A Cunning Plan

Integrating Physics-Based Haulage Estimates into Strategic Mine Planning

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Summary

*IMC developed a **first-principles, physics-based** haulage engine that simulates the full cycle, incorporating OEM rimpull and retarder limits, grade and rolling resistance, tiered cornering speeds, and anticipatory braking across a real-world haul network.*

*Validated against more than 100,000 tactical paths with a **near 1:1 time correlation**, the engine produces a block-to-destination cycle-time matrix suitable for strategic schedulers (e.g. Minemax Scheduler). This allows haulage to be modelled as a **primary, non-linear** cost driver.*

*The outcome is a **defensible**, **value-optimised** life-of-mine plan, delivering realistic fleet hours, credible truck sizing, and the ability to rapidly test new routes, speed limits, and technologies such as **BEVs** and **trolley assist**.*

Introduction

*IMC developed a detailed haulage model to provide a **defensible, physics-based** framework for estimating productivity, operating and capital costs for **life-of-mine** planning. A pre-computed block-to-destination cycle-time matrix is passed into Minemax Scheduler, allowing the MILP to choose destinations with haulage treated as a primary, non-linear cost driver*

The objective was to create a transparent, physics-based model that could:

- *Calculate accurate cycle times by explicitly simulating truck performance over a defined haul network.*
- *Provide reliable truck hour forecasts for fleet planning and cost estimation.*
- *Allow for the evaluation of value-based trade-offs in the mine plan, such as optimising waste dump filling sequences.*

A haulage model was developed using Python to allocate a cycle time from each block on a bench to the ramp entry point, up the ramp to the pit crest. Once at the pit crest, the final destination and haul path was chosen using a Mixed Integer Linear Programming model to optimise life-of-mine value.

The components of the haulage cycle as modelled are shown below:

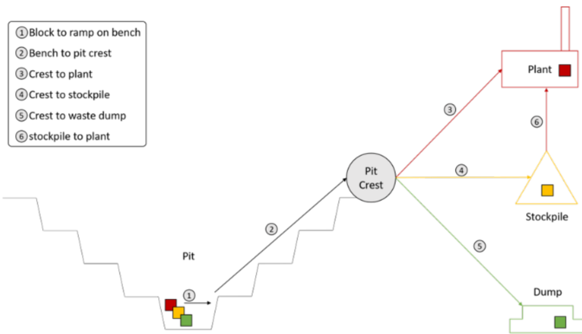

Figure 1 Haulage Network diagram

The applied methodology provides an alignment between long-term strategic and the short-term tactical haulage estimates, addressing a common disconnect between these mine planning horizons.

Truck Physics 101: The Balance of Forces

A haul truck's movement is governed by a tug-of-war between forces that propel it forward and forces that resist its motion. The truck's acceleration is a result of the net balance of these forces, as described by Newton's Second Law (F = ma) where m is the mass of the truck (loaded or empty).
The simulation engine calculates this balance for every segment of the haul road by quantifying two key sets of forces:

1. ***Driving Force (Tractive Effort):*** *This is the force delivered by the engine and drivetrain to the wheels, also known as **rimpull**. It's the power that propels the truck. Tractive effort is not constant; it varies with the truck's speed, a relationship defined by the truck's rimpull curve.*
2. ***Resistive Forces:*** *These are the forces that work against the truck's motion:*
   - ***Grade Resistance:*** *The component of gravity that acts parallel to the road surface. When travelling uphill, it's the force pulling the truck backwards. When travelling downhill, this force reverses and assists motion, pushing the truck forward.*
   - ***Rolling Resistance:*** *The friction between the tyres and the road surface. This force is influenced by factors like road conditions, tyre pressure, and road maintenance.*

When a loaded truck travels uphill, the engine must produce enough tractive effort to overcome both the grade resistance and the rolling resistance (Figure 2).

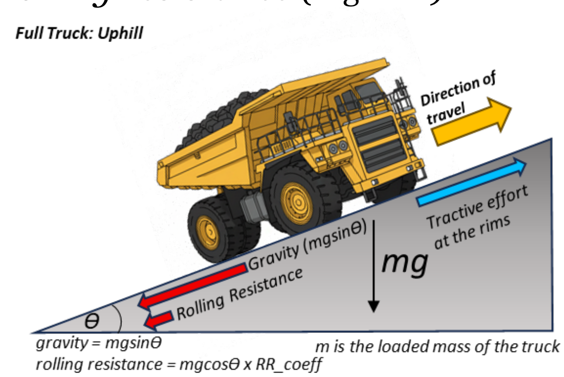

Figure 2: Forces on a loaded truck travelling uphill. The engine's Tractive Effort must overcome the combined Grade Resistance (gravity) and Rolling Resistance to move forward.

*When an empty truck travels downhill, the force of gravity is now pushing it forward. To maintain a safe speed, the truck uses its **dynamic retarder** to create a braking force that counteracts gravity and rolling resistance (*Figure 3*).*

A battery-electric truck would harness this potential energy for regenerative braking, which causes the wheel motors to function as generators, creating a braking force while recapturing energy.

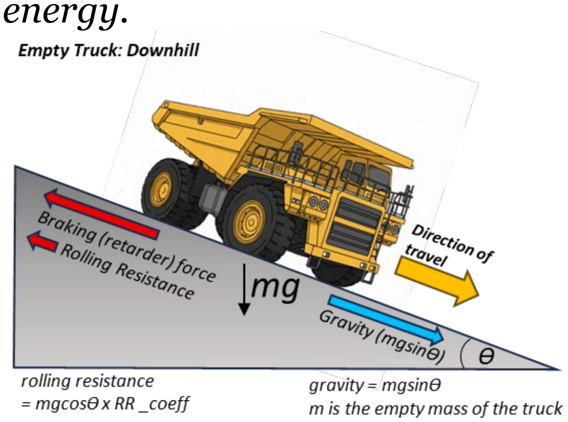

Figure 3: Forces on an empty truck travelling downhill. The Retarding Force works to control the speed, counteracting the push from gravity.

Model Framework and Methodology

*The cycle time model was built on three core components: the **haul route network**, a **truck performance model (physics engine)**, and a system of **dynamic speed limits** that simulates operator behaviour.*

Haul Route Network

The physical layout of the mine is represented by a network of haul routes constructed from individual segments, including all in-pit ramps and surface roads to dumps, stockpiles, and the crusher(s). To ensure a realistic simulation from the loading unit, fixed flat haulage segments with a higher rolling resistance were programmatically added to the start and end of each haul path, simulating the final approach to the shovel, tiphead or crusher.

The Physics Engine

The model is based on a physics engine that calculates truck acceleration, initial speed, final speed, and travel time for each segment based on first principles. Each truck's performance is influenced by its rimpull and retarder curves, empty and loaded vehicle mass.

*For every segment, the simulation calculates the net forces acting on the truck, deriving acceleration from the balance of **tractive effort** (from the rimpull curve) and **resistive forces** (gravity and rolling resistance). This segment-by-segment calculation ensures that cycle times reflect real-world truck behaviour under changing gradients and loads.*

Simulating Operator Behaviour

To model operator behaviour, the simulation incorporates a hierarchy of operational speed limits. The truck's maximum allowable speed is governed by the

<u>lowest applicable speed limit</u>, whether it's a site-wide cap, a temporary ramp restriction, or coming into or out of a sharp corner like a switchback.

*The model also simulates **anticipatory braking**. The simulation "looks ahead" a fixed distance along the haul path for upcoming restrictions. If a slower zone is detected, the model applies a comfortable deceleration rate (0.4m/s²) to begin reducing speed before reaching the speed restricted zone, preventing unrealistic, instantaneous changes in velocity.*

A tiered speed limit system applies increasingly restrictive speed caps based on the sharpness of the turn, enforced over a fixed distance coming into the corner to navigate the switchback safely. Acceleration out of the corner is also moderated by the physics engine (Figure 4).

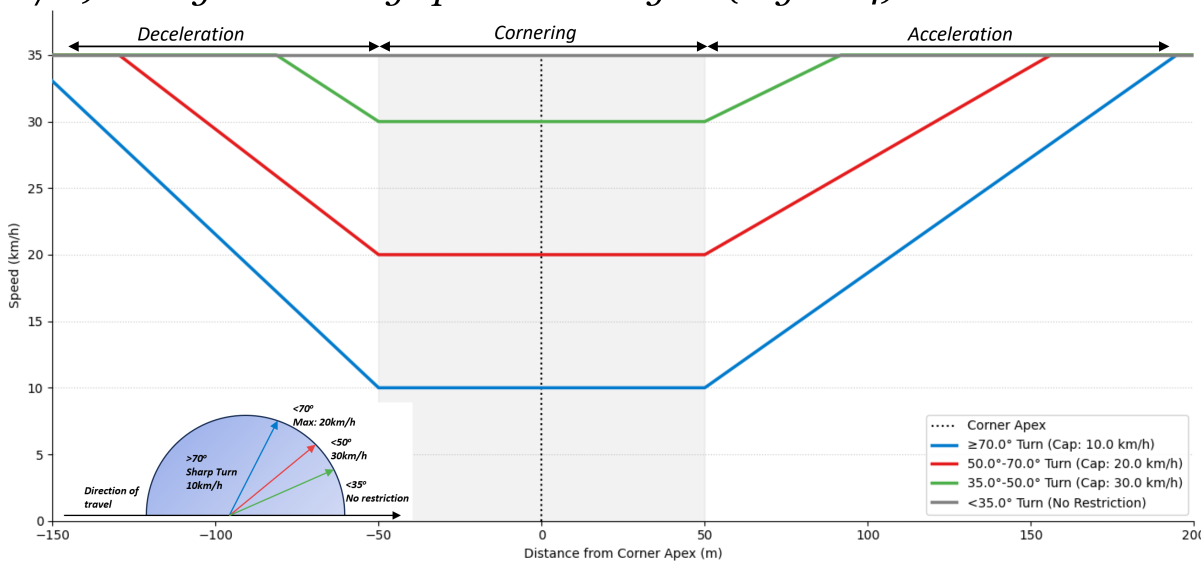

Figure 4 Tiered Cornering Speed Restrictions

Key Parameters and Assumptions

The model was configured with site-specific operational parameters, many of which were aligned with the site's incumbent tactical haulage model and existing fleet management system inputs.

*The truck payload is an important input for truck productivity modelling, which is constrained by either the truck's maximum rated **tonnage** or its volumetric **capacity** (the physical size of the tray). The model accounts for this by calculating the payload based on the density and swell factor of the specific material being hauled. High-density material, such as fresh ore, is often **tonnage-limited**, meaning the truck reaches its maximum weight capacity before the tray is physically full. Conversely, lower-density materials, like some "fluffier" waste rocks, are often*

volume-limited, *filling the tray's volume before the maximum weight is reached, resulting in a lower tonnage payload for that cycle which could translate into a faster cycle time (less mass). Larger trays or hungry boards should be considered if trucks are often volume constrained.*

The model assigns a specific ***rolling resistance*** *to each segment of the haul network, which is an important input for calculating the net force and achievable speed. Rolling resistance varies significantly with the quality of the road surface. Permanent haul roads use* ***2–3 %*** *RR; active benches and dump lifts use* ***4–5 %***. *Each segment is assigned an RR% used directly in the force balance. This enables the modelling of the increased tractive effort required to travel on these surfaces, leading to more realistic speed and fuel burn estimates.*

Example Haul Profile

An example of a typical haulage profile (elevation vs cumulative distance) and truck speed vs distance for a loaded and empty truck is shown in Figure 5. The modelled speed limit and gradient of each haul segment is also illustrated in the figure. The speed limit is often not achieved, especially for full trucks, as the rimpull force is maxed out on loaded uphill hauls. Downhill empty hauls tend to be speed limited by site specific rules to ensure a safe and controllable speed is maintained.

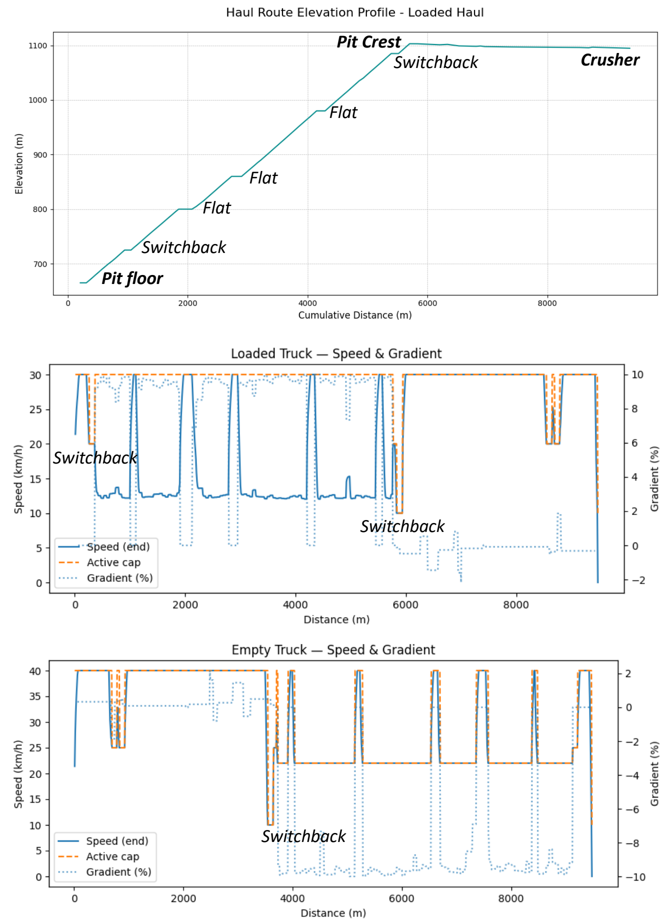

Figure 5 Haulage Profile, Speed Restrictions – Loaded and Empty Truck

Model Validation

To validate its accuracy, the physics-based model was compared against the site's incumbent tactical planning model. Over 100,000 individual haul paths were simulated in both systems. The results showed a very strong correlation, with a near-perfect 1:1 relationship for haul times and a time difference distribution tightly centred around zero. This confirmed that the physics-based model is well-

calibrated and provides a reliable basis for strategic planning.

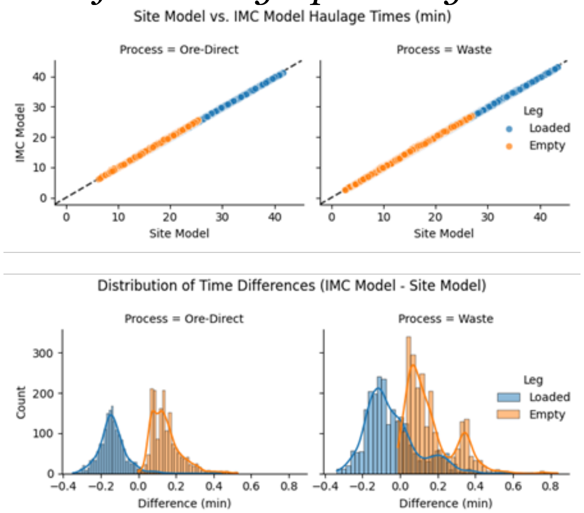

Figure 6 Cycle Time Comparison Plots with Site Tactical Model

Integration with Strategic Scheduling

The primary application of the haulage model is to inform the strategic scheduling process. A matrix of cycle times is pre-calculated for every potential block-to-destination pair in the mine plan. This matrix is then used to populate the scheduling inventory for ***Minemax Scheduler****. The waste cycle time estimate for each block in the block model is shown in the figure below.*

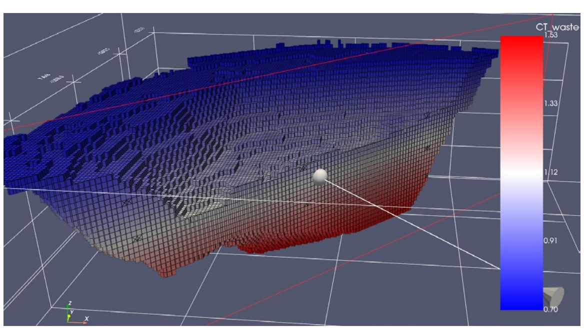

Figure 7 Mining Block Model Flagged with Waste Cycle Time

During schedule optimisation, the algorithm uses the cycle time data to determine the optimal destination for every block of material, balancing mining, processing, and haulage constraints to maximise the overall project NPV. This integrated approach ensures that haulage is represented as both a primary cost driver and an operational bottleneck, providing a defensible basis for fleet sizing, cost forecasting, and value-based dump sequencing decisions.

The scheduled output of truck hours is shown in the figure below. Changing speed limits, fixed cycle time components or using alternative haulage paths can be re-simulated in minutes.

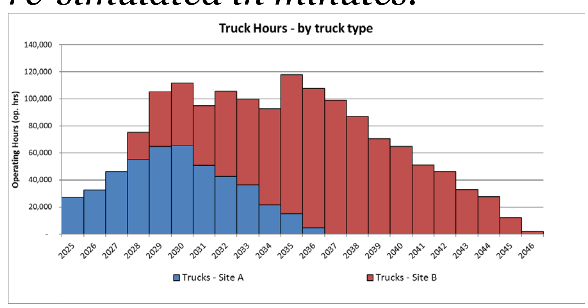

Figure 8 Scheduled Truck Hours

The methodology provides a powerful bridge between long-term strategic goals and short-term tactical achievability, directly addressing a common disconnect in the mine planning process.

Future Applications and Model Extensions

The validated physics engine provides a foundation for assessing a range of operational *and technological scenarios. The framework can be extended to conduct quantitative trade-off studies for key capital decisions. Potential applications include:*

- ***Fleet Technology Analysis:*** *Simulating the performance of alternative fleets, such as Battery Electric Vehicles (BEVs), by substituting their specific rimpull curves and regenerative braking characteristics for direct comparison against conventional diesel (ICE) trucks.*
- ***Trolley Assist Studies:*** *Evaluating the benefits of trolley assist by modifying the available tractive effort on designated haul segments to forecast changes in speed, cycle time, and productivity.*
- ***System-Level Simulation:*** *Integrating the cycle time engine into a Discrete Event Simulation (DES) framework to model dynamic fleet interactions, including queuing at loading/dumping points and traffic congestion across the haul network.*

Conclusion

The implementation of a first-principles, physics-based haulage model strengthens the defensibility of the strategic planning process. By moving away from simplified factors and assumptions and explicitly simulating the physics behind the truck's movement along a haul path, the model provides a more accurate and defensible estimate of one of the mine's most significant cost drivers.

The key outcomes of this approach are:

1. ***Improved Accuracy:*** *Cycle times realistically reflect the non-linear impact of depth, gradient, switchbacks, flats, hauling around pit voids and temporary downhill loaded segments (e.g. ramp de-stacking).*
2. ***Enhanced Mining Fleet Forecasting:*** *Annual and peak truck hour requirements are based on a dynamic simulation, leading to better fleet planning.*
3. ***True Optimisation:*** *By providing a detailed cost and time matrix to the strategic scheduler, the mine plan can be optimised based on a realistic representation of haulage constraints, that consider both the operating and the capital cost of achieving the mine production plan.*

This approach represents a shift from planning based on averages to optimising based on a simulation of reality. By embedding tactical detail into the strategic scheduling framework, the resulting mine plan and truck hour estimate required to achieve the plan is better aligned. This provides stakeholders higher confidence that the estimated value can and will be delivered.