia polytechnic institute and state university. The tool simulates multiple trains on any network with the ability to resolve trains conflict. Any conflict in trains' paths are being solved using signals located at conflict zones. The conflict resolution is done by giving higher priority to the closest train to the conflict zone while the other trains wait at the zone signals. The simulator also has the ability to optimize trains trajectory to reduce their energy Consumption.

Authors

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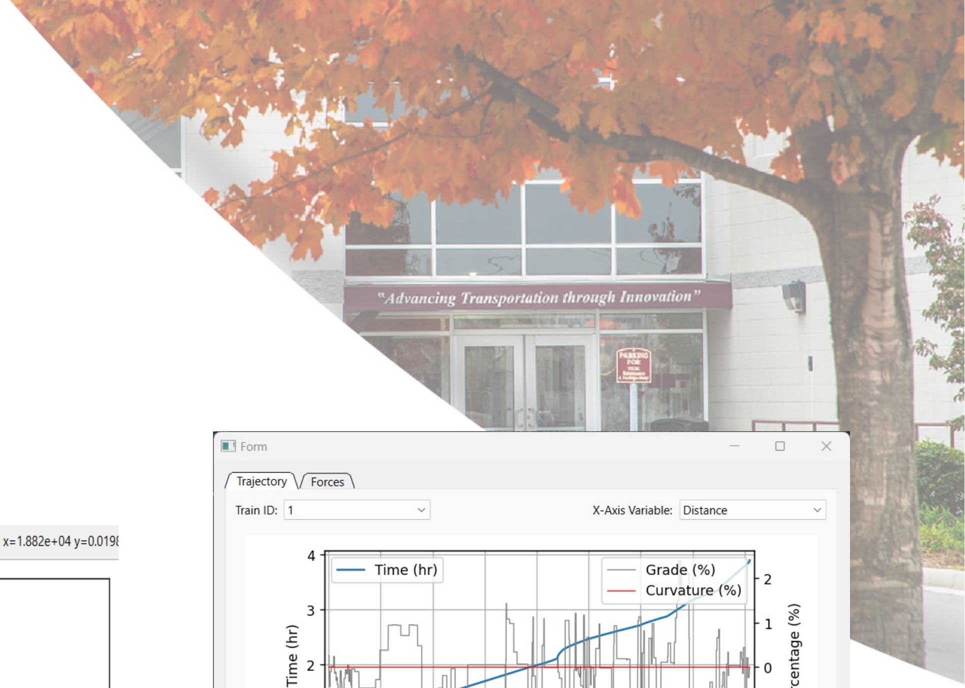
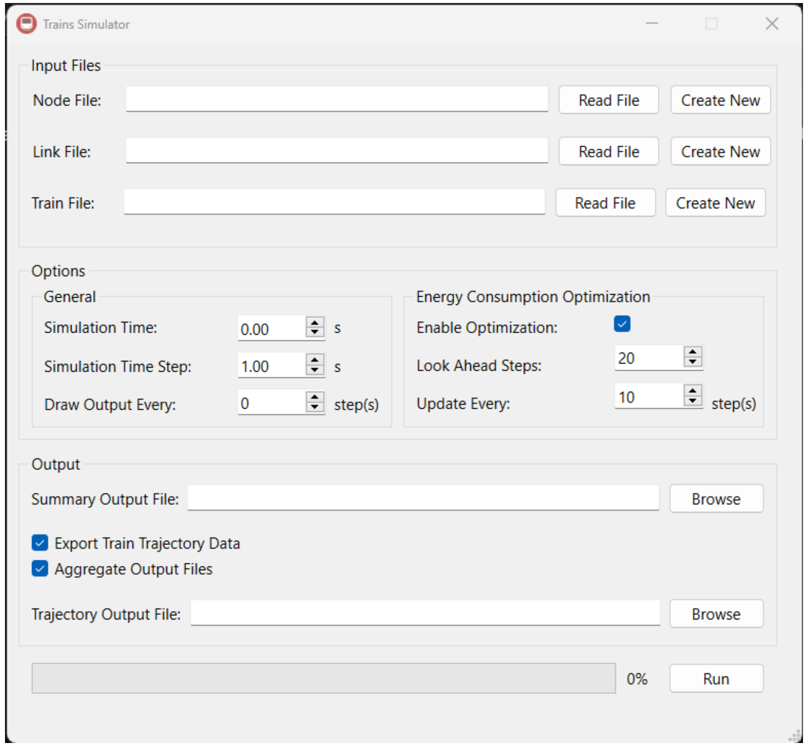
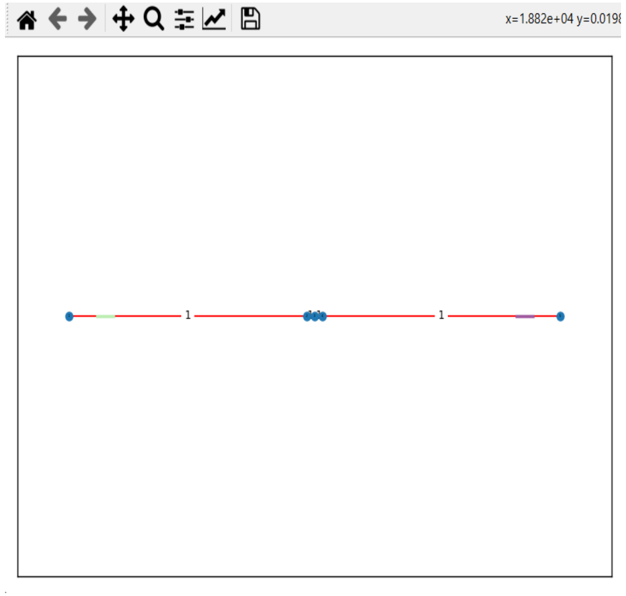
5. NeTrainSim GUI

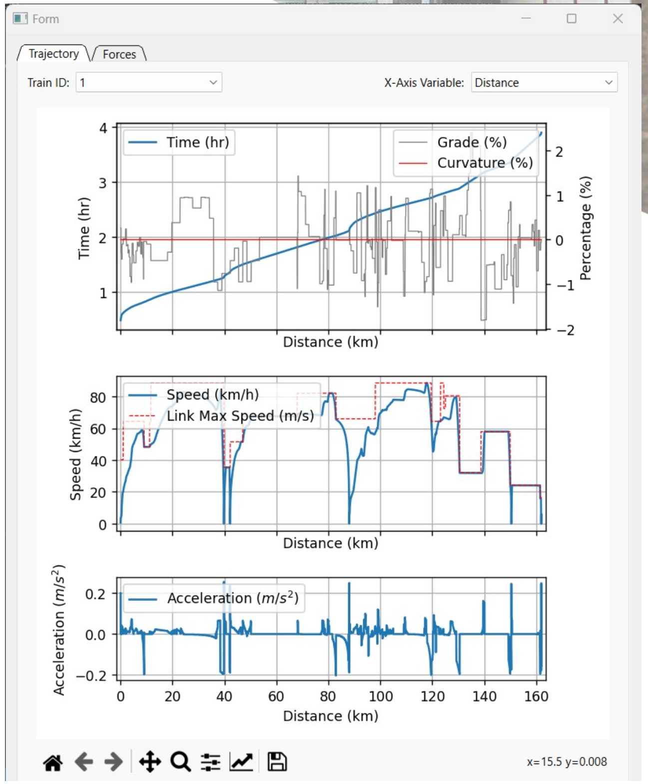




(a) Pre-processing GUI



(b) Simulation Visualization

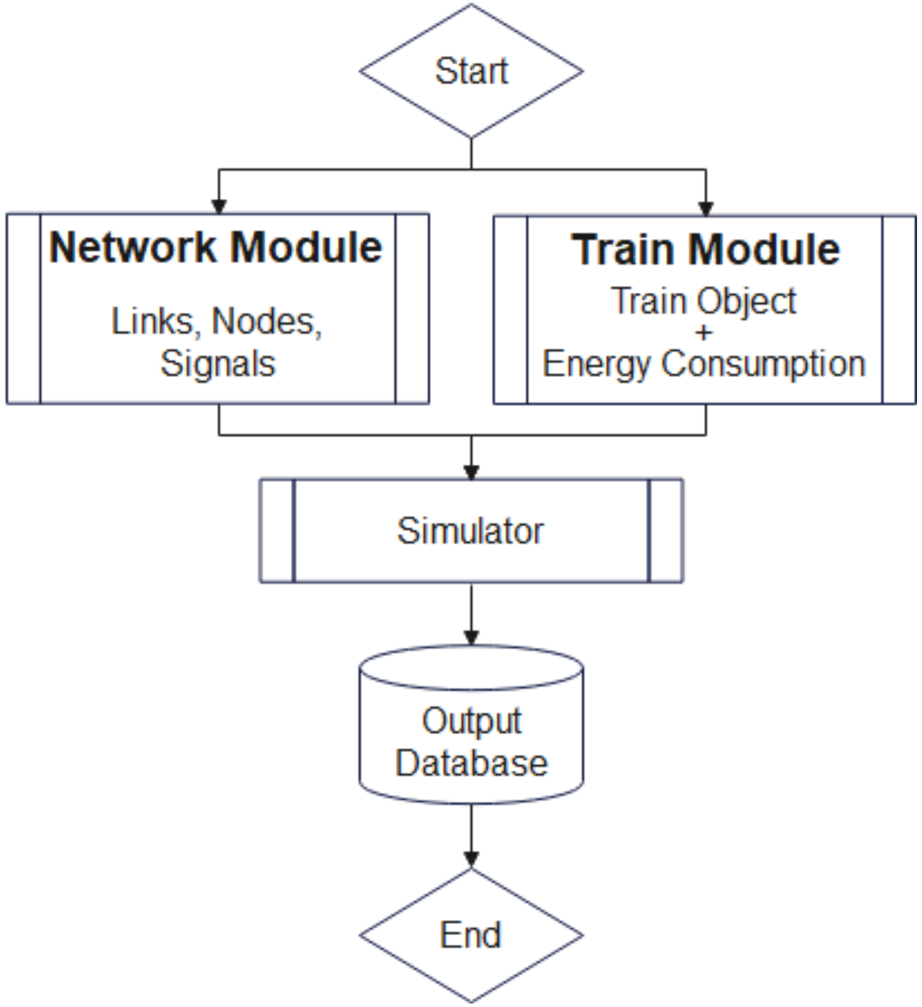


(c) Post-processing GUI

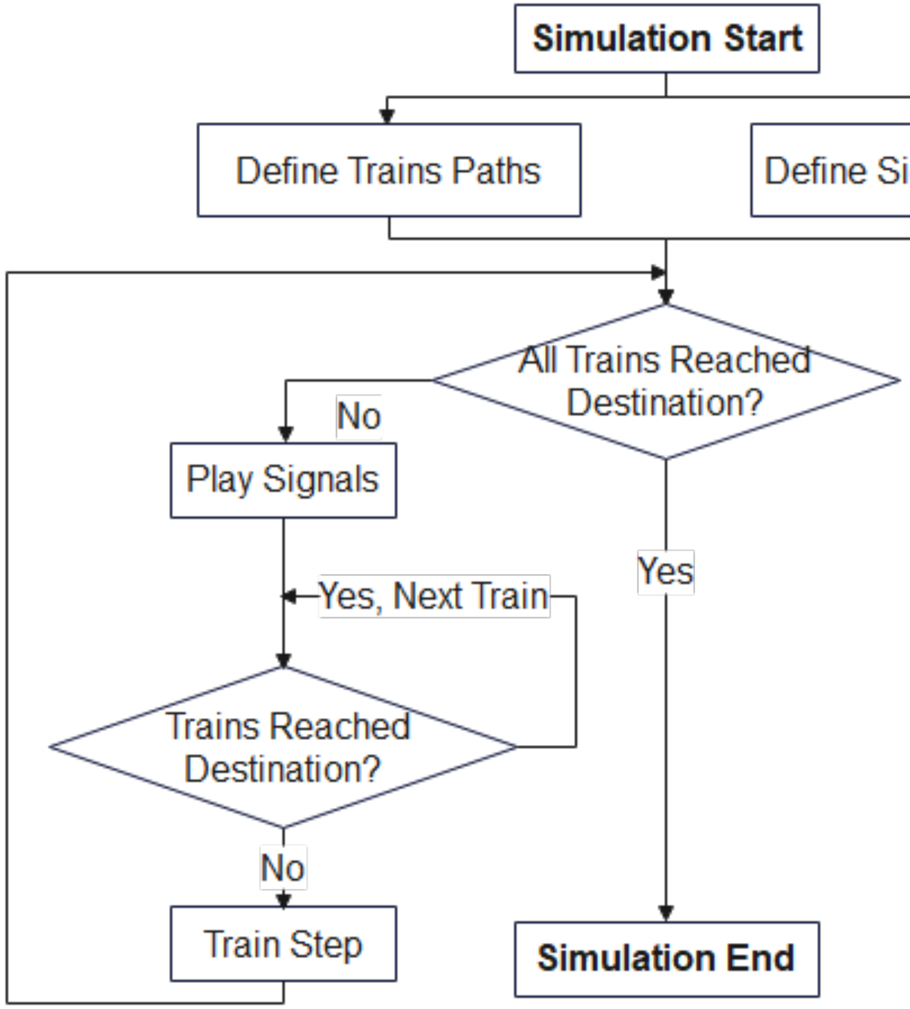
5. NeTrainSim Inputs

1. A network graph (nodes, links, signals),
2. Train configuration and schedule,
   - Energy sources
     - — Diesel
     - — Electric battery
     - — Electric gantry
     - — Hydrogen fuel cell

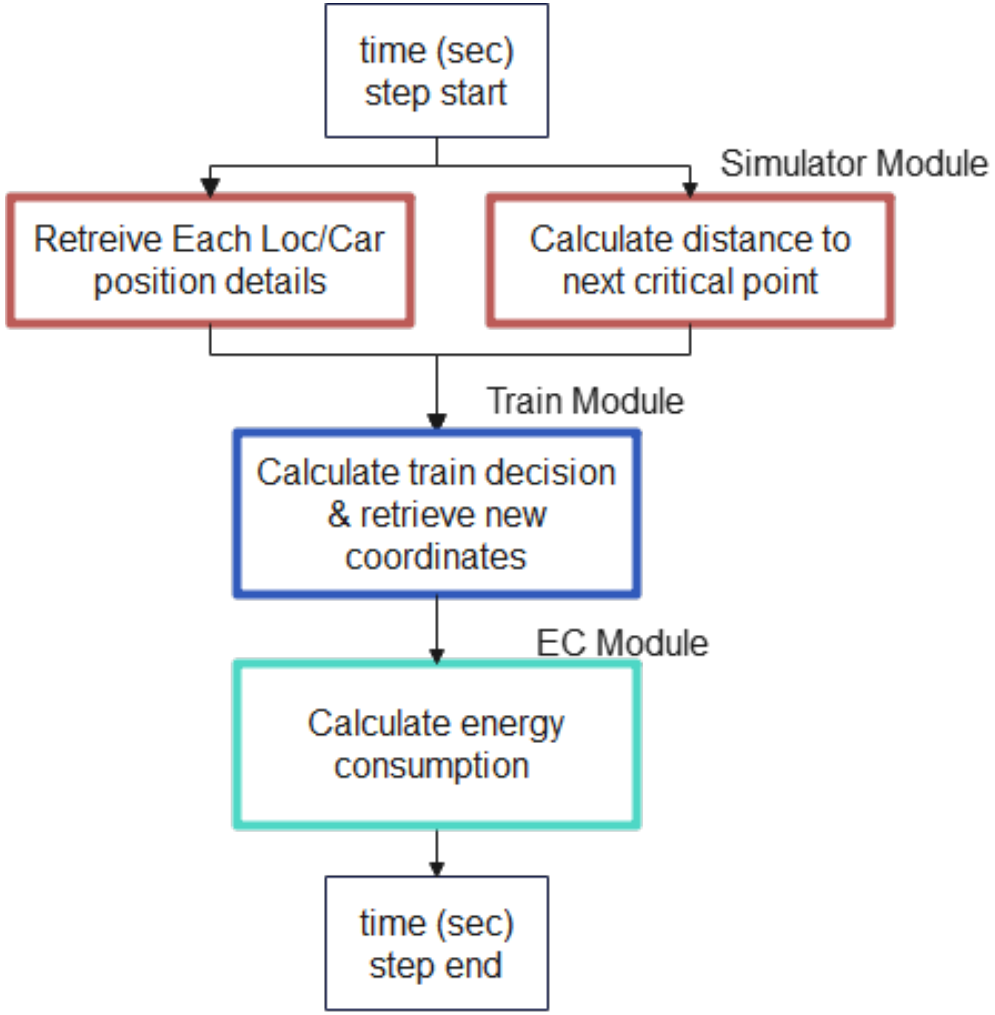
5. NeTrainSim Input/Output Interface



5. NeTrainSim High-level Logic



5. NeTrainSim Detailed Logic



6. NeTrainSim Model: Train Longitudinal Motion Modeling

Tractive Force (N):

$$F_{t|n}(t) = \sum_{l} min\left(\frac{1000\eta_n\lambda_n(t)P_l^{max}}{u_n(t)}, \mu m_l g\right)$$

Resistance Force (N):

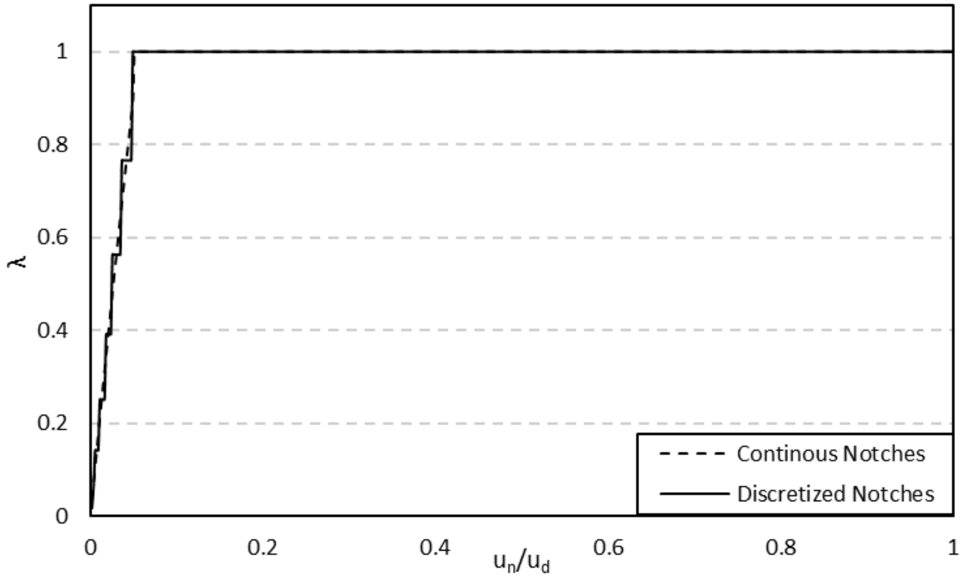
$$R_r = \frac{4.44822\times1.10231}{1000}\sum_{c,l} m_{c,l}\left(\begin{array}{c} 1.5+\frac{16329.34}{m_{c,l}^{a}}+0.0671u_n(t)+ \\ \frac{48862.37A_{c,l}K_{c,l}u_n(t)^2}{m_{c,l}}+20\left(G_{c,l}(t)+0.04\left|C_{c,l}(t)\right|\right) \end{array}\right)$$

$\boldsymbol{m}$: total weight of car/locomotive, $\boldsymbol{\eta}$: Transmission efficiency, $\boldsymbol{\lambda_n}$: Throttle level (notch number). P_l^{max}: Max power of locomotive, $\boldsymbol{u_n(t)}$: Current speed, $\boldsymbol{\mu}$: Friction coef., $\boldsymbol{A_{c,l}}$: Frontal area, $\boldsymbol{K_{c,l}}$: Streamlining coef., **G**: Grade, **C**: Curvature

Hay, W.W., 1991. Railroad engineering. John Wiley & Sons.

6. NeTrainSim Model: Train Longitudinal Motion Modeling (Cont.)

λ_n- Notch number:



Wang, J., Rakha, H.A., 2018. Longitudinal train dynamics model for a rail transit simulation system. Transp. Res. Part C Emerg. Technol. 86, 111–123. https://doi.org/10.1016/j.trc.2017.10.011

6. NeTrainSim Model: Train Longitudinal Motion Modeling (Cont.)

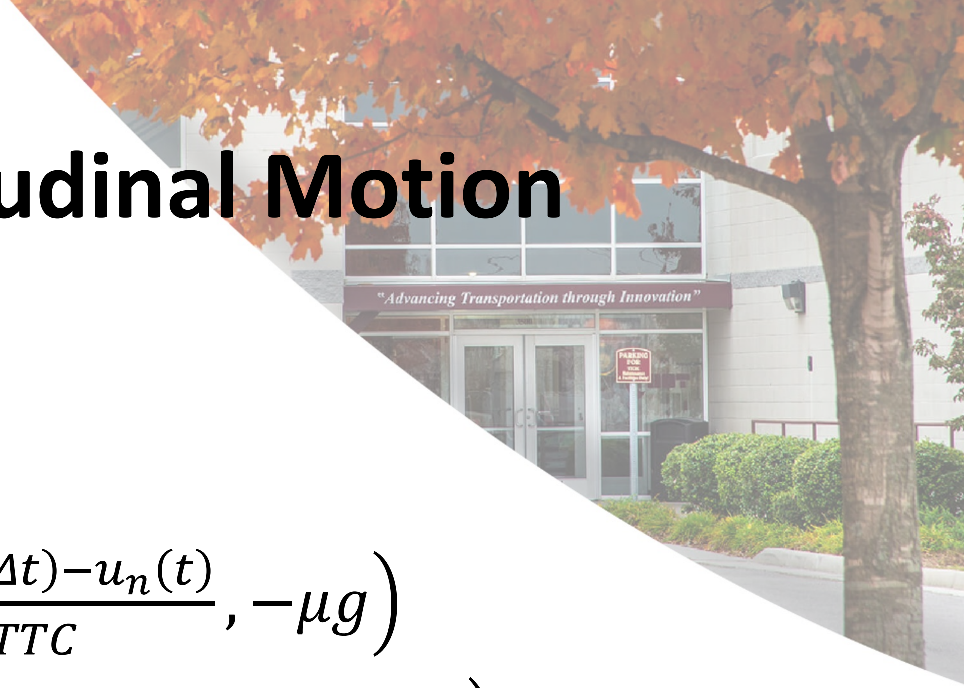
Time to activate brakes: $$T_n = \frac{L_c^{max}}{u_s} + t_{pr}$$

Safe spacing: $$s_n(t) = s_n^j + T_n\, u_n(t)$$

Speed estimate: $$\tilde{u}_n(t + \Delta t) = min\left(\frac{s_n(t) - s_n^j}{T_n}, u_f\right)$$

Time to collision: $$TTC = min\left(\frac{s_n(t) - s_n^j}{max(u_n(t) - u_{n-1}(t), 0.0001)}, TTC_{max}\right)$$

$\boldsymbol{u_s}$: Speed of Sound, $\boldsymbol{L_c^{max}}$: Brakes signal travelled length, $\boldsymbol{t_{pr}}$: Driver perception-reaction time, $\boldsymbol{s_n^j}$: Spacing when stopped, **TTC**: Time To Collision, $\boldsymbol{\mu}$: friction coef., $\boldsymbol{T_n}$: time step, $\boldsymbol{a_n^{max}(t)}$: max acceleration, $\boldsymbol{s_n(t)}$: train Spacing, $\boldsymbol{s_n^j}$: train critical length.



6. NeTrainSim Model: Train Longitudinal Motion Modeling (Cont.)

Acceleration:

Estimate: $$a_{n,1-1}(t) = \max\left(\frac{\tilde{u}_n(t+\Delta t) - u_n(t)}{TTC}, -\mu g\right)$$

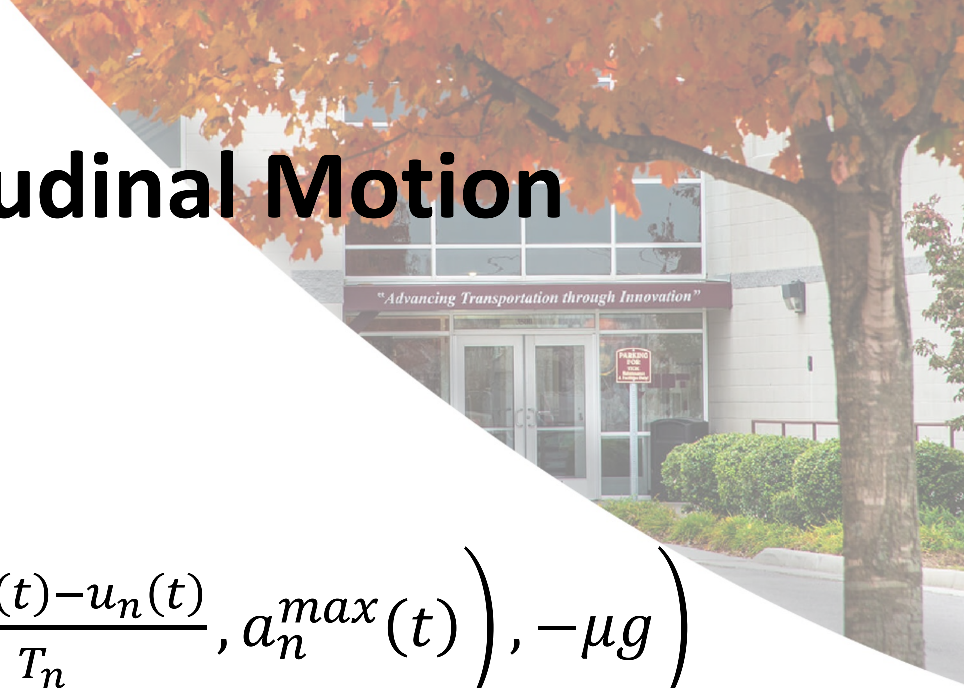
Clear headway: $$a_{n,1-2}(t) = \min\left(\frac{\tilde{u}_n(t+\Delta t) - u_n(t)}{T_n}, a_n^{max}(t)\right)$$

Acceleration selection: $$a_{n,1-3}(t) = (1-\beta_1)a_{n,1-1}(t) + \beta_1 a_{n,1-2}(t)$$

$$\beta_1 = \begin{cases} 0, & a_{n,1-1}(t) < 0 \\ 1, & a_{n,1-1}(t) \geq 0 \end{cases}$$

$\boldsymbol{u_n(t)}$: current speed, $\boldsymbol{u_{n-1}(t)}$: leader speed, $\boldsymbol{\tilde{u}_n(t+\Delta t)}$: next time step predicted speed,. **TTC**: Time To Collision, $\boldsymbol{\mu}$: friction coef., $\boldsymbol{T_n}$: Time to activate brakes, $\boldsymbol{a_n^{max}(t)}$: max acceleration, $\boldsymbol{\mu}$: Friction coef.

6. NeTrainSim Model: Train Longitudinal Motion Modeling (Cont.)



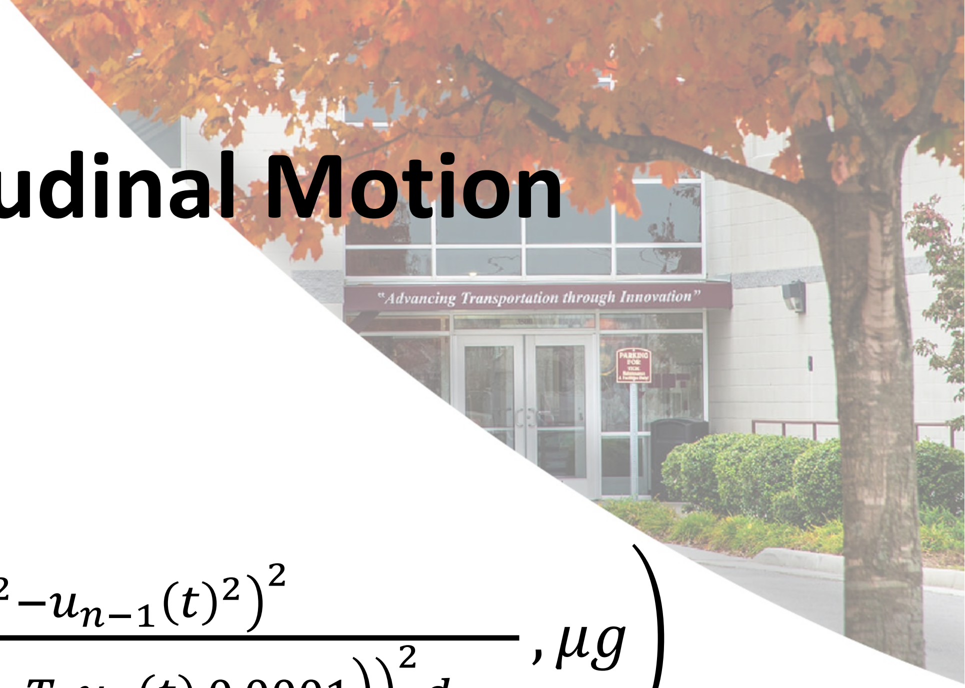
Acceleration:

Train Following: $$a_{n,1-4}(t) = max\left(min\left(\frac{u_{n-1}(t)-u_n(t)}{T_n}, a_n^{max}(t)\right), -\mu g\right)$$

Acceleration selection: $a_{n,1}(t) = \beta_2 a_{n,1-3}(t) + (1-\beta_2)a_{n,1-4}(t)$

$$\beta_2 = \begin{cases} 1, & spacing\ ahead\ is\ within\ range\ policy \\ 0, & spacing\ ahead\ is\ not\ within\ range\ policy \end{cases}$$

$\boldsymbol{u_n(t)}$: current speed, $\boldsymbol{u_{n-1}(t)}$: leader speed, $\boldsymbol{\mu}$: friction coef., $\boldsymbol{a_n^{max}(t)}$: max acceleration.



6. NeTrainSim Model: Train Longitudinal Motion Modeling (Cont.)

Acceleration:

Deceleration: $$a_{n,2}(t) = \min\left(\frac{\left(u_n(t)^2 - u_{n-1}(t)^2\right)^2}{4\left(\max\left(s_n(t) - s_n^j - T_n u_n(t), 0.0001\right)\right)^2 d_{des}}, \mu g\right)$$

Acceleration selection: $$a_n(t) = (1-\gamma)a_{n,1}(t) + \gamma a_{n,2}(t)$$

$$\gamma = \frac{u_n(t) - u_{n-1}(t) + \sqrt{\left(u_n(t) - u_{n-1}(t)\right)^2}}{2\times \max(|u_n(t) - u_{n-1}(t)|, 0.0001)}$$

$\boldsymbol{u_n(t)}$: current speed, $\boldsymbol{u_{n-1}(t)}$: leader speed, $\boldsymbol{\mu}$: friction coef.

6. NeTrainSim Model: Train Longitudinal Motion Modeling (Cont.)

Acceleration Summary:

$$\left.\begin{array}{ll}\left.\begin{array}{ll}\left.\begin{array}{ll}\textbf{Estimate:} & a_{n,1-1}(t) = max\left(\frac{\tilde{u}_n(t+\Delta t)-u_n(t)}{TTC}, -\mu g\right) \\ \textbf{Clear headway:} & a_{n,1-2}(t) = min\left(\frac{\tilde{u}_n(t+\Delta t)-u_n(t)}{T_n}, a_n^{max}(t)\right)\end{array}\right\} a_{n,1-3}(t) \\ \textbf{Train Following:} & a_{n,1-4}(t) = max\left(min\left(\frac{u_{n-1}(t)-u_n(t)}{T_n}, a_n^{max}(t)\right), -\mu g\right)\end{array}\right\} a_{n,1}(t) \\ \textbf{Collision Avoidance:} & a_{n,2}(t) = min\left(\frac{\left(u_n(t)^2-u_{n-1}(t)^2\right)^2}{4\left(max\left(s_n(t)-s_n^j-T_n u_n(t), 0.0001\right)\right)^2 d_{des}}, \mu g\right)\end{array}\right\} a_n(t)$$

$u_n(t)$: current speed, $u_{n-1}(t)$: leader speed, $\tilde{u}_n(t+\Delta t)$: next time step predicted speed,. **TTC**: Time To Collision, μ: friction coef., T_n: Time to activate brakes, $a_n^{max}(t)$: max acceleration, $s_n(t)$: train Spacing, s_n^j: train critical length.

Wang, J., Rakha, H.A., 2018. Longitudinal train dynamics model for a rail transit simulation system. Transp. Res. Part C Emerg. Technol. 86, 111–123. https://doi.org/10.1016/j.trc.2017.10.011

6. NeTrainSim Model: Train Longitudinal Motion Modeling (Cont.)

Acceleration:

Acceleration Smoothing: $$\boldsymbol{a_n(t) = \alpha \times a_n(t) + (1-\alpha) \times a_n(t-\Delta t)}$$

Jerk constraint: $$\boldsymbol{\tilde{a}_n(t) = min(|a_n(t)|, |a_n(t-\Delta t)| + j_{max}\Delta t) * -1^p}$$

$$p = \begin{cases} 0, & a_n(t) \geq 0 \\ 1, & a_n(t) < 0 \end{cases}$$

Speed: $$\boldsymbol{u_n(t+\Delta t) = max\left(min\left(u(t) + \tilde{a}(t) \times \Delta t, u_f\right), 0\right)}$$

$\boldsymbol{u_n(t)}$: current speed, $\boldsymbol{u_{n-1}(t)}$: leader speed, $\boldsymbol{\tilde{u}_n(t+\Delta t)}$: next time step predicted speed,. **TTC**: Time To Collision, $\boldsymbol{\mu}$: friction coef., $\boldsymbol{T_n}$: time step, $\boldsymbol{a_n^{max}(t)}$: max acceleration, $\boldsymbol{s_n(t)}$: train Spacing, $\boldsymbol{s_n^j}$: train critical length.

Wang, J., Rakha, H.A., 2018. Longitudinal train dynamics model for a rail transit simulation system. Transp. Res. Part C Emerg. Technol. 86, 111–123. https://doi.org/10.1016/j.trc.2017.10.011

6. NeTrainSim Model: Energy Consumption

Train power: $$P_{W|n}(t) = \left(m_n a_n(t) + R_n(t)\right) \times u_n(t)$$

Regenerative coef.: $$\eta_{re}(t) = \begin{cases} \dfrac{1}{e^{\frac{\gamma}{|a(t)|}}} & \forall\, P_{W|n}(t) < 0 \\ 0 & \forall\, P_{W|n}(t) \geqslant 0 \end{cases}$$

Consumed power: $$P_{B,n}(t) = \begin{cases} \dfrac{P_{W|n}(t)}{\eta_{W-T}} + P_A, & \forall\, P_{W|n}(t) > 0 \\ P_{W|n}(t) \times \eta_{re|n} \times \eta_{W-T} + P_A & \forall\, P_{W|n}(t) \leq 0 \end{cases}$$

$\boldsymbol{\eta_{re}}$: regenerative eff., $\boldsymbol{\gamma}$: regenerative coef., **a(t)**: train acceleration, $\boldsymbol{P_{W|n}}$: driving used power, $\boldsymbol{\eta_{W-T}}$: driveline eff., $\boldsymbol{P_A}$: used auxiliary power

Wang, J., Rakha, H.A., 2017. Electric train energy consumption modeling. Appl. Energy 193, 346–355. https://doi.org/10.1016/J.APENERGY.2017.02.058

7. Case Studies

A. 2 Scenarios: Validate train dynamics results,

B. 1 Scenario : Test conflict resolution, and

C. 1 Scenario : Network run.

7. Case Studies (Cont.)

- **2 Scenarios**: Validate train dynamics results:

Train Characteristics	**Value**
Track Length (km)	162
Max Locomotive Power (kW)	3262
Number of Locomotives	3
Number of Cars	71
Locomotive Weight (ton)	198
Car Weight (ton)	44

Trains Characteristics in Scenario I

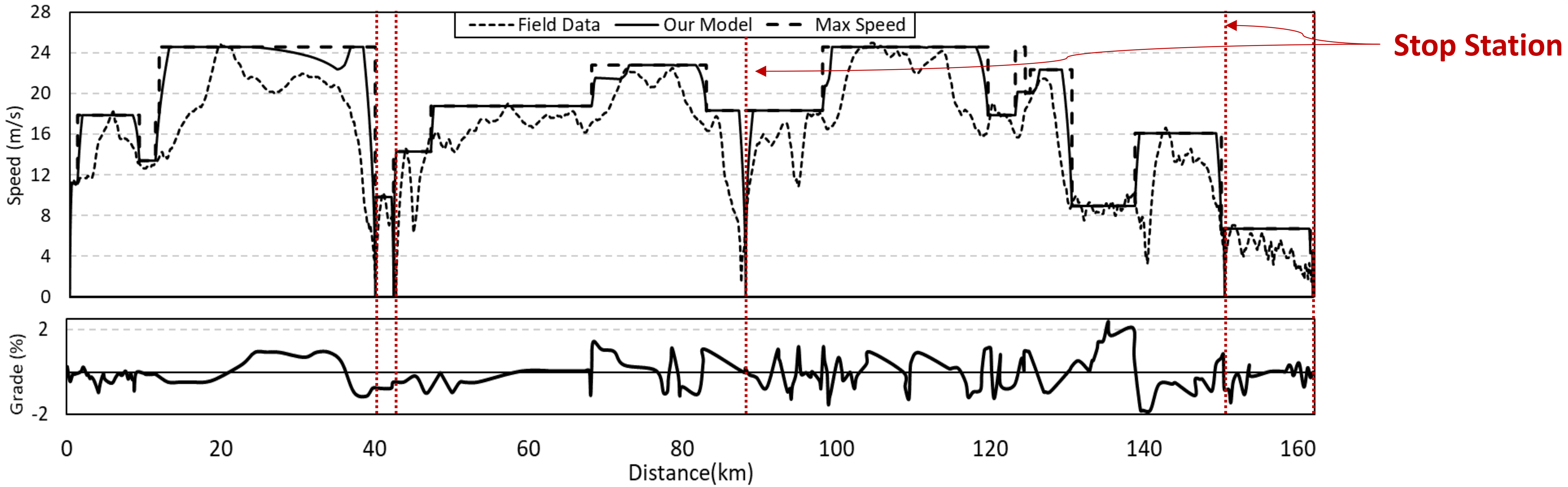
Train Characteristics	**Value**
Track Length (km)	322
Max Locomotive Power (kW)	2445.9
Number of Locomotives	11
Number of Cars	139
Locomotive Weight (ton)	190
Car Weight (ton)	100

Trains Characteristics in Scenario II

7. Case Studies (Cont.)

A. Validate train dynamics results – Scenario I

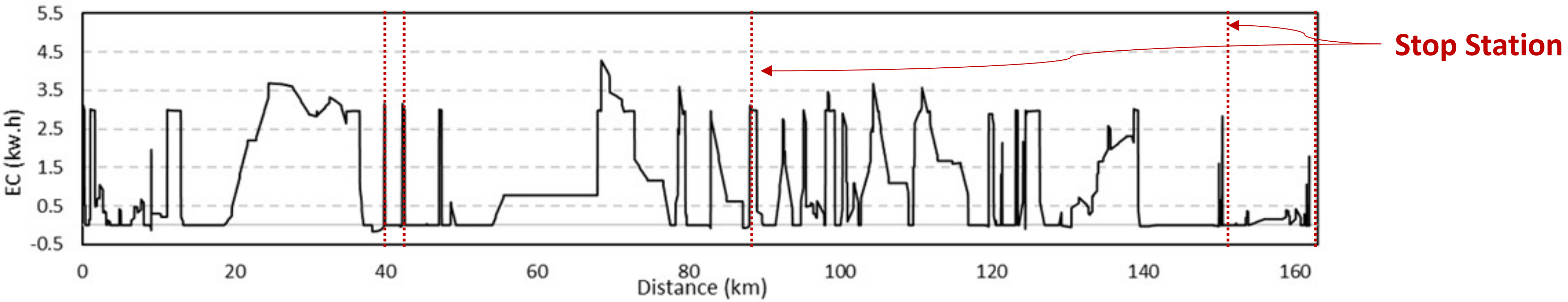
Speed Profile in Scenario I



7. Case Studies (Cont.)

A. Validate train dynamics results – Scenario I (Cont.)

Instantaneous Energy Consumption in Scenario I



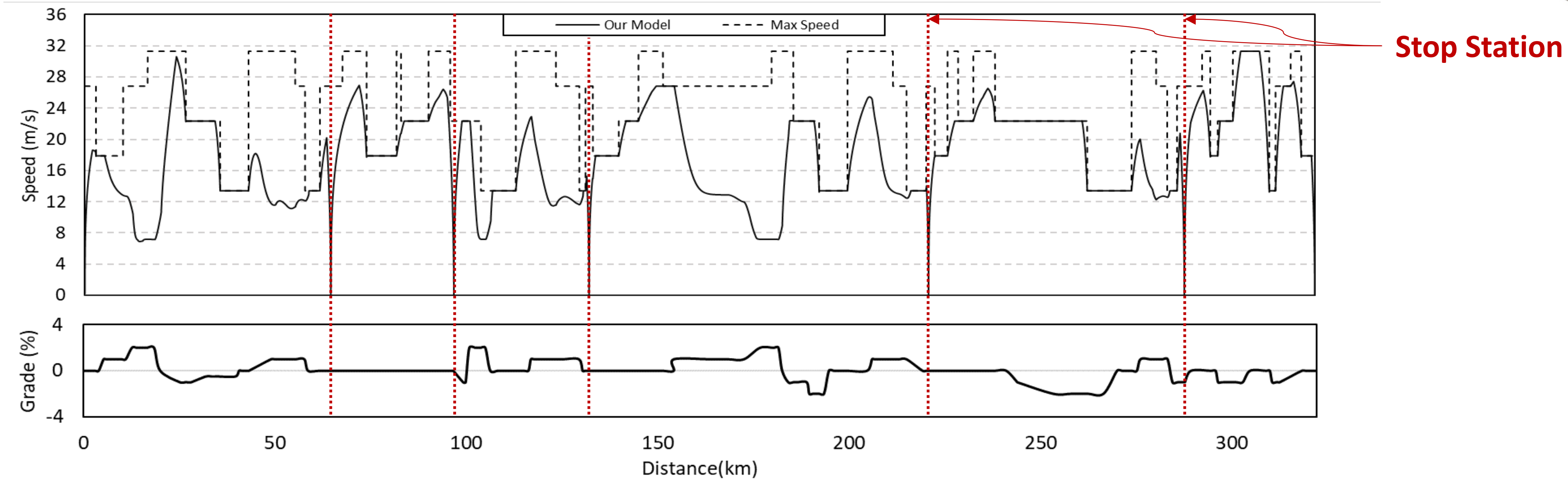
Electric Total Energy Consumption (MWh) = 10.12 (Predicted)

10.58 (Ground Truth)

7. Case Studies (Cont.)

A. Validate train dynamics results – Scenario II

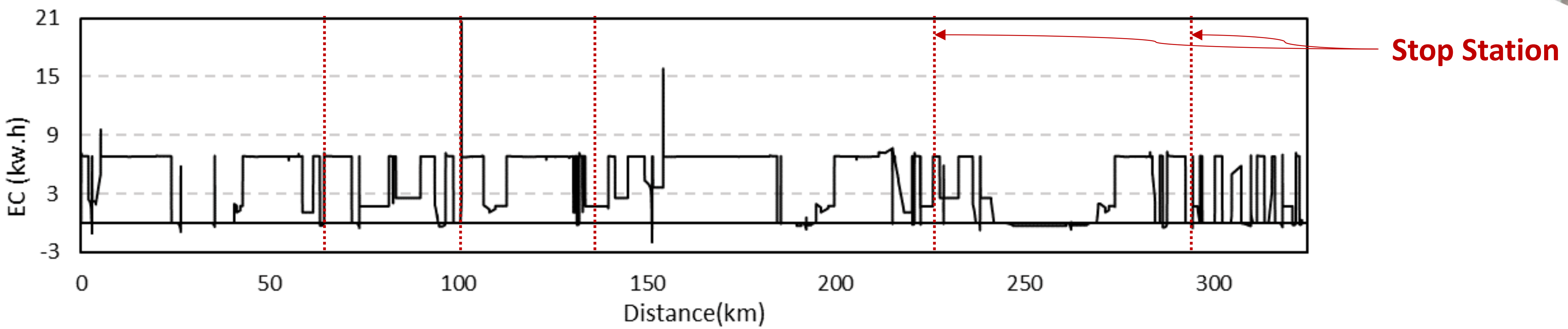
Speed Profile in Scenario II



7. Case Studies (Cont.)

A. Validate train dynamics results – Scenario II (Cont.)

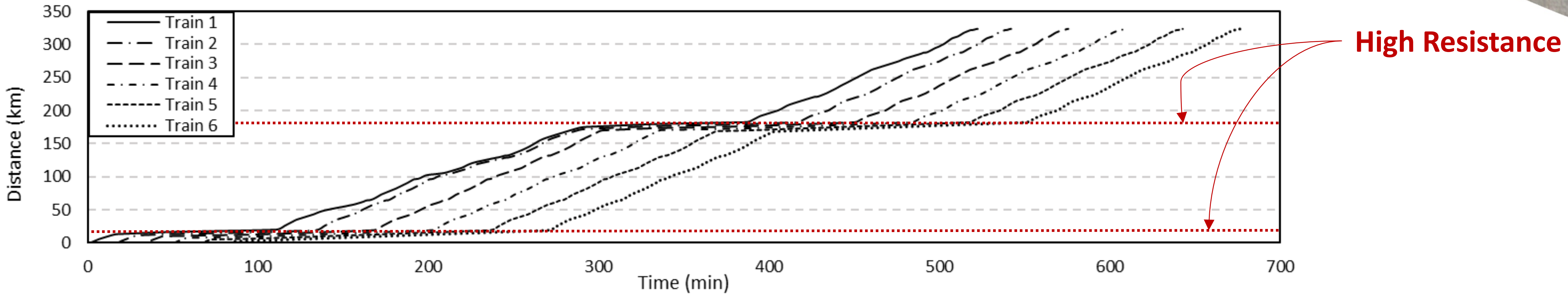
Instantaneous Energy Consumption in Scenario II



Electric Total Energy Consumption (MWh) = 83.5

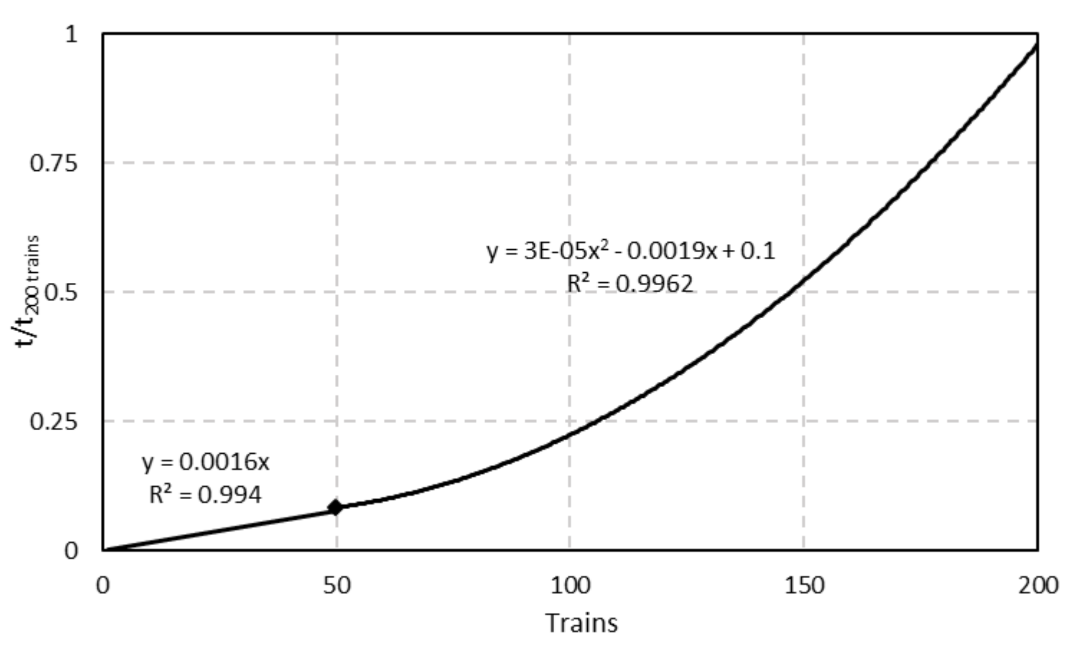
7. Case Studies (Cont.)

A. Scenario II – Extension – Following Model



7. Case Studies (Cont.)

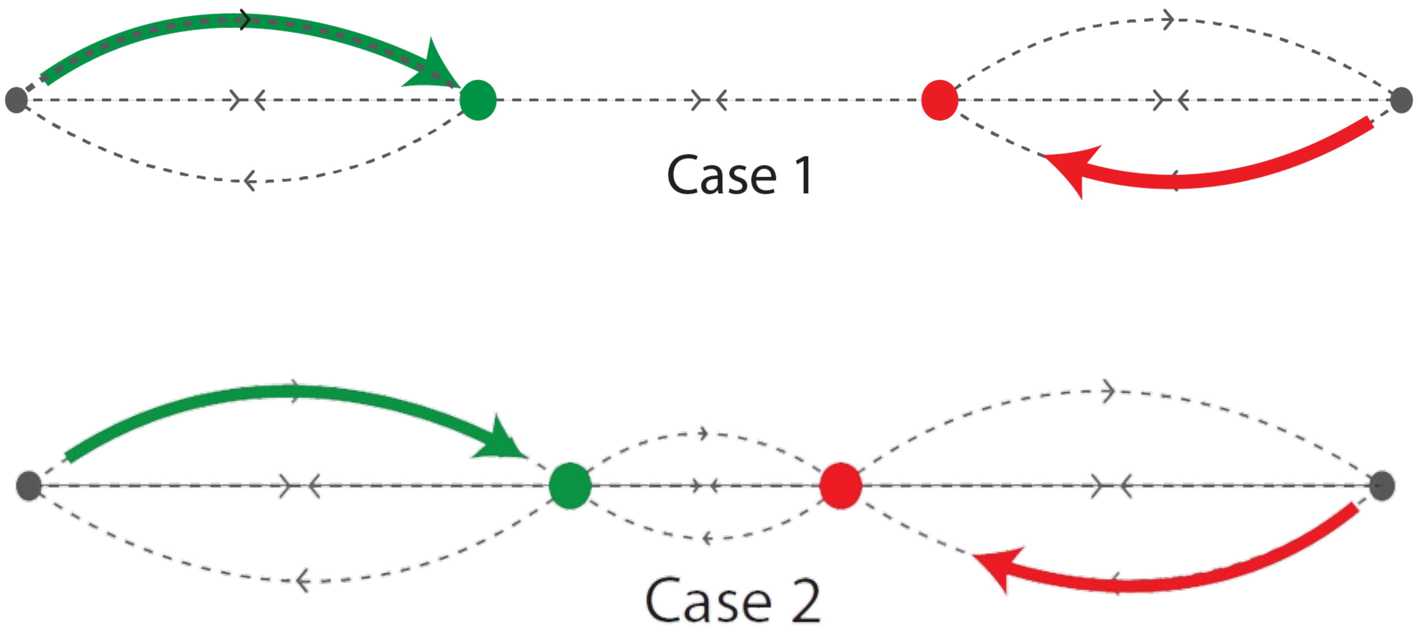
A. Scenario II – Extension – Following Model (Cont.)



$\mathbf{O(\#train^2)}$

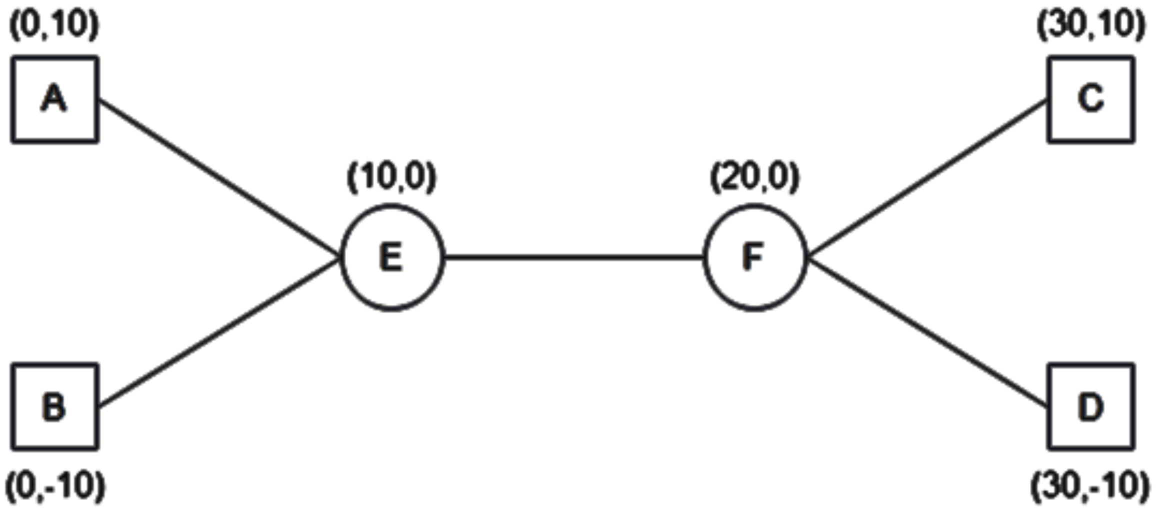
7. Case Studies (Cont.)

B. Test conflict resolution – Scenario III:



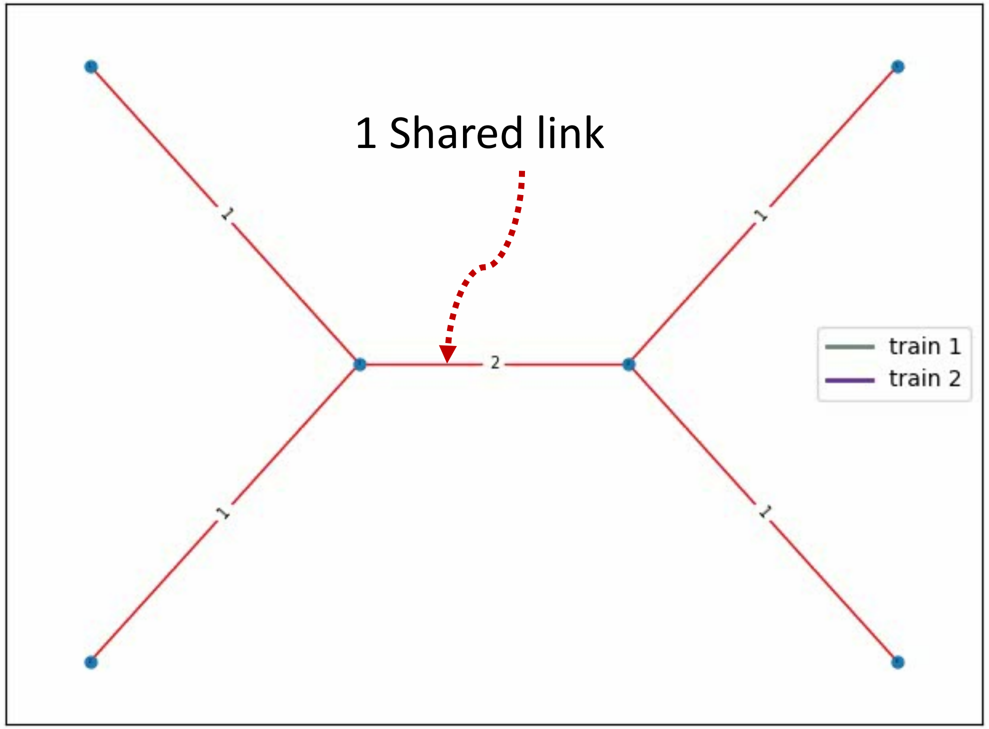
7. Case Studies (Cont.)

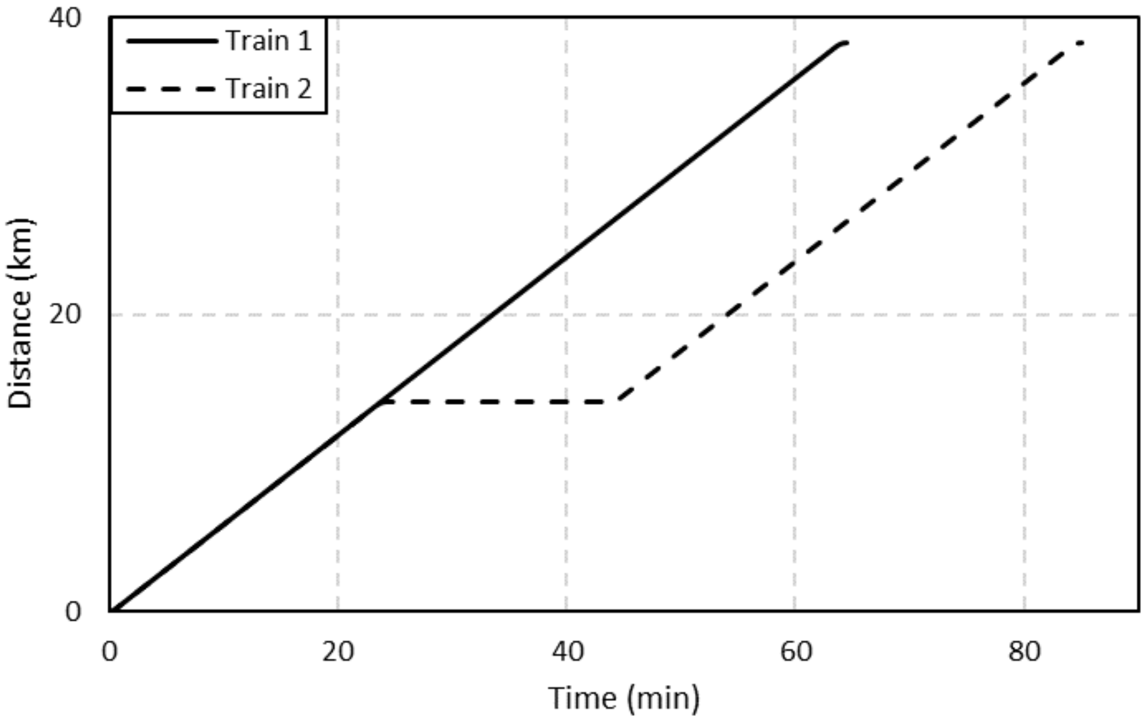
B. <u>Test conflict resolution – Scenario III (Cont.):</u>



7. Case Studies (Cont.)

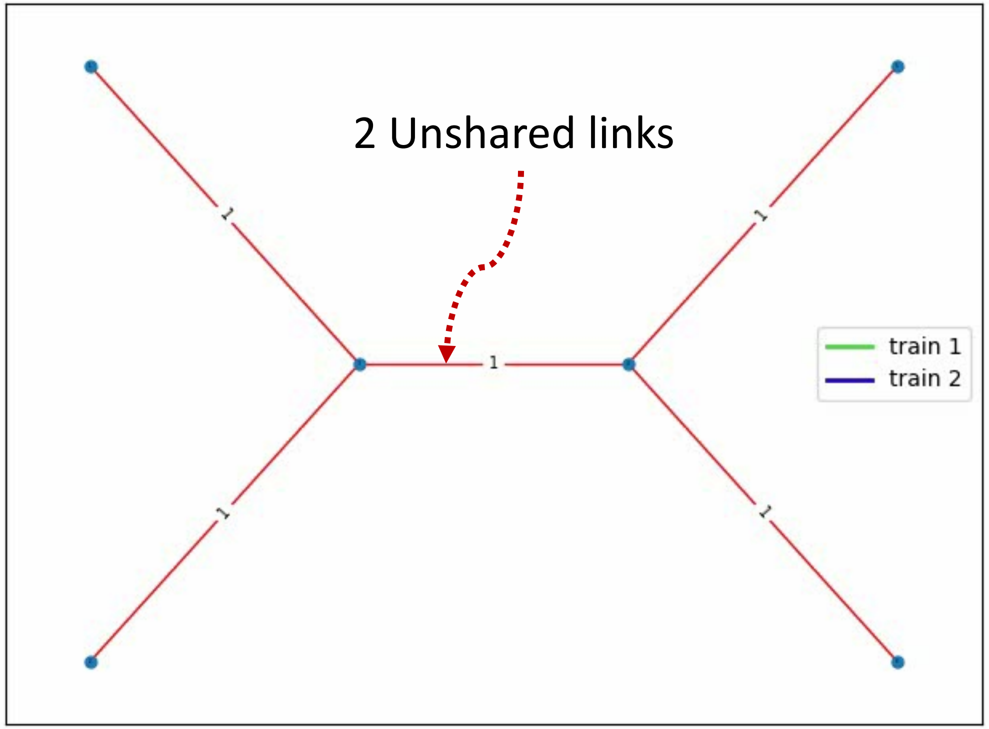
B. Test conflict resolution – Scenario III – Case 1:

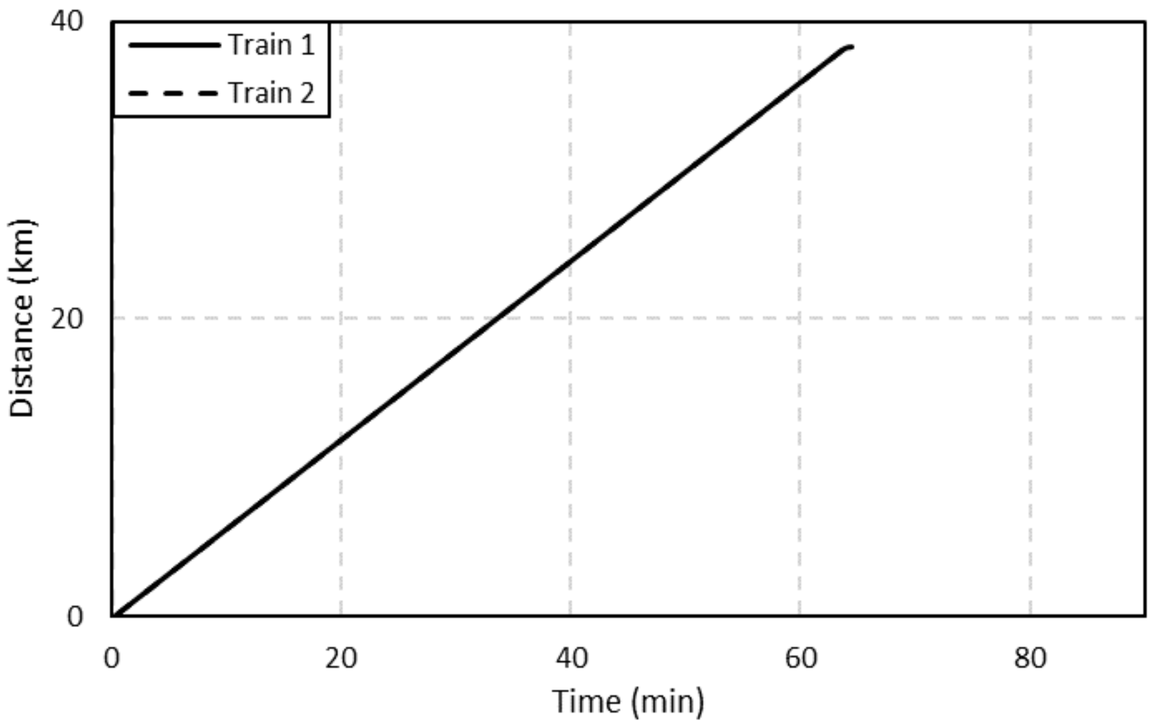




7. Case Studies (Cont.)

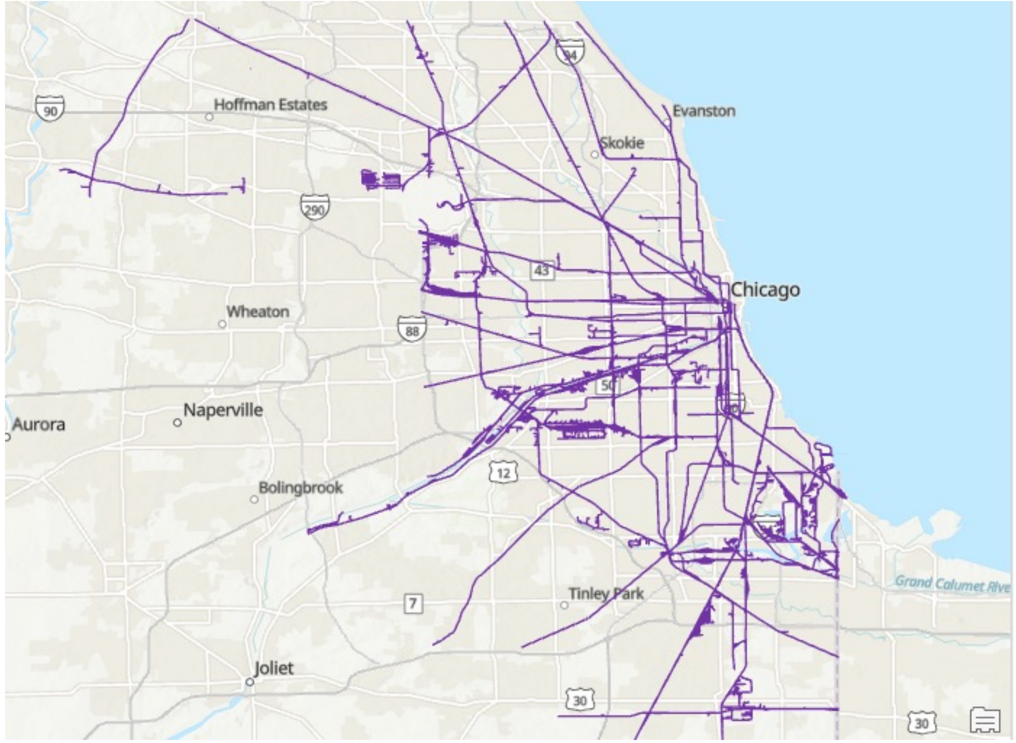
B. Test conflict resolution – Scenario III – Case 2:



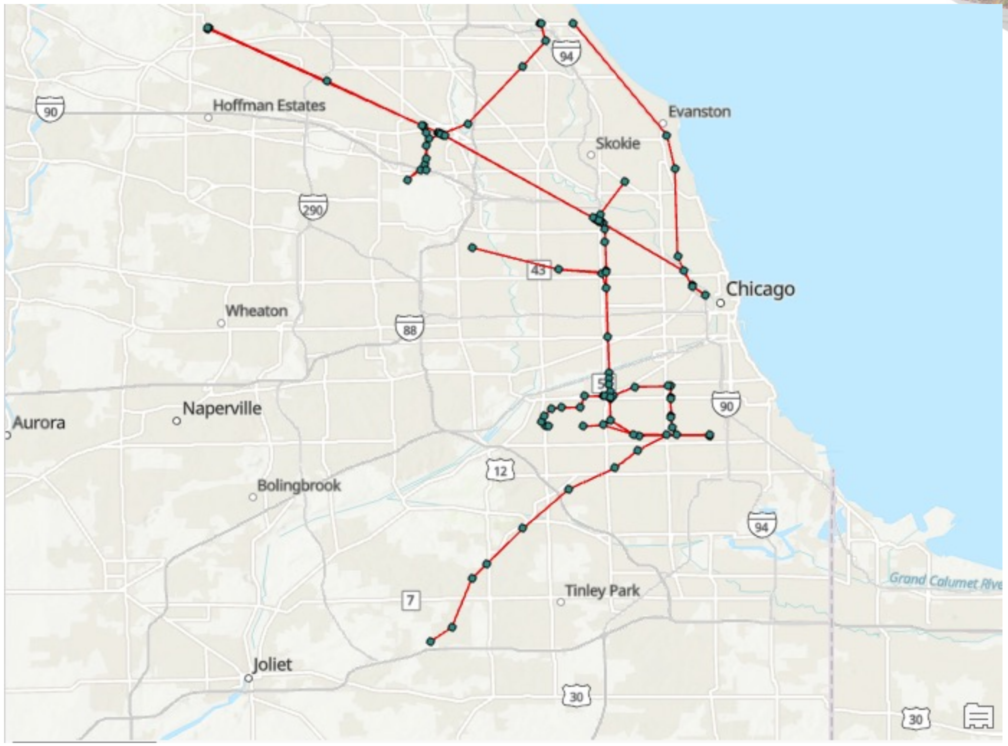


7. Case Studies (Cont.)

B. Network Run – Scenario VI:



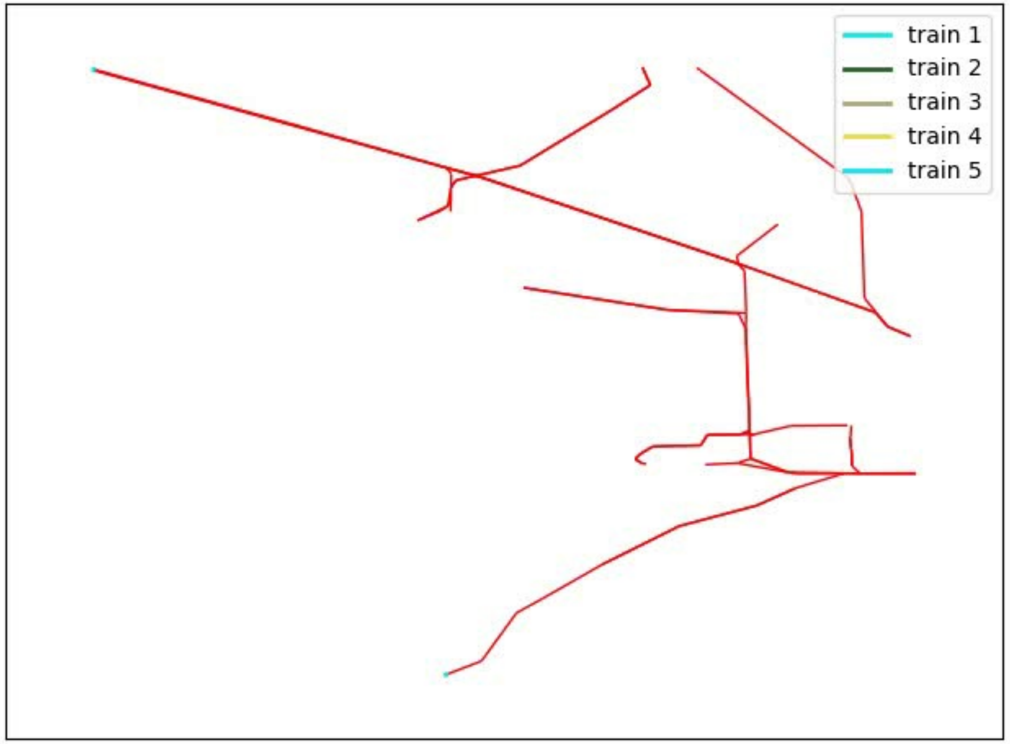
(a) Original Chicago Network

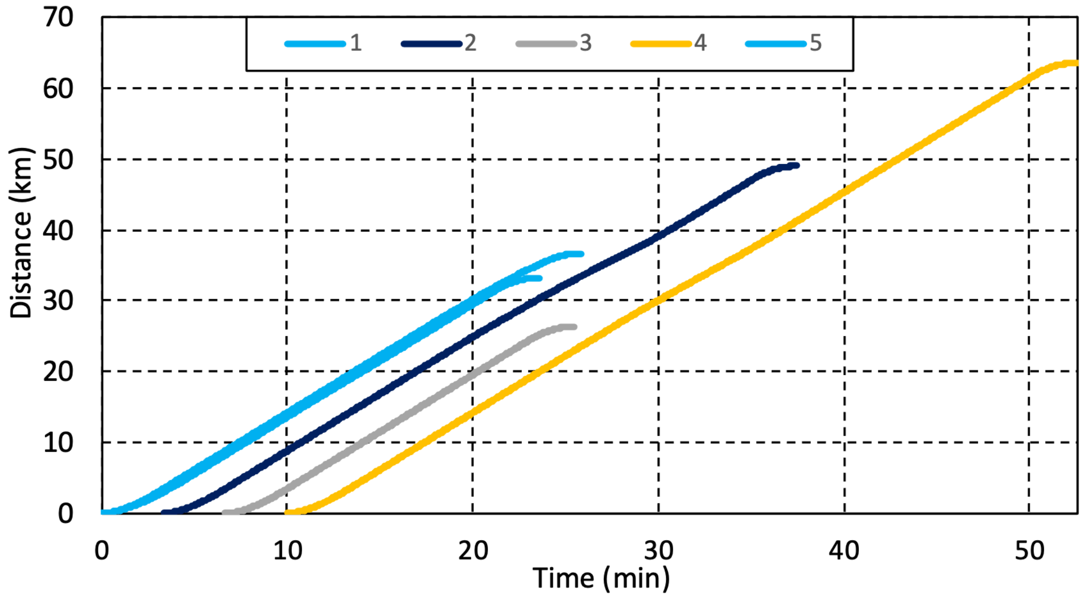


(b) Simplified Chicago Network

7. Case Studies (Cont.)

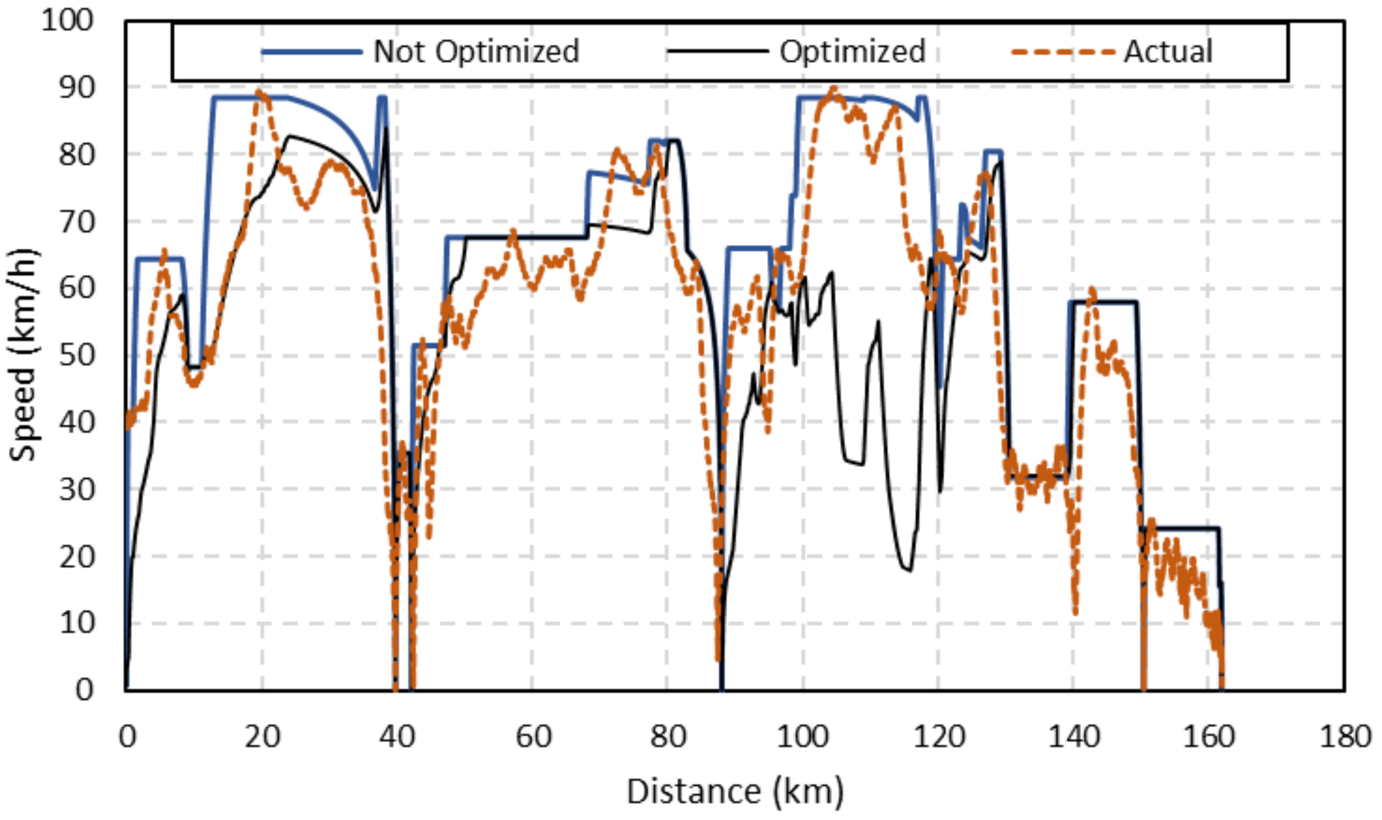
B. Network Run – Scenario VI (Cont.):

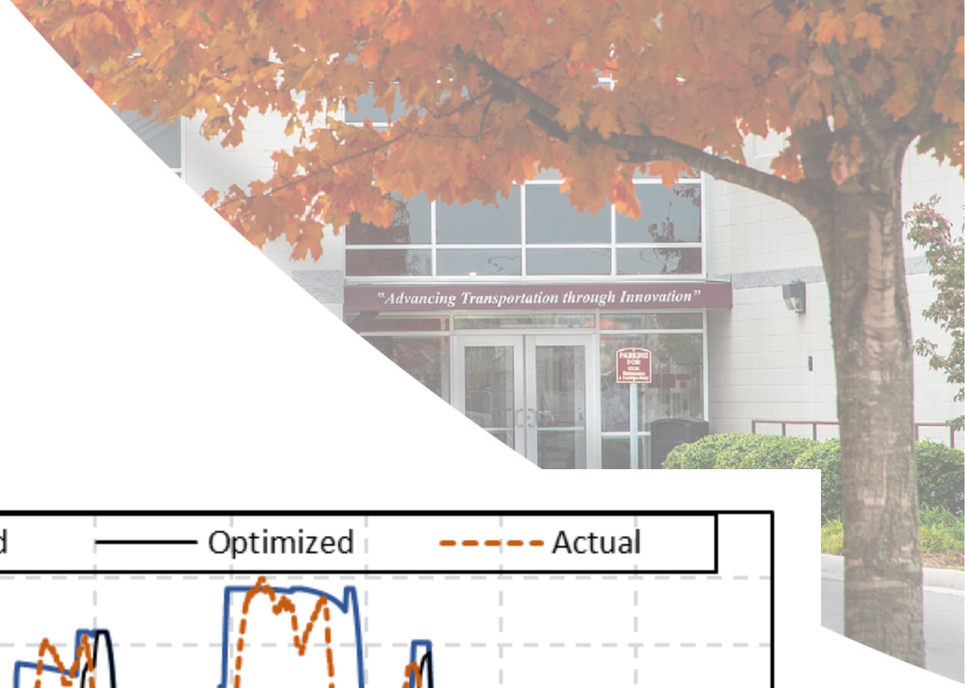




7. Trajectory Optimization

- Lookahead distance?
- Update throttle level?





8. Other Potential Utilization Areas

- Commodities path planning,
- Compare energy consumption of different energy sources,
- Optimize recharge station locations,
- Infrastructure-decision-making-investment tool.

9. Conclusion

- **NeTrainSim**: A Network Train Simulator.
- Energy consumption for different powertrains.
- Train following.
- Conflict resolution.
- Trajectory optimization.

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Thank you!

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Literature Review

- <u>Simulator Types:</u>
  - **Macroscale** simulators typically **ignore the in-train forces** to achieve scalability.
  - **Microscale** simulators include **longitudinal dynamics** and/or any **relative motion between vehicles** in the direction of the train movement.

Iwnicki, S., M. Spiryagin, C. Cole, and T. McSweeney, Eds. Handbook of Railway Vehicle Dynamics. CRC press, 2006.

Literature Review (Cont.)

- <u>Simulator Types (Cont.)</u>:
  - **Whole-trip** simulators replicate one **fixed-configuration** train running on a **fixed route** for the **in-train forces** and their patterns.
  - **Short-trip** provide a **microanalysis** of a single train vehicle or the train as a whole.

Wu, Q. Optimisations of Draft Gear Designs for Heavy Haul Trains. Central Queensland University, Australia, 2017.

Literature Review (Cont.)

- Whole-trip Simulators in Literature:
  - Cipek et al.:
    - Converted a diesel locomotive to a battery hybrid equivalent,
    - Derived fuel consumption and gases emissions models.

Cipek, M., D. Pavković, Z. Kljaić, and T. J. Mlinarić. Assessment of Battery-Hybrid Diesel-Electric Locomotive Fuel Savings and Emission Reduction Potentials Based on a Realistic Mountainous Rail Route. Energy, Vol. 173, 2019, pp. 1154–1171. https://doi.org/10.1016/j.energy.2019.02.144.

Literature Review (Cont.)

- <u>Whole-trip Simulators in Literature (Cont.)</u>:
  - Train Energy and Dynamics Simulator (TEDS) for:
    - Safety and risk evaluations,
    - Energy consumption studies,
    - Incident investigations,
    - Train operation studies,
    - Ride quality evaluations.

Andersen, D. R., G. F. Booth, A. R. Vithani, S. P. Singh, A. Prabhakaran, M. F. Stewart, and S. K. (John) Punwani. Train Energy and Dynamics Simulator (TEDS): A State-of-the-Art Longitudinal Train Dynamics Simulator. 2012.

Literature Review (Cont.)

- <u>Whole-trip Simulators in Literature (Cont.)</u>:
  - Analysis of Train/Track Interaction Forces Simulator (ATTIF) for:
    - Accident investigation,
    - Train configuration evaluation,
    - Assist in the training of train operators.

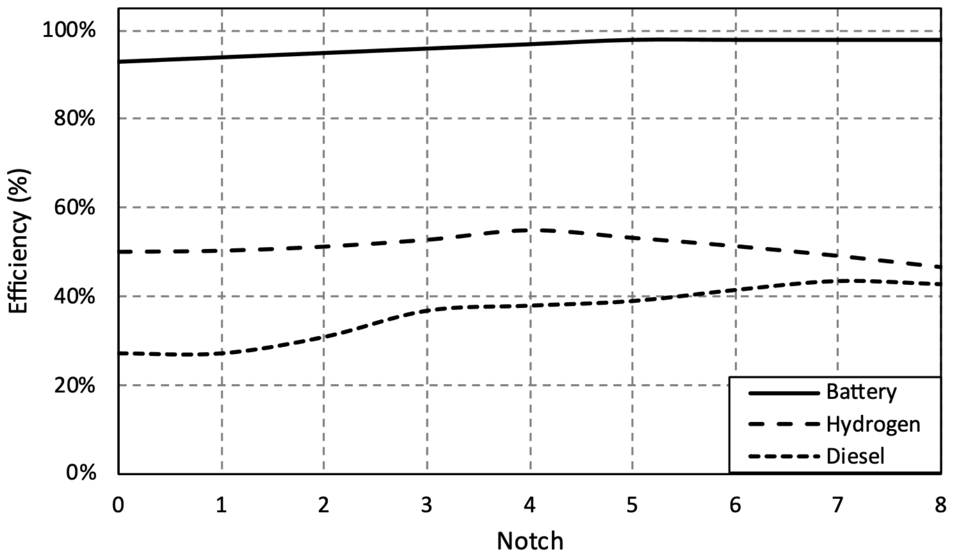
Sanborn, G. G., J. R. Heineman, and A. A. Shabana. A Low Computational Cost Nonlinear Formulation for Multibody Railroad Vehicle Systems. 2007 Proceedings of the ASME, Vol. 5 PART C, 2009, pp. 1847–1856. https://doi.org/10.1115/DETC2007-34522.

Literature Review (Cont.)

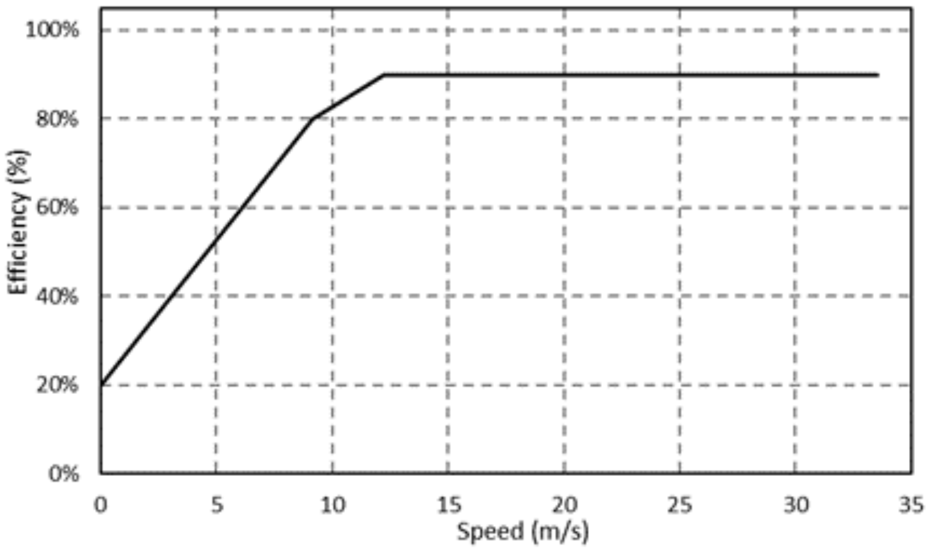
- Whole-trip Simulators in Literature (Cont.):
  - Train Dynamics and Energy Analyzer/train Simulator
  - (TDEAS) for:
    - Longitudinal train dynamics,
    - Energy analyses.

Wu, Q., S. Luo, and C. Cole. Longitudinal Dynamics and Energy Analysis for Heavy Haul Trains. Journal of Modern Transportation, Vol. 22, No. 3, 2014, pp. 127–136. https://doi.org/10.1007/s40534-014-0055-x.

NeTrainSim Model: Energy Consumption



(A) DC Bus to Tank Efficiency by Notch Number



(B) Wheel to DC Bus Efficiency by train Speed

Locomotives drive-line efficiencies by energy source