CHALMERS
UNIVERSITY OF TECHNOLOGY

Improvement of Carry-back Problem on Dumper Body

Master's thesis in Mobility Engineering

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DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
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Cover: DEM simulation of a BEV dumper body showing material accumulation in certain areas.

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Abstract

Carry-back in hauler dumper bodies can reduce unloading efficiency and result in material being transported back to the loading area. This thesis investigates potential methods for reducing carry-back, with particular focus on solutions applicable to battery-electric haulers. The work began with an investigation of the carry-back problem and its influencing factors, followed by the development and screening of several solution concepts. Two approaches were selected for further study: a material-based approach involving UHMW-PE liners and geometric modifications, and an energy-based approach involving the heating of selected dumper-body surfaces. The material-based approach was investigated using Discrete Element Method simulations in Altair EDEM, while the energy-based approach was examined through engineering calculations of the required heating energy.

The study considers the influence of surface properties, dumper-body geometry, operating conditions, and energy requirements on carry-back reduction. Field observations from an UHMW-PE liner application were also included to provide practical context for the material-based approach. In addition, the energy-based approach was assessed for different heating scenarios, including the potential use of the traction battery in a battery-electric hauler as the energy source. The findings provide a basis for comparing material-based and energy-based concepts and for identifying requirements for their continued development and validation.

Keywords: Carry-back, articulated hauler, dumper body, battery-electric hauler, UHMW-PE liner, geometric modification, Discrete Element Method, Altair EDEM, thermal analysis.

Preface

This report presents the outcome of my master's thesis project, conducted at the Department of Mechanics and Maritime Sciences at Chalmers University of Technology in collaboration with Volvo Construction Equipment. The project was carried out at Volvo Construction Equipment's facility in Braås during the spring of 2026. The project focused on investigating potential methods for reducing carry-back in articulated hauler dumper bodies, with particular attention to solutions suitable for battery-electric vehicles. The work included a study of the carry-back problem, ideation and screening of several solution concepts, and detailed investigations of material-based and energy-based approaches. The thesis was carried out with technical support from Volvo Construction Equipment. The project was supervised by Yang Shin and Lena Sollenlid at Volvo Construction Equipment and examined by Simone Sebben at the Vehicle Engineering and Autonomous Systems (VEAS) Division at Chalmers University of Technology.

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I would also like to thank Mira Jhala at Volvo Construction Equipment's Braås facility, as well as Erik Magnemark from Siemens who provided technical assistance with the software used throughout the project. Their support was invaluable in carrying out simulations and iterative study to mitigate the carry-back problem.

I would like to express my sincere gratitude to my manager, Per Lagerlöf, and to the entire Structure Department at Volvo Construction Equipment's Braås facility for welcoming me into the team. I greatly appreciate the dedicated workspace, access to the necessary software and resources, and the support provided throughout the project. I am also thankful for the department's kind invitations to internal events, which made my time at Volvo Construction Equipment both enjoyable and enriching.

Saket Sharad Sapre, Gothenburg, August 2026

Declaration on the use of 'Artificial Intelligence'

I hereby declare that the use of generative 'Artificial Intelligence' tools within the scope of this project was limited to improving my understanding of concepts, providing LaTeX suggestions, and assisting with grammar checks and language improvements. The thesis has been reviewed, and I take full responsibility for its contents.

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

A25	Volvo's 25-tonne payload capacity articulated hauler model designation
A30 Electric	Volvo's 29-tonne payload capacity electric articulated hauler model designation
A40 Electric	Volvo's 39-tonne payload capacity electric articulated hauler model designation
A60	Volvo's 55-tonne payload capacity articulated hauler model designation
BEV	Battery Electric Vehicle
CaC	Charge air cooler
DEM	Discrete Element Method
DoD	Depth of Discharge
DOE	Design of Experiments
EEPA	Edinburgh Elasto-Plastic Adhesion
h	Hour
ICE	Internal Combustion Engine
JKR V2	Johnson-Kendall-Roberts Version 2
km	Kilometre
km/h	Kilometres per hour
kW	Kilowatt
kWh	Kilowatt-hour
LHV	Lower Heating Value
min	Minute
P-P	Particle to particle contact surface energy
P-G	Particle to geometry contact surface energy
RPM	Revolutions per minute
SoC	State of Charge
UHMW-PE	Ultra High Molecular Weight Polyethylene

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Indices

$ageing$	Battery ageing
$available$	Power available for dumper body heating
$battery$	Battery-related quantity
c	Channels
CaC	Charge air cooler
$coolant$	Engine-coolant heat loss
cp	Chute plate
cyl	Cylinders
$cycle$	One operating cycle
db	Dumper body
DoD	Depth of discharge
$emitted$	Emitted heat
$engine$	useful engine output
$exhaust$	Exhaust gas related quantity
$fuel$	Fuel related quantity
fw	Front wall
$heat$	Heating-related quantity
$heater$	Heater or heater circuit
i	Index for exhaust power split scenario, S
$loaded$	Loaded travel condition
$loading$	Loading phase
max	Maximum observed value

nominal	Nominal installed energy
normal	Normal operating conditions
operation	Complete vehicle operating period
pb	Post box
pump loss	pumping loss caused by exhaust back pressure
unloading	Unloading phase
usable	Usable energy
utilized	Power actually used for heating the selected dumper body surfaces
reserve	Energy reserve
return	Return travel without load
system	System-related quantity
temperature	Temperature-related effect

Sets

S	Set of exhaust power split scenarios

Parameters

A	Total surface area in contact in m^2
A_{surf}	Surface area of heated dumper body part in m^2
$\rho_{exhaust}$	Density of exhaust gas in kg/m^3
f_{ageing}	Battery-ageing factor
f_{DoD}	Usable depth-of-discharge factor
$f_{reserve}$	Battery-energy reserve factor
$f_{temperature}$	Battery-energy reserve factor
ρ_{fuel}	Density of fuel in kg/l
h	Convective heat transfer coefficient in $W/m^2 \cdot K$
h_{eff}	Effective heat transfer coefficient in $W/m^2 \cdot K$
k	Thermal conductivity of a material in $W/m \cdot K$
k_{bulk}	Thermal conductivity of bulk material in $W/m \cdot K$
k_{surf}	Thermal conductivity of surface material in $W/m \cdot K$
L	Thickness of a material in m
L_{bulk}	Thickness of bulk material layer in m

L_{surf}	Thickness of heated dumper body part in m
LHV_{fuel}	Lower Heat Value of fuel in J/kg
$\dot{m}_{exhaust}$	Mass flow rate of exhaust in kg/s
N	Engine speed in RPM
N_{cyl}	Number of cylinders
$P_{db,required}$	Required heating power for the dumper body in kW
ΔP_{max}	Maximum observed exhaust back pressure in kPa
R	Thermal resistance to heat flow in $m^2 \cdot K/W$
s	Travel distance from the loading site to the unloading site in km
$t_{heat,cycle}$	Heater operating time or energy-demand duration per cycle in h
$t_{loading}$	Bulk-material loading time in min or h
$t_{operation}$	Vehicle operating time available with one full battery charge in min or h
$t_{unloading}$	Bulk-material unloading time in min or h
$\dot{V}_{fuel}$	Volumetric flow rate of fuel in l/h
v_{loaded}	Vehicle speed during loaded travel in km/h
v_{return}	Vehicle speed during loaded travel in km/h
η_{system}	Heater-system efficiency

Variables

$E_{battery,nominal}$	in Installed nominal battery energy required after applying derating and reserve factors kWh
$E_{battery,usable}$	Usable battery energy that must be delivered to the heater circuit in kWh
$E_{heater,operation}$	Total energy required by the heater during the vehicle operating period in kWh
$\dot{m}_{fuel}$	Mass flow rate of fuel in kg/s
N_{cycle}	Number of operating cycles possible with one full charge
P	Power required for heat transfer in kW
P_c	Power requirement for heating channels region of dumper body in W
P_{cp}	Power requirement for heating chute plate region of dumper body in W
$P_{coolant}$	Heat loss associated with the engine coolant in kW
P_{CaC}	Charge air cooler heat loss in kW

$P_{db,available,Si}$	Exhaust power available for dumper-body heating in kW
$P_{db,utilized}$	Total power utilized to maintain the average temperature of selected dumper body surfaces in kW
$P_{emitted}$	Emitted heat loss in kW
P_{engine}	Useful engine power in kW
$P_{engine,normal}$	Useful engine power under normal load conditions in kW
$P_{exhaust}$	Power carried by the exhaust gases in kW
$P_{exhaust,normal}$	Power carried by the exhaust gases under normal load conditions in kW
P_{fuel}	Total chemical fuel power supplied to the engine through combustion in kW
$P_{fuel,normal}$	Total fuel power under normal-load conditions in kW
P_{fw}	Power requirement for heating front wall region of dumper body in W
P_{pb}	Power requirement for heating post box region of dumper body in W
$P_{pump\ loss}$	Engine-power loss caused by exhaust-system back pressure in kW
$\dot{Q}$	Rate of heat transfer in W
q''	Heat flux in W/m^2
T	Temperature in in K
T_{bulk}	Bulk material temperature in K
T_{surf}	Surface temperature in K
ΔT	Temperature difference in K
∇T	Temperature gradient factor
t_{cycle}	Total duration of one operating cycle in min or h
t_{loaded}	Travel time from the loading site to the unloading site with a load in min or h
t_{return}	Return-travel time from the unloading site to the loading site min or h
$V_{exhaust}$	Volumetric flow rate of exhaust gas in m^3/s

Mathematical operators

∇	Nabla operator
$(\dot{\ })$	Newton dot notation
Δ	Uppercase delta operator

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1
Introduction

The introduction provides the contextual framework for the thesis and outlines the research problem addressed in the study. It explains the significance of the topic, outlines the objectives of the study, and defines the scope of the investigation.

1.1 Background

A dumper truck is a heavy vehicle used to transport bulk materials such as soil, sand, gravel, rock, or waste from one location to another. These vehicles are commonly used in construction, quarrying, mining, and other earth-moving activities where large amounts of material need to be moved efficiently, often on unpaved ground. In articulated haulers, the front and rear sections are connected by a joint, which improves steering and mobility on difficult terrain and makes the machine suitable for demanding off-road applications. Volvo Construction Equipment is one of the leading producers of articulated haulers, offering a wide range of payload capacities from 25 tonnes in the A25 model to 55 tonnes in the A60 articulated hauler.

Carry-back refers to bulk material sticking to the dumper body surfaces during unloading and being carried back to the loading location. It is a common problem when transporting adhesive materials such as soil and clay. Carry-back builds up over repeated unloading cycles and results in loss of productivity and energy. In ICE-powered machines, this issue is addressed by applying heat to the dumper body surfaces. The heat is generated by circulating exhaust gases underneath the dumper body, which helps loosen the adhesion bonds between the bulk material and the dumper body surfaces. Over the years, Volvo has improved articulated hauler technology toward a more sustainable future with its latest battery-electric haulers, the A30 Electric and A40 Electric. Since electric haulers do not produce waste heat, there is a clear need for a separate system to replace the existing solution.

1.2 Aim and Objectives

The carry-back problem has previously been addressed through geometric improvements in dumper body design, and these measures were proven effective in ICE haulers. However, in BEV haulers, geometric optimization alone has not been sufficient to eliminate carry-back in the dumper body. The aim of this thesis is therefore to identify the carry-back areas on an improved dumper body geometry through real-life observations, reproduce these conditions in a simulation environment, and investigate the feasibility of promising solution concepts for carry-back reduction. To achieve this aim, the research addresses the following objectives:

- To develop a correlation between dumper body simulations and real-world carry-back behavior by recreating a reference carry-back scenario observed in the field.
- To select two solution concepts for detailed investigation based on their potential to reduce carry-back in the identified critical areas.
- To evaluate the first solution concept in a simulation environment through a parametric study of material properties.
- To estimate the energy requirement for heating the dumper body by developing a calculation model based on ICE hauler's dumper body heating technique and applying it to the BEV machine.

1.3 Scope and Limitations

The scope of this thesis is limited to the investigation of carry-back in dumper bodies under representative operating conditions, using a combination of simulation and analytical work. The study builds on an existing DEM simulation framework and uses available field observations, client feedback, and in-house test data to define a reference carry-back scenario. Where direct data are unavailable, reasonable engineering assumptions are made to support the modelling work. Within this scope, the study is subject to the following limitations:

- The analysis focuses on two contrasting carry-back scenarios and therefore the results do not cover all possible material and operating conditions.
- The detailed investigation is limited to two solution concepts selected for further study. Other possible solutions are not examined in detail.
- The work is based on numerical simulations and analytical calculations rather than full-scale physical validation, so the quantitative accuracy of the predicted carry-back reduction depends on the fidelity of the models and the assumptions used.
- The quality and completeness of the results depend on the available field observations, client feedback, in-house testing data, and the engineering assumptions adopted in the simulation and calculation models.

2
Theory

This chapter provides information on articulated haulers and the carry-back problem, which is necessary for understanding the context of the work. It also introduces the Discrete Element Method and the EDEM contact models used to represent particle interaction in the simulation. Together, these concepts frame the simulation approach applied in this thesis for dumper body unloading and carry-back analysis.

2.1 Articulated Haulers

Articulated haulers are off-road transport machines developed for efficient material movement in demanding environments such as quarrying, mining, and construction. Their articulated steering concept, all-terrain capability, and robust drivetrain make them well suited for operations where traction, maneuverability, and productivity must be maintained on uneven ground. Volvo has a long history in this product segment and is widely recognized as the originator of the articulated hauler concept, having introduced the first model in 1966. Today, Volvo's articulated haulers are designed to deliver high productivity, operator comfort, durability, and off-road performance across a wide range of hauling applications (Figure 2.1).

Figure 2.1: J-Series articulated-hauler lineup, adapted from [1].

2.1.1 A40 Electric

The Volvo A40 Electric is a battery-electric articulated hauler in Volvo CE's electric machine portfolio and is one of the company's largest electric hauling machine to date (Figure 2.2). The model entered serial production together with the A30 Electric, marking Volvo CE's launch of electric articulated haulers in this size class. The

A40 BEV has a payload capacity of 39 tonnes and is powered by a 350 kW electric driveline. In the present study, the A40 BEV is used as the reference machine for simulation and analysis.[2]

Figure 2.2: A40 Electric Articulated Hauler, adapted from [3].

2.2 Carry-back

Carry-back refers to the bulk material that remains in the dumper body after unloading and is carried back to the loading location. Instead of leaving the body completely during tipping, part of the payload adheres to the internal surfaces and gradually accumulates over repeated loading cycles. Although this issue may be less concerning to those outside the hauling industry, it is well recognized by customers and manufacturers, since it reduces payload capacity and overall transport efficiency.

Carry-back behavior can vary considerably between different sites and operating conditions because it is influenced by several interacting factors, including the material's properties, moisture content, temperature, particle-size distribution, cohesiveness, degree of compaction, loading method, payload distribution, tipping angle, unloading duration, and the geometry and surface condition of the dumper body. Features such as sharp corners, geometric transitions, uneven surfaces, and worn areas may create locations where material accumulates and remains attached during unloading. These factors differ from one site to another, therefore the distribution of carry-back is difficult to predict consistently. Figure 2.3 shows a collection of carry-back examples observed at different sites.

Figure 2.3: Examples of carry-back on dumper bodies from multiple sites.

2.2.1 Causes

Carry-back occurs through the combined influence of material properties, operating conditions, and dumper body geometry. Materials with high cohesion or adhesion, such as wet clay, are more likely to adhere to the body surface. This tendency becomes more pronounced when the moisture content is high or temperatures are low, as the material adheres to the steel surface or freeze during transport and unloading. The geometry of the dumper body also strongly influences carry-back because it determines how the material flows during tipping. Sharp corners, abrupt transitions, front-end regions, side-wall intersections, and ramp areas disrupt the flow and create local retention zones where the payload does not discharge completely.

2.2.2 Countermeasures

Carry-back has been addressed in several ways across the hauling industry with manufacturers adopting solutions that either optimize dumper body geometry to improve material flow or introduce additional mechanisms such as heating, chemical treatments, vibration systems, load ejectors and suspended dumper body concepts to reduce adhesion. Over the years, Volvo has also investigated several non-geometrical approaches over the years, but these have not produced a fully satisfactory outcome. At present, the company relies primarily on heating the dumper bed by circulating exhaust-gas and improving dumper body geometry.

2.2.2.1 Exhaust gas heating

Exhaust-gas heating is one of the established countermeasures used to reduce carry-back in internal combustion engine haulers and dump trucks, particularly in cold operating conditions. In this approach, engine exhaust is redirected through the dumper body so that heat is transferred to the surfaces where material would usually stick or freeze. The system reduces adhesion by raising the body temperature, and improves the release of moist or frozen material during unloading. This method addresses carry-back by changing the surface conditions inside the dumper body rather than the geometry of the body itself. It has therefore become a practical traditional solution in ICE-based applications, where waste heat from the engine can be used to support cleaner discharge. However, with increasingly stringent emission requirements, modern engines have become more dependent on advanced after-treatment systems and controlled exhaust strategies, which has made the use of exhaust heat for body warming less effective than in earlier vehicle generations.

2.2.2.2 Dumper body geometry improvement

Another established countermeasure is to modify the geometry of the dumper body so that the payload can discharge more effectively during tipping. Since carry-back often develops in regions where the material flow is interrupted, geometrical changes are intended to reduce sharp corners, abrupt transitions, and local retention zones that prevent complete unloading. However, geometry development is not a straightforward process as the design must balance carry-back reduction with practicality and production feasibility. Previous thesis work addressed this by proposing a modified dumper body in which sharp angles were eased by adding plates at selected locations and inclinations (Figure 2.4). The plate angles were determined through iterative simulation studies to improve material flow while keeping the design feasible for production. This work resulted in a carry-back-friendly dumper body geometry variant that was later adopted for BEV applications.[4]

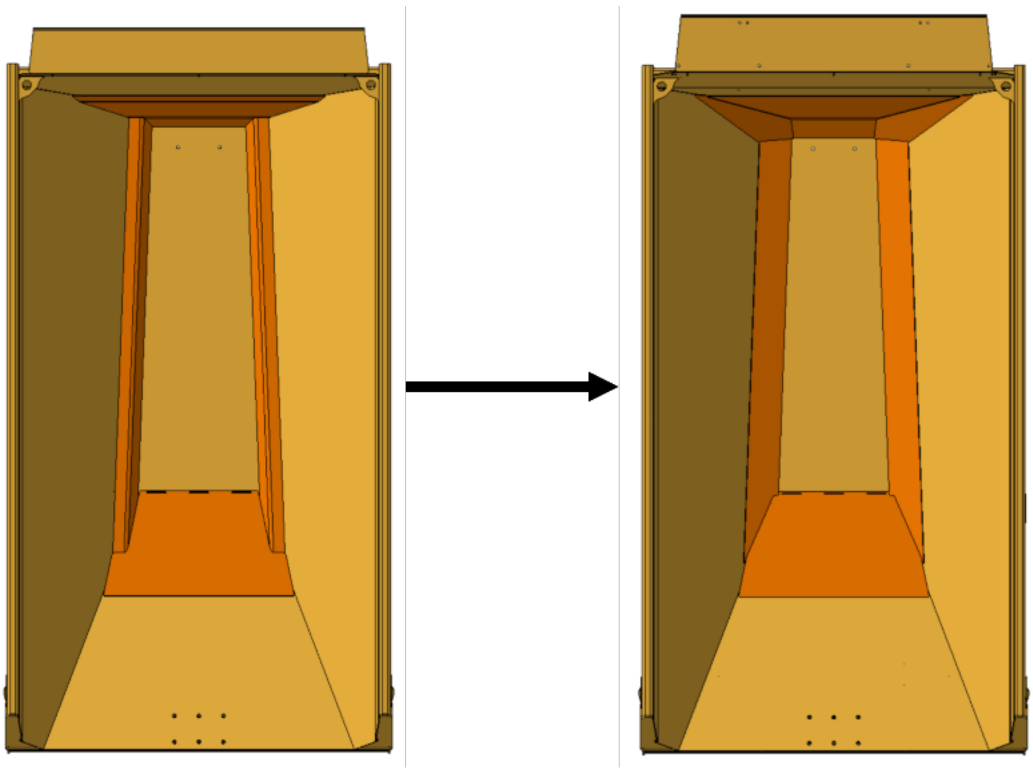


Figure 2.4: Geometrical improvement of dumper body [4].

Practical testing showed that carry-back was significantly reduced compared with the original design, although residual material still remained in some key areas of the body. These remaining regions of material retention form an important basis for further investigation.

2.3 Simulation method

A part of this study is based on Discrete Element Method simulations and uses Altair EDEM and Altair HyperStudy as the main software tools for the analysis. EDEM is used to model and simulate bulk material behavior and its interaction with dumper body surfaces, while HyperStudy is used to support parameter studies and the evaluation of design variations. Together, these tools make it possible to investigate carry-back behavior in a controlled virtual environment and to compare different alternatives efficiently. Following Siemens' acquisition of Altair, these products are now known as Simcenter EDEM and Simcenter Hyperstudy and form part of the Siemens Xcelerator portfolio.[5] The study builds on the final simulation model developed in a previous thesis project, which is used here as the starting point for the present work.[4]

2.3.1 Discrete Element Method

Discrete Element Method, DEM, is a numerical approach used to simulate the behavior of bulk and granular materials by tracking the motion of separate particles. In each time step, contacts are detected and the forces acting at those contacts are evaluated, after which the particle positions and velocities are updated. In the context of a dumper body simulation, this makes it possible to study how the material moves, accumulates, detaches, or remains on the body surface as unloading progresses.

2.3.2 Contact behavior in EDEM

In EDEM, the material response is governed by contact models, which describe how elements behave when they come into contact with each other. Altair describes base contact models as the part of the physics definition that governs the physical collision between particles or between particles and geometry, typically through spring and damping forces in the normal and tangential directions. In the present simulation framework, the contact behavior is based on the EEPA and Hertz Mindlin with JKR V2 formulations, which provide the constitutive description of adhesion, deformation, and separation relevant to the unloading process.[6]

2.3.2.1 Edinburgh Elasto-Plastic Adhesion

Edinburgh Elasto-Plastic Adhesion, or EEPA, is defined as a contact model that captures the history dependence and the key characteristic behavior of cohesive solids. The physics model comprises of a nonlinear hysteretic spring formulation to account for elastic-plastic contact deformation together with an adhesive force component that depends on the plastic contact deformation. This means that the contact response depends not only on the current state of contact but also on the loading history, which is relevant for cohesive bulk materials subjected to repeated compression and release during unloading.[6]

2.3.2.2 Hertz Mindlin with JKR V2

Hertz Mindlin with JKR Version 2 is defined as a model that captures the behavior of multiple materials and uses a more accurate implementation of JKR theory. The model calculates the additional work required to break the contact after physical detachment of particles, making it suitable for elastic and adhesive systems and particularly relevant for contacts involving very small particles. In practical terms, this formulation is used to represent adhesive elastic contact and the force required for separation once contact has been established.[6]

2.3.3 Parametric study

HyperStudy was used to organise and automate the parametric studies carried out with the EDEM model. Rather than manually changing the input parameters and running each simulation separately, the selected variables were defined in HyperStudy and linked to the corresponding EDEM model inputs. This made it possible to generate a set of design variants in a structured manner and to run the associated simulations as part of the same study.

A Design of Experiments (DOE) approach was used to investigate how changes in the selected parameters affected the carry-back response. For each parameter variation, HyperStudy created the input configuration, managed the simulation run, and collected the relevant output values in terms of total mass of bulk material from EDEM. The results could then be compared across all evaluated cases, making it easier to identify parameter combinations that reduced carry-back. Adopting this workflow avoided repetitive manual model preparation and provided a clearer overview of the relationship between the design parameters and the simulation response. HyperStudy supports automated design exploration through DOE methods, automated execution of simulation workflows, and result extraction for subsequent evaluation.[7]

2.4 Liners

Liners are a common design feature in dump bodies and other bulk-material handling systems because they protect the structural surface from abrasion and impact while also supporting cleaner unloading of the carried material. In general, the liner concept is used where repeated contact with rock, ore, gravel, clay, or other difficult bulk materials would otherwise increase wear and make discharge less efficient. Patent literature confirms that lined dump truck and quarry truck bodies are already an established engineering solution. A patent for a quarry dump truck body describes internal lining elements on the front wall and sidewalls for protection against abrasive loading, showing that the use of liners in haul-body design is not a new concept but a recognized structural approach for heavy-duty material transport.[8]

2.4.1 Ultra High Molecular Weight Polyethylene

Ultra High Molecular Weight Polyethylene (UHMW-PE) is an engineering polymer with a history of industrial use in wear- and sliding-contact applications. The material is characterised by chemical inertness, lubricity, impact resistance, and abrasion resistance. UHMW-PE has been used in industrial applications since the 1950s, including linings for coal chutes and dump trucks.[9]

These characteristics make UHMW-PE a relevant candidate material for lining selected internal surfaces of a dumper body. Compared with an unlined steel surface, the liner is expected to modify the material-body interface and to protect the underlying structure from abrasive contact. However, the effect on carry-back depends on the transported material, local body geometry, environmental conditions, and liner installation. Based on material-property data obtained from suppliers, this study examines the potential of UHMW-PE as a liner material for dumper bodies and its influence on carry-back behavior.

3

Methodology

This chapter describes the overall approach followed to investigate carry-back reduction concepts. It begins by outlining the workflow of the study, from understanding the carry-back problem and identifying possible solution concepts to selecting the approaches for detailed investigation.

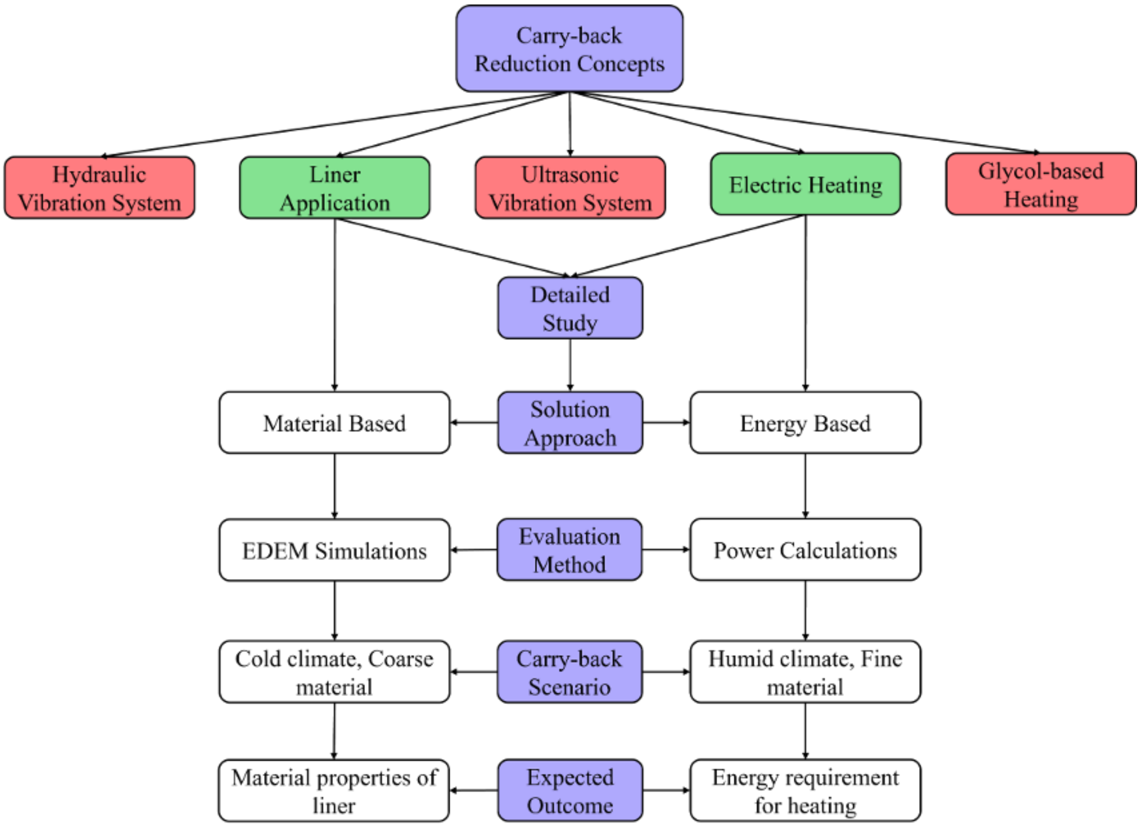


Figure 3.1: Overview of methodology adopted for the study.

3.1 Carry-back reduction concepts

Following the initial study of the carry-back problem, five potential methods were identified for reducing material retention in the dumper body. As shown in Figure 3.1, these methods were hydraulic vibration, liner application, ultrasonic vibration, electric heating, and glycol-based heating.

- **Hydraulic vibration system:**
  A dedicated hydraulic unit generating vibrations in the dumper body during unloading to help release retained material. The system includes additional components such as actuators, hydraulic lines, a reservoir, and an electrical power supply.

- **Liner application:**
  A low-friction liner is applied to areas where carry-back commonly occurs. By reducing friction and adhesion between the material and the dumper body, the liner supports smoother material discharge.

- **Ultrasonic Vibration system:**
  Ultrasonic transducers generate high-frequency vibrations at selected locations on the dumper body. The aim was to influence the material locally without vibrating the complete body.

- **Electric heating:**
  Resistive or inductive heating warms selected dumper-body surfaces to reduce material adhesion. This approach is particularly relevant for BEV haulers, where exhaust heat is unavailable.

- **Glycol-based heating:**
  A water–propylene glycol mixture circulates through heating channels to warm selected surfaces. The system uses waste heat in internal-combustion-engine haulers but requires a separate heat source in BEV vehicles.

3.2 Selection for detailed study

The concepts were screened based on their expected effect on carry-back, suitability for the dumper-body environment, and integration requirements. Hydraulic vibration was not selected because previous tests produced unsatisfactory results, while the required vibration levels could affect driver comfort and would require bulky hydraulic equipment. Ultrasonic vibration was not taken further because its application in dumper bodies is not well established and the transducers would need to withstand a demanding operating environment. Glycol-based heating was excluded due to the additional pumps, piping, leakage concerns, and the need for a separate heat source in a BEV hauler. Liner application and electric heating, highlighted in green in Figure 3.1, were selected for detailed study because both concepts were considered more practical to integrate and better aligned with current and future hauler development. Liner systems are already used in comparable bulk-material applications, while electric heating offers a potential alternative to exhaust-based heating for BEV haulers.

The following chapters present the detailed investigation of the selected material-based and energy-based approaches.

4

Material-based Approach

This chapter investigates a material-based approach to reduce carry-back through simulation-based evaluation of Ultra-High-Molecular-Weight Polyethylene (UHMW-PE) as a liner material for dumper bodies.

4.1 Simulation setup

The simulation setup describes the process used to develop the simulation model. It defines the geometry, material representation, and motion conditions that were combined to recreate the unloading process under controlled simulation conditions. Although the simulated particle size and run time sequence does not correspond exactly to real operating times, they are calibrated to reproduce unloading behavior that is consistent with field observations.

4.1.1 Geometry and loading condition

The geometry used in the simulations was based on the A40 BEV dumper body geometry. A particle factory was placed above the body to reproduce the loading phase, introducing bulk material in a controlled manner corresponding to wheel loader filling (Figure 4.1). The generated bulk material was allowed to accumulate in the dumper body before the unloading motion began. For all A40 BEV cases, the material quantity was kept consistent with the previous work.

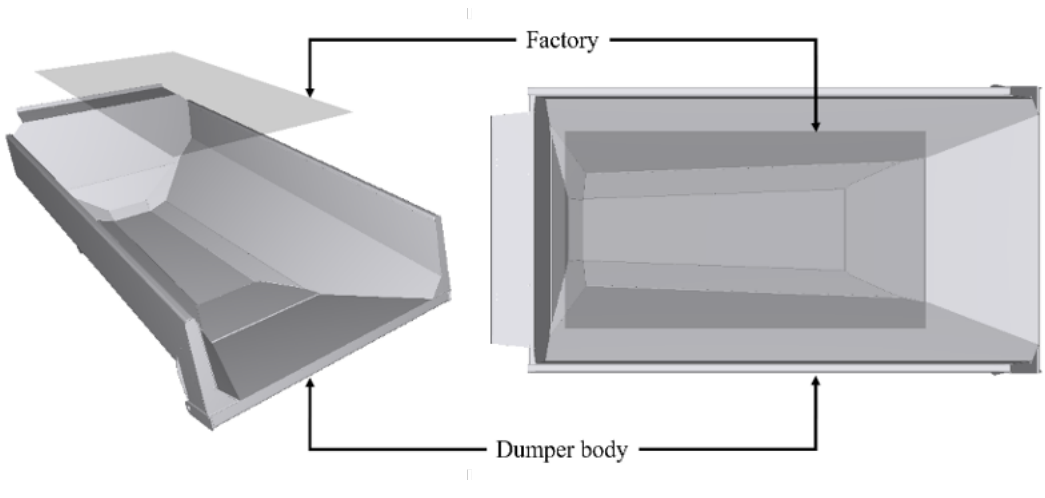


Figure 4.1: Dumper body and factory setup in EDEM.

4.1.2 Motion sequence

The motion sequence was set up as a time-dependent unloading cycle (Figure 4.2). After the bulk material had been introduced and given some time to settle, a sinusoidal vibration motion was applied to the dumper body to represent transport conditions and allow the material to rearrange before tipping. The body was then tilted gradually until the maximum tipping angle of the real machine was reached. It stayed in this position for a short period before the return motion was applied to bring it back to its original position. Most of the motion settings were kept from the previous work, but return motions were added in the present study so that the dumper body could be brought back after unloading and a cyclic effect could also be studied to examine whether material build-up develops over repeated cycles. The complete simulation time for a cycle was set to 50 seconds, which is 15 seconds longer than in the previous work. The residual mass was measured after the simulation using a mass sensor defined by the dimensions and position of the selected region. Depending on the case, the sensor covered either the full dumper body or a specified portion of it.

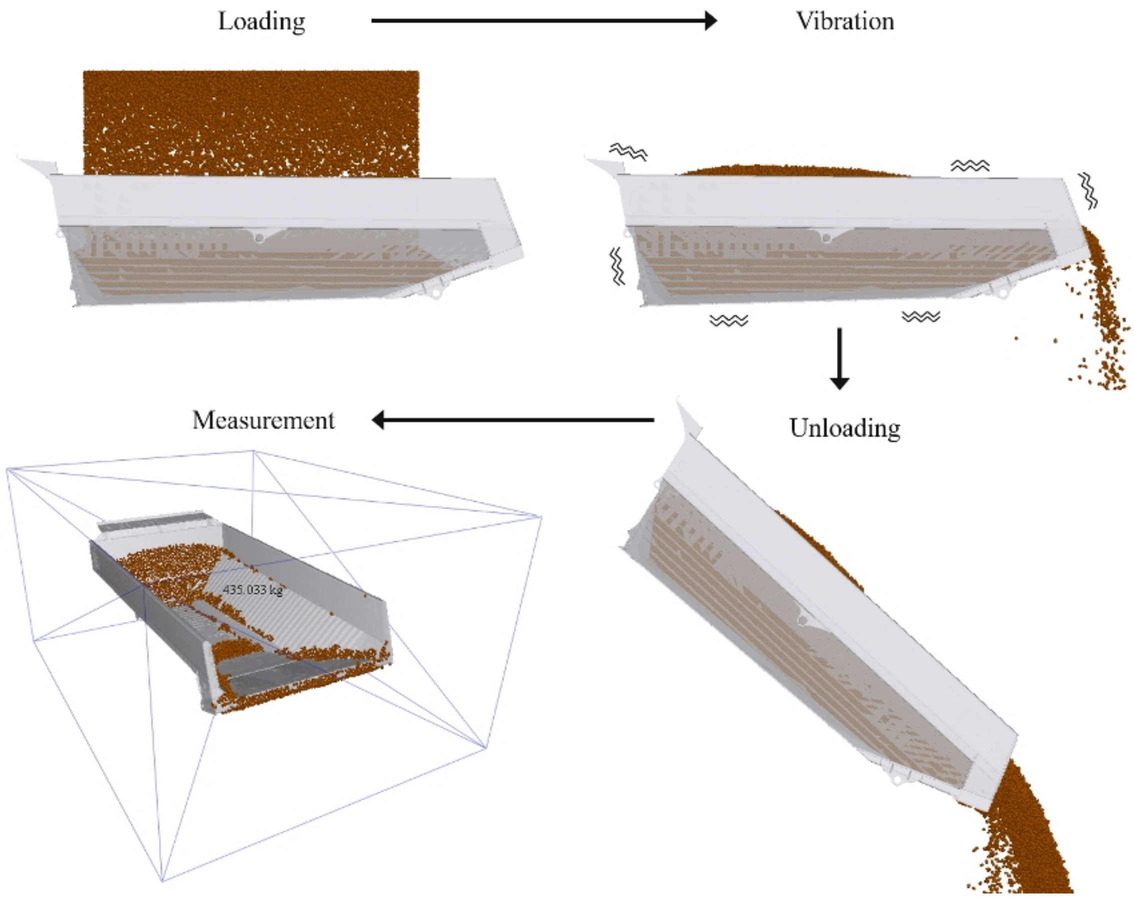


Figure 4.2: Dumper body simulation sequence in EDEM.

4.2 Correlation to reality

The need to correlate simulation results with field observations arose from the final simulation model developed in the previous thesis project. In EDEM, material adhesion is governed by the surface energy assigned to particle-particle (P-P) and particle-geometry (P-G) contacts. The corresponding values used previously, 89.18 J/m^2 and 166.74 J/m^2, were adopted as initial references in this study. However, the earlier model represented a different carry-back scenario, involving humid conditions and fine, sticky bulk material, whereas the present BEV dumper body observations were made under dry conditions with a coarser mixture of clay, debris, and aggregates. As these factors influence adhesive behavior, the previous surface energy values could not be applied directly to the present case.

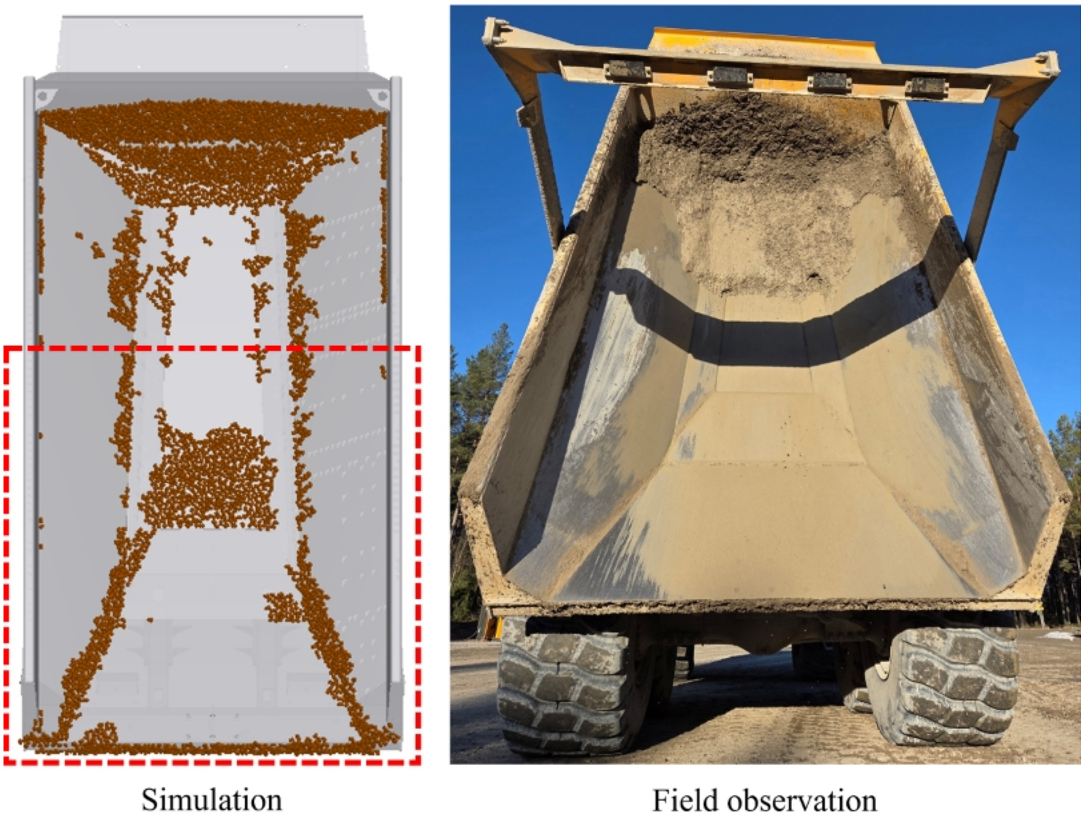


Figure 4.3: Carry-back pattern comparison from the previous simulation study and the field observation, surface-energy values based on [4].

As shown in Figure 4.3, the previous simulation study did not reproduce the retained material pattern observed at the end of unloading in the field. Therefore, a new correlation case was established for the present scenario.

4.2.1 Surface energy calibration

The surface energy calibration was done in two steps using design of experiments (DOE) in HyperStudy. In the first DOE, both particle-particle (P-P) and particle-geometry (P-G) surface energy values were varied over a defined range over eight simulation runs, (Table 4.1) to identify which surface energy parameter had the stronger influence on the rear-end carry-back response.

Table 4.1: DOE 1 parameter matrix and corresponding carry-back response

Iteration	P-P SE (J/m^2)	P-G SE (J/m^2)	M_{total} (kg)	M_{rear} (kg)
1	89.3	147	407.08	134.57
2	93.1	159	496.82	190.26
3	96.9	141	380.09	116.02
4	100.7	153	461.64	170.18
5	86.26	161.4	496.39	191.44
6	96.1	140	373.32	114.96
7	96.7	143	395.66	126.09
8	97.3	139	385.58	122.25

DOE 1 results were plotted in two graphs, P-G versus carry-back in the rear end and P-P versus carry-back in the rear end (Figure 4.4). The plots showed that P-G had the stronger influence on the rear-end carry-back than P-P. Based on the distribution of the low-carry-back cases, the P-P value was therefore fixed at 96 J/m^2 for the second step.

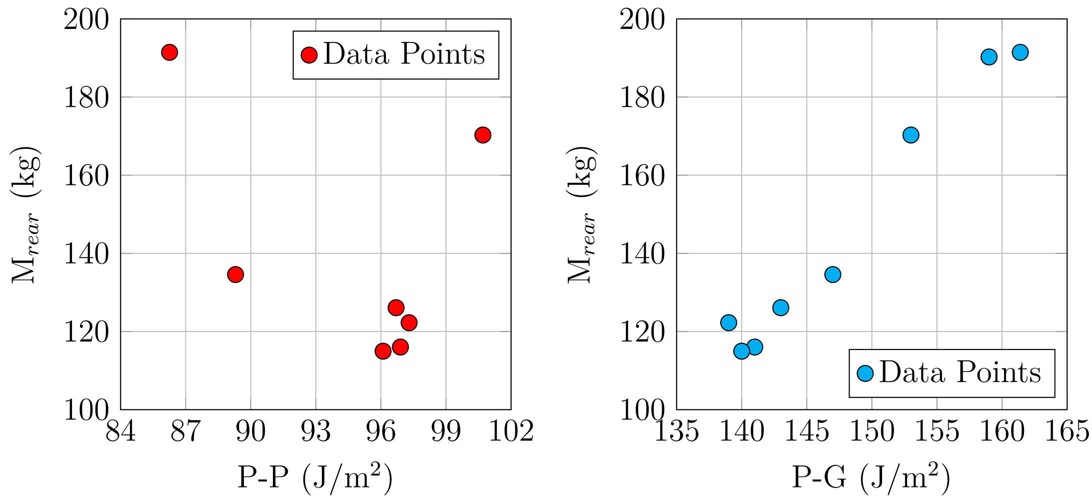


Figure 4.4: Surface energy plots from DOE 1.

For second DOE, the P-G value was varied in a narrower range around the region where the lowest carry-back had been observed. This DOE consisted of twelve simulation runs (Table 4.2). The resulting carry-back pattern was again evaluated visually at the end of each run, since the aim was not only to reduce carry-back but specifically to remove it from the rear end in order to match the observed scenario. The final surface energy value for P-G in the cold-climate baseline scenario was set to 124.5 J/m^2. The resulting carry-back behavior obtained with the finalized surface energy values is shown in Figure 4.5.

Table 4.2: DOE 2 parameter matrix and corresponding carry-back response

Iteration	P-P SE (J/m^2)	P-G SE (J/m^2)	M_{total} (kg)	M_{rear} (kg)
1	96	141.5	391.15	123.47
2	96	139.75	377.63	123.84
3	96	143.25	384.27	119.22
4	96	138.87	371.91	115.14
5	96	134	347.15	96.93
6	96	132	314.73	68.85
7	96	136	341.14	89.09
8	96	131	312.59	74.9
9	96	129	311.22	70.44
10	96	124.5	273.42	41.7
11	96	133	332.41	87.47
12	96	122	266.48	41.74

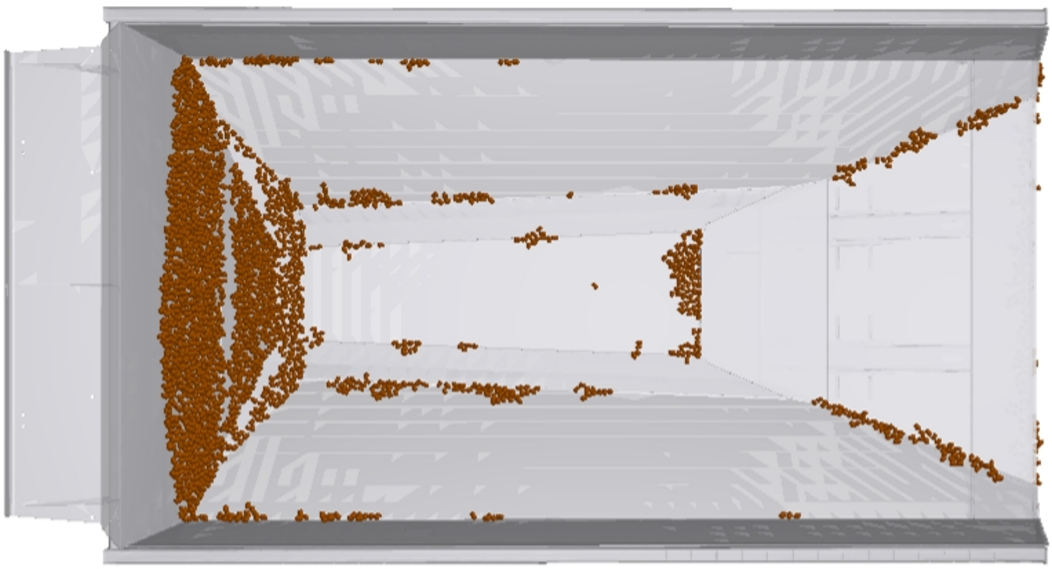


Figure 4.5: Carry-back pattern observed with calibrated surface energy values.

4.2.2 Load cycle test

A cyclic loading test was simulated in EDEM using the calibrated surface energy values from the baseline simulation. The purpose of this simulation was to evaluate carry-back behavior under repeated loading and unloading cycles, representative of real operating conditions. Figure 4.6 illustrates the carry-back pattern observed at the end of each loading and unloading cycle. Overall, the pattern and weight of accumulated material remains largely consistent, with deposition occurring in the same regions and only minor variations between cycles.

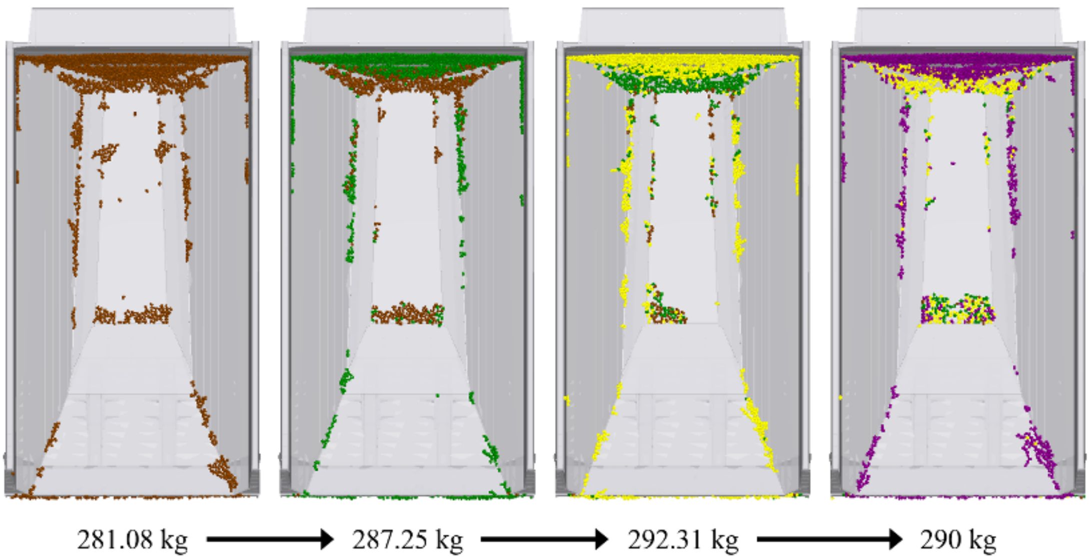


Figure 4.6: Carry-back pattern and weight with cyclic loading and unloading.

A notable observation was that, at the end of each successive cycle, the bulk material appeared to replace the layer adhered to the dumper body surfaces during the previous cycle. Both the visual observations and the measured mass of deposited material indicate the same phenomenon: the newly deposited material tends to displace or remove the previously adhered first layer during unloading. A similar behavior has also been observed in field conditions, where freshly deposited material often carries away part of the existing adhered layer during discharge.

This test provided important insight into the direction of the study, suggesting that efforts should focus on preventing the formation of the initial deposited layer, thereby reducing subsequent build-up during continuous operation.

4.3 UHMW-PE application

The baseline calibration and field observations consistently showed that bulk material accumulation was concentrated in the front region of the dumper body. Based on this finding, UHMW-PE properties were applied in the simulation only to these specific regions. This localized approach was considered more practical than lining the entire dumper body, since UHMW-PE is a low-friction material with relatively high cost. Restricting its application to the most critical areas therefore provided a suitable balance between material usage and potential improvement in carry-back performance.

In EDEM, the definition of a new equipment material requires a set of input properties governing its contact behaviour. For UHMW-PE, the available supplier data were combined with literature-reported ranges for the unknown parameters. Since some of these properties may vary across UHMW-PE grades and manufacturers, the unknown parameters were not assigned single calibrated values. Instead, a design of experiments (DOE) was performed by varying the unknown parameters within their respective literature-based ranges, while keeping the known material properties constant. The complete set of known properties and unknown parameter ranges used for the UHMW-PE definition is presented in Table 4.3.

Table 4.3: UHMW-PE material properties

Parameter	**Value**	**Unit**
Poisson's Ratio	0.35	-
Solid Density	940	kg/m^3
Tensile Modulus	575	MPa
Coefficient of Static Friction	0.1	-
Coefficient of Restitution	0.2 - 0.4	-
Coefficient of Rolling Friction	0.05 - 0.1	-
Interfacial Surface Energy	0.031 - 0.036	J/m^2

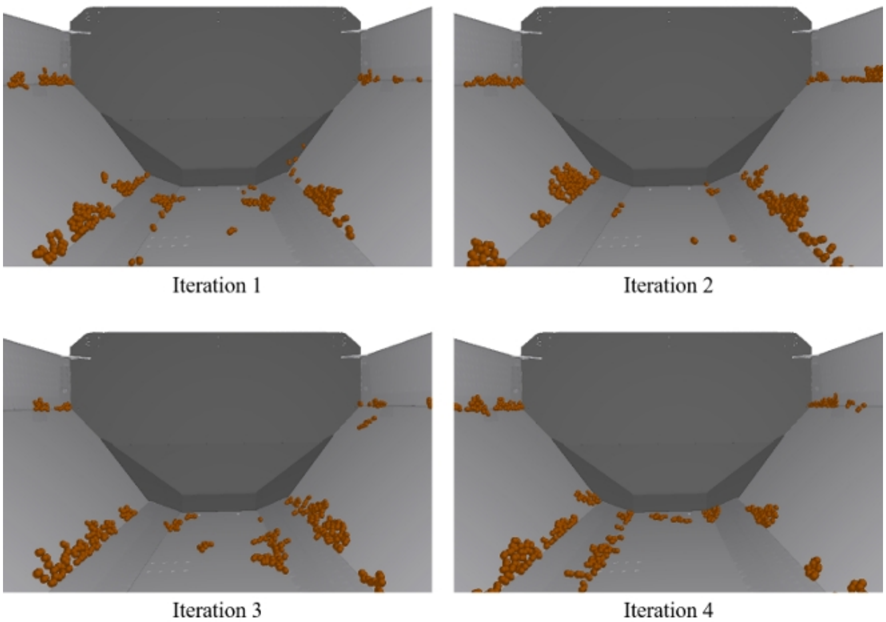


Figure 4.7: Carry-back pattern observed with UHMW-PE application.

The simulation results showed a consistent response across all tested parameter combinations. No material deposition was observed on the UHMW-PE-applied regions in any of the DOE iterations (Figure 4.7). This consistent behavior indicates that the performance of UHMW-PE in the identified regions was not sensitive to the variation of the unknown parameters within the investigated ranges. These findings support the viability of UHMW-PE as a liner material for reducing carry-back in the critical front region of the dumper body. Although some material properties remain manufacturer-specific, the DOE-based assessment showed that the proposed solution remained effective throughout the investigated parameter space.

4.4 Field observations with liner application

To complement the simulation study, carry-back observations were made on an A60 hauler equipped with a standard dumper body after the application of a liner. Figure 4.8 show examples of the material remaining in the body before and after liner application. In the observed post-liner condition, material was present in the regions that had been identified in this study as the intended target areas for carry-back reduction, while the remaining areas of the dumper body appeared largely clear.

Dumper body without liner   Dumper body with liner

Figure 4.8: Liner performance on an A60 hauler having standard dumper body.

At first sight, this observation does not follow the trend predicted by the simulation results. However, it should not be interpreted as a direct validation or rejection of the simulation study. The field observation was made for an older dumper-body design, whereas the DEM investigation was conducted using the updated dumper-body geometry adopted for the BEV haulers. In addition, the operating and material conditions during the observation may have differed from those represented in the simulations. Most importantly, the images were not obtained from successive unloading cycles and therefore represent only individual observations rather than the overall material-discharge behavior. Since carry-back can vary between cycles depending on loading, material condition, and operating conditions, a single observation cannot be considered representative of liner performance. A structured field trial using the same dumper-body geometry, defined operating conditions, and repeated unloading cycles would be required for a meaningful comparison with the DEM predictions.

5

Energy-based Approach

This chapter investigates an energy-based approach to mitigate carry-back through the use of externally mounted electric heating devices on dumper body surfaces. The heating system is considered to be powered either by the traction battery or by a dedicated auxiliary battery. The chapter presents a method for estimating the required energy demand by comparing a conventional exhaust-heated standard dumper body with the improved dumper body configuration developed for BEVs. The aim was to study the effect of heating selected dumper body surfaces on material adhesion, particularly through possible changes in the surface energy of the bulk material. However, the standard EDEM physics models do not support temperature-dependent cohesion. Additionally, developing a custom plug-in was also not considered suitable, as it would increase the simulation time without ensuring a reliable representation of the physical behavior. Therefore, a calculation-based method was adopted for the present analysis.

5.1 Reference carry-back scenario

The formula derivation and the subsequent calculations are based on a specific carry-back scenario involving an A45 ICE hauler with exhaust gases circulation beneath the dumper body to and reduce adhesion between the bulk material and the dumper body surfaces by heat application.[10] The assumed ambient conditions are humid, with an ambient temperature of 25 °C. The transported bulk material is moist clay with a fine particle composition. This reference scenario is based on a real-life case in Liberia that was previously examined in the earlier thesis work.[4]

The following assumptions were made to simplify the analysis:

- Based on the body heating test reports, only selected dumper body surfaces were considered as heated surfaces in the calculations.
- The system was assumed to operate under steady-state conditions, with the observed average temperature maintained uniformly over the entire selected surface during operation.
- Since the heated surfaces are covered by bulk material, heat transfer between the surface and the bulk material was assumed to occur only by conduction. Accordingly, convective and radiative heat losses were neglected.
- The thickness of the first deposited bulk material layer was assumed to be uniform over the entire area of the selected surfaces.

5.2 Formula derivation

The derivation is based on Newton's Law of Cooling which states that the rate of heat loss of a body is directly proportional to the difference in the temperatures between the body and its surroundings provided the temperature difference is small and the nature of radiating surface remains the same.

Mathematically,

$$q'' = h \cdot \Delta \mathrm{T}$$

Where,

$$q'' = \text{heat flux } \left(\frac{\mathrm{W}}{\mathrm{m}^2}\right)$$

$$h = \text{convective heat transfer coefficient } \left(\frac{\mathrm{W}}{\mathrm{m}^2} \cdot \mathrm{K}\right)$$

$$\Delta T = \text{temperature difference (K)}$$

To calculate the total rate of heat transfer ($\dot{Q}$), we multiply the heat flux with the total surface area in contact.

$$\dot{Q} = A \cdot h \cdot \Delta T$$

Which can be also written as,

$$P = A \cdot h \cdot \Delta T \tag{5.1}$$

Where,

$$P = \text{power required for heat transfer}$$

Following the assumptions made earlier, the effects of convection and radiation are neglected in this case, therefore the formula needs to be modified to have heat transfer based on pure conduction. The Fourier's Law of Conduction states that the rate of heat conduction per unit area is directly proportional to the temperature gradient.

Mathematically,

$$\dot{Q} = -k \cdot A \cdot \nabla T$$

Where,

$$k = \text{Thermal conductivity of material}$$

$$\nabla T = \text{Temperature gradient vector}$$

The $(-)$ negative sign enforces the second law of thermodynamics, meaning heat naturally flows from hot regions to cold regions.

Integrating the temperature gradient over a layer thickness L gives,

$$\dot{Q} = -\left(\frac{k \cdot A \cdot \Delta T}{L}\right) = -\left(\frac{k \cdot A \cdot (T_{surf} \; - \; T_{bulk})}{L}\right)$$

Removing (−) negative sign to quantify heat transfer as a positive value,

$$\dot{Q} = \frac{k \cdot A \cdot \Delta T}{L}$$

Which can be also written as,

$$P = \frac{k \cdot A \cdot \Delta T}{L} \tag{5.2}$$

Equating (1) and (2) the effective heat transfer coefficient can be written as,

$$h_{eff} = \frac{k}{L} \tag{5.3}$$

When heat conduction happens between two solids, we consider the thermal resistance (R) of the material to heat flow,

$$R = \frac{L}{k} \tag{5.4}$$

Solving (3) and (4) we can relate the effective heat transfer coefficient with the thermal resistance of material as,

$$h_{eff} = \frac{1}{R} = \frac{1}{\frac{L}{k}} = \frac{1}{\frac{L_{surf}}{k_{surf}} + \frac{L_{bulk}}{k_{bulk}}} \tag{5.5}$$

Replacing h with h_{eff} in (1), the final equation can be written as,

$$\boxed{\boldsymbol{P = A_{surf} \cdot h_{eff} \cdot \Delta T = A_{surf} \cdot \left(\frac{1}{\frac{L_{surf}}{k_{surf}} + \frac{L_{bulk}}{k_{bulk}}}\right) \cdot (T_{surf} - T_{bulk})}} \tag{5.6}$$

Where the following values are assumed for thermal conductivity and bulk material layer thickness:

$$k_{surf} = 40 \ \frac{\mathrm{W}}{\mathrm{m}} \cdot \mathrm{K}$$

$$k_{bulk} = 1.3 \ \frac{\mathrm{W}}{\mathrm{m}} \cdot \mathrm{K}$$

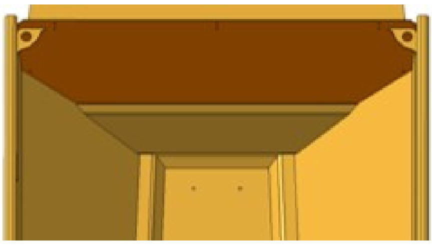
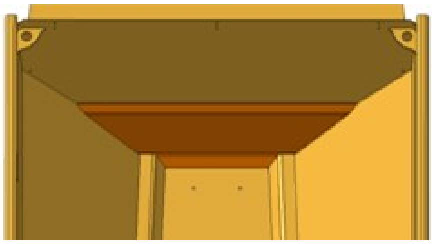
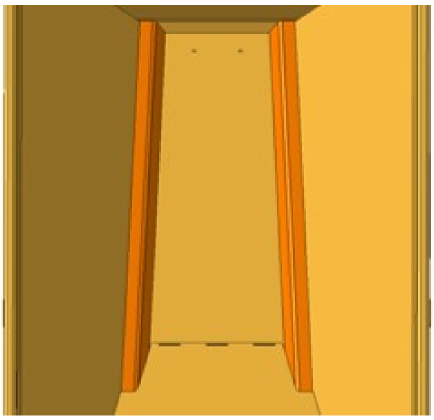
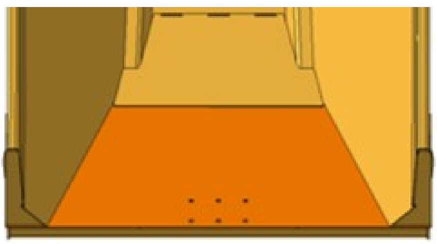
$$L_{bulk} = 0.04 \ \mathrm{m}$$

Thus, the derived expression (5.6) provides the power required to maintain a selected surface at the desired temperature under steady-state conditions with heat transfer assumed to occur purely by conduction. In the following section, this relation is applied to estimate the power requirement for the specific dumper body surfaces considered in this study.

5.3 Power requirement calculation for standard dumper body

The dumper body heating test reports showed that certain dumper body surfaces experienced an increase in surface temperature due to their exposure to exhaust gases flowing beneath the dumper body. Table 5.1 summarizes the input parameters of the selected surfaces.

Table 5.1: Input parameters of the selected dumper body surfaces of standard dumper body

Surface	Illustration	Input parameters
Front wall		$A_{surf} = 2.046\ \text{m}^2$ $L_{surf} = 0.008$ m $T_{surf} = 113.39\ °\text{C} = 386.54$ K
Post box		$A_{surf} = 1.025\ \text{m}^2$ $L_{surf} = 0.01$ m $T_{surf} = 123.39\ °\text{C} = 396.54$ K
Channels		$A_{surf} = 1.778\ \text{m}^2$ $L_{surf} = 0.01$ m $T_{surf} = 59.95\ °\text{C} = 333.1$ K
Chute plate		$A_{surf} = 4.299\ \text{m}^2$ $L_{surf} = 0.016$ m $T_{surf} = 44.63\ °\text{C} = 317.78$ K

- Power requirement for front wall:

$$P_{fw} = 2.046 \cdot \left(\frac{1}{\frac{0.008}{40} + \frac{0.04}{1.3}} \right) \cdot (386.54 - 298.15) = 5839.54 \text{ W}$$

- Power requirement for post box:

$$P_{pb} = 1.025 \cdot \left(\frac{1}{\frac{0.010}{40} + \frac{0.04}{1.3}} \right) \cdot (396.54 - 298.15) = 3251.2 \text{ W}$$

- Power requirement for channels:

$$P_{c} = 1.778 \cdot \left(\frac{1}{\frac{0.010}{40} + \frac{0.04}{1.3}} \right) \cdot (333.1 - 298.15) = 2003.31 \text{ W}$$

- Power requirement for chute plate:

$$P_{cp} = 4.299 \cdot \left(\frac{1}{\frac{0.016}{40} + \frac{0.04}{1.3}} \right) \cdot (317.78 - 298.15) = 2707.46 \text{ W}$$

The total power utilized to maintain the average temperature on the selected surfaces is calculated as,

$$P_{db,utilized} = 5839.54 + 3251.2 + 2003.31 + 2707.46 = 13801.48 \text{ W}$$

$$\therefore \boxed{\boldsymbol{P_{db,utilized} = 13.8 \text{ kW}}} \tag{5.7}$$

This power calculation provided an estimate of the heating power required to maintain the selected dumper body surfaces at their observed temperature levels under the assumed steady-state, conduction-dominated conditions. It also established the thermal demand associated with the reference carry-back scenario and formed the basis for assessing whether such a demand can be supported by the available energy source in the conventional exhaust-heated system.

5.4 Power distribution calculation for A45 ICE Hauler

The next step in the analysis was to determine the power distribution for the reference carry-back scenario to assess whether the power supplied to the dumper body is sufficient to meet the estimated heating demand. The calculation was based on the engine test datasheet for Volvo's D16J internal combustion engine used in the A45 articulated hauler, together with thermal measurements of the dumper body surfaces and a set of generalized assumptions. Since the available engine test data corresponded to high load operation, the analysis began with this condition. The power distribution was then re-evaluated for normal load conditions in the following section.

5.4.1 High engine load condition

The engine power distribution under high load was evaluated using the available test data together with standard reference values for the missing fuel properties. The input parameters used in the calculation are listed below.

- Engine speed, $N = 1700$ RPM $= 28.33$ rev/s
- Number of cylinders, $N_{cyl} = 6$
- Volumetric flow rate of fuel, $\dot{V}_{fuel} = 83$ l/h
- Density of fuel, $\rho_{fuel} = 0.85$ kg/l at 25 °C
- Lower Heat Value of fuel, $LHV_{fuel} = 42.5 \cdot 10^6$ J/kg
- Mass flow rate of exhaust, $\dot{m}_{exhaust} = 0.48$ kg/s
- Density of exhaust gas, $\rho_{exhaust} = 0.85$ kg/m^3 at 413 °C
- Maximum observed exhaust back pressure, $\Delta P_{max} = 3.6$ kPa

The total fuel power was considered to be distributed among useful engine power, coolant heat losses, charge air cooler heat losses, emitted heat, and exhaust power. Accordingly, the fuel power can be expressed as:

$$P_{fuel} = P_{engine} + P_{coolant} + P_{CaC} + P_{emitted} + P_{exhaust} \tag{5.8}$$

For the tested engine operating condition, the power distribution showed that 41 % of the fuel power was converted into useful engine power, 32 % was associated with coolant, charge air cooler, and emitted heat losses, and 25 % was carried by the exhaust gases. From the available volumetric flow rate and density of fuel the mass flow rate of fuel ($\dot{m}_{fuel}$) was calculated as:

$$\dot{m}_{fuel} = \dot{V}_{fuel} \cdot \rho_{fuel} = 83 \cdot 0.85 = 70.55 \text{ kg/h} = 0.0196 \text{ kg/s}$$

The fuel power was then calculated using the mass flow rate of fuel and the lower heating value of fuel. This represents the total chemical energy supplied to the engine through fuel combustion.

$$P_{fuel} = \dot{m}_{fuel} \cdot LHV_{fuel} = 0.0196 \cdot 42.5 \cdot 10^6 = 833000 \text{ W} = \mathbf{833\ kW} \tag{5.9}$$

The exhaust power was then calculated from the fuel power obtained in Expression (5.9), using the percentage distribution observed for the tested engine.

$$P_{exhaust} = 833 \cdot 0.25 = \mathbf{208.25\ kW}$$

Since the exact distribution of exhaust power between the chimney outlet and the exhaust routed beneath the dumper body is not known and may vary with operating conditions, three different split scenarios are considered in the analysis. For each scenario, the corresponding power available for dumper body heating is calculated from the exhaust power obtained previously.

- One-third of the exhaust power is routed beneath the dumper body

$$P_{db,available,S1} = \frac{1}{3} \cdot 208.25 = \mathbf{69.41\ kW}$$

- One-fourth of the exhaust power is routed beneath the dumper body

$$P_{db,available,S2} = \frac{1}{4} \cdot 208.25 = \mathbf{52.06\ kW}$$

- One-fifth of the exhaust power is routed beneath the dumper body

$$P_{db,available,S3} = \frac{1}{5} \cdot 208.25 = \mathbf{41.65\ kW}$$

After determining the exhaust power available for dumper body heating under each considered scenario, it was compared with the heating power required by the dumper body (5.7). The comparison showed that the available exhaust power was sufficient to satisfy the heating demand in all cases and the percentage power utilization is estimated to vary in the range of 19.88 % to 33.13 %.

5.4.1.1 Effect of back pressure

Exhaust back pressure is the additional pressure that exhaust gases must push against as they flow out of the engine through the exhaust system, caused by flow restrictions such as pipe geometry, bends, silencers, and other components in the exhaust line. It is the resistance to exhaust gas flow that makes the piston do extra work during the exhaust stroke to expel the gases and creates a pumping loss of engine power. This pumping loss in terms of power was calculated as,

$$P_{pump\ loss} = \dot{V}_{exhaust} \cdot \Delta P_{max}$$

Where the volumetric flow rate of exhaust was calculated as,

$$\dot{V}_{exhaust} = \frac{\dot{m}_{exhaust}}{\rho_{exhaust}} = \frac{0.48}{0.85} = 0.57\ \mathrm{m^3/s}$$

$$\therefore P_{pump\ loss} = 0.57 \cdot 3600 = 2052\ \mathrm{W} = \mathbf{2.05\ kW}$$

When compared with the fuel power (833 kW), this additional power contribution of 2.05 kW represents only about 0.25 % of the fuel power. This comparison indicates that the back pressure level observed during the tests did not have a direct or significant effect on dumper body heating performance and was therefore excluded from this thermal analysis.

5.4.2 Normal engine load condition

At normal load conditions, the engine operates at approximately one-third of its maximum power. According to the specification sheet of A45 articulated hauler, powered by a D16J engine, the maximum engine power is 365 kW.

$$\therefore \; P_{engine,normal} = \frac{1}{3} \cdot 365 = \mathbf{121.67\ kW},$$

$$P_{fuel,normal} = \frac{P_{engine,normal}}{0.41} = \frac{121.67}{0.41} = \mathbf{296.76\ kW}$$

and,

$$P_{exhaust,normal} = 296.76 \cdot 0.25 = \mathbf{74.19\ kW}$$

Recalculating the power available for heating the dumper body under the three scenarios defined earlier yields:

$$P_{db,available,S1} = \frac{1}{3} \cdot 74.19 = \mathbf{24.73\ kW},$$

$$P_{db,available,S2} = \frac{1}{4} \cdot 74.19 = \mathbf{18.55\ kW}$$

and,

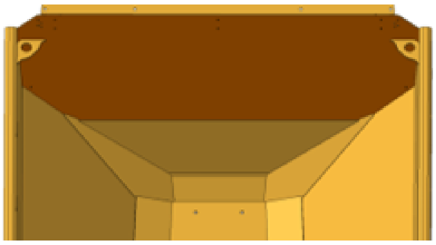
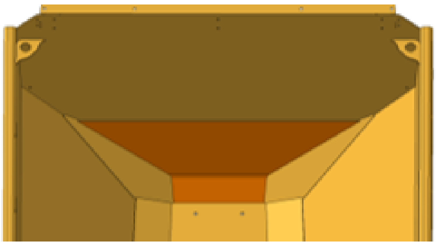
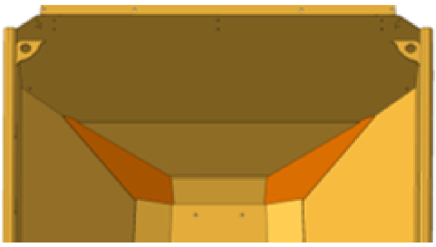
$$P_{db,available,S3} = \frac{1}{5} \cdot 74.19 = \mathbf{14.84\ kW}$$

The results obtained for the three normal-load scenarios show that the heating power demand of the dumper body can be satisfied in all cases. Even when the lowest assumed fraction of exhaust power is considered, the available thermal power remains sufficient to meet the required demand. Although this analysis is based on several assumptions, they are considered reasonable and appropriate for the present evaluation.

5.5 Power requirement calculation for geometrically improved dumper body

The power estimation for the selected surfaces of the standard dumper body equipped with exhaust-based body heating showed that approximately 60 % of the total heating power demand was associated with the front region (front wall and post box surfaces). Furthermore, field observations of JA40 BEV's geometrically improved dumper body indicated that the front portion is the main area in which bulk material accumulates over time. Based on these considerations, the surfaces prioritized for heat application in the revised geometry were the front wall, the modified post box, and the corner plates. The input parameters corresponding to these selected surfaces are summarized in Table 5.2.

Table 5.2: Input parameters of the selected dumper body surfaces of geometrically improved dumper body

Surface	Illustration	Input parameters
Front wall		$A_{surf} = 2.319$ m^2 $L_{surf} = 0.008$ m $T_{surf} = 113.39$ °C $= 386.54$ K
Post box		$A_{surf} = 1$ m^2 $L_{surf} = 0.011$ m $T_{surf} = 123.39$ °C $= 396.54$ K
Corner plates		$A_{surf} = 0.384$ m^2 $L_{surf} = 0.010$ m $T_{surf} = 123.39$ °C $= 396.54$ K

The surface temperatures recorded for the standard dumper body were adopted for the corresponding surfaces of the improved geometry to ensure a consistent reference basis for comparison between the two heating approaches. Since exhaust-based body heating is not available in BEVs, the alternative electric heating system should be capable of achieving equivalent thermal performance, in terms of the surface temperatures achieved.

- Power requirement for front wall:

$$P_{fw} = 2.319 \cdot \left(\frac{1}{\frac{0.008}{40} + \frac{0.04}{1.3}} \right) \cdot (386.54 - 298.15) = 6618.71 \text{ W}$$

- Power requirement for post box:

$$P_{pb} = 1 \cdot \left(\frac{1}{\frac{0.011}{40} + \frac{0.04}{1.3}} \right) \cdot (396.54 - 298.15) = 3169.35 \text{ W}$$

- Power requirement for corner plates:

$$P_{cp} = 0.384 \cdot \left(\frac{1}{\frac{0.010}{40} + \frac{0.04}{1.3}} \right) \cdot (396.54 - 298.15) = 1218.01 \text{ W}$$

The total power utilized to maintain the average temperature on the selected surfaces is calculated as,

$$P_{db,utilized} = 6618.71 + 3169.35 + 1218.01 = 11006.07 \text{ W}$$

$$\therefore \boxed{\boldsymbol{P_{db,utilized} = 11.01 \text{ kW}}} \tag{5.10}$$

The comparison of power utilization on both dumper bodies indicates that the geometrically improved dumper body enables a more effective and targeted use of heating power. Although the front surfaces of the improved geometry require approximately 2 kW more than the corresponding front surfaces of the standard dumper body, the total heating power requirement is lower by about 2.8 kW because heating is limited to the most critical region. In the standard dumper body, additional surfaces along the body length (channels) and rear section (chute plate) are also heated due to exhaust circulation, but these surfaces attain comparatively lower temperatures as the exhaust gas cools rapidly downstream. This reduces the thermal effectiveness of the distributed heating. Therefore, the improved geometry is advantageous because it concentrates the heating power where it is most needed, resulting in lower overall power demand and a more function-oriented heating strategy.

5.6 Conceptual battery sizing for geometrically improved dumper body heating system

Battery sizing depends on the operating conditions under which the heating system must function. For this reason, the analysis adopts a representative hauler operating scenario as the basis for the assessment. The following points present the specific assumptions and parameters of this scenario.

- Travel distance from loading site to unloading site, $s = 3$ km
- Speed of vehicle with load, $v_{loaded} = 30$ km/h
- Speed of vehicle without load (return travel), $v_{return} = 35$ km/h
- Bulk material loading time, $t_{loading} = 5$ minutes
- Bulk material unloading time: $t_{unloading} = 1$ minute
- Vehicle operation time with one full charge, $t_{operation} = 6$ hours $= 360$ minutes

5.6.1 Operation cycle

An operating cycle of the hauler comprises the total time required for all activities, beginning with loading the bulk material and ending with the vehicle's return to the loading site. It is therefore calculated as the sum of the time associated with each individual activity, as shown below.

- **Loaded travel time:**

$$t_{loaded} = \frac{s}{v_{loaded}} = \frac{3}{30} = 0.1 \text{ h} = 0.1 \cdot 60 = 6 \text{ minutes}$$

- **Return travel time:**

$$t_{return} = \frac{s}{v_{return}} = \frac{3}{35} = 0.0857 \text{ h} = 0.0857 \cdot 60 = 5.14 \text{ minutes}$$

- **Total operation time for a cycle:**

$$t_{cycle} = t_{loading} + t_{loaded} + t_{unloading} + t_{return} \ = 5{+}6{+}1{+}5.14 = \mathbf{17.14\,minutes}$$

With the operating time for one cycle determined, the number of cycles that the hauler can complete on a single charge can be estimated as follows:

$$N_{cycle} = \frac{t_{operation}}{t_{cycle}} = \frac{360}{17.14} \approx \textbf{21 cycles}$$

5.6.2 Total heater energy

The total energy required by the heaters to meet the power demand of the dumper body surfaces depends on the duration of heater operation. For a continuous operating time of 6 hours, the corresponding energy requirement can be calculated as follows:

$$E_{heater,operation} = \ P_{db,required} \cdot N_{cycle} \cdot t_{heat,cycle}$$

Where, $t_{heat,cycle}$ denotes the energy demand period per cycle.

For the feasibility study, four different scenarios are considered, each representing a different energy demand at various stages of the operating cycle.

- **A: Heating during loaded travel phase**

$$E_{heater,operation} = 11.01 \cdot 21 \cdot 0.1 = 23.12 \text{ kWh}$$

- **B: Heating during loaded travel and unloading phases**

$$E_{heater,operation} = 11.01 \cdot 21 \cdot (0.1 + 0.0167) = 26.98 \text{ kWh}$$

- **C: Heating during loading, loaded travel and unloading phases**

$$E_{heater,operation} = 11.01 \cdot 21 \cdot (0.1 + 0.0167 + 0.0833) = 46.24 \text{ kWh}$$

- **D: Heating throughout the hauler operation**

$$E_{heater,operation} = 11.01 \cdot 21 \cdot 0.2857 = 66.06 \text{ kWh}$$

5.6.3 Usable battery energy

Usable battery energy refers to the amount of energy that the battery must deliver to the heater circuit after accounting for system efficiency losses. A system efficiency of 92 % is assumed for the conceptual design.

$$\therefore \; E_{battery,usable} = \frac{E_{heater,operation}}{\eta_{system}} = \frac{E_{heater}}{0.92} \tag{5.11}$$

5.6.4 Nominal battery energy

Nominal battery energy refers to the installed battery capacity required to ensure the desired usable energy. It is determined after applying battery de-rating factors such as allowable depth of discharge, aging, reserve margin, and temperature effects, since not all of the energy stored in the battery is available for use by the heater system.

$$\therefore \; E_{battery,nominal} = \frac{E_{battery,usable}}{f_{DoD} \cdot f_{ageing} \cdot f_{reserve} \cdot f_{temperature}}$$

Where,

- $\boldsymbol{f_{DoD} = 0.8}$ (assumption)
  f_{DoD} is the factor of usable depth of discharge. For battery health and safety, its operation is limited to a usable State of Charge (SoC) window. If the allowed operating range is 90 % to 10 % then only 80 % is intentionally usable. Using full depth of discharge (100 %) shortens battery life and may create voltage drop issues in near empty state.

- $\boldsymbol{f_{ageing} = 0.85}$ (assumption)
  A new battery may provide 100 % if its nominal capacity, but after years of use it may provide only 80 % to 90 % of that capacity. f_{ageing} factor is considered to size the battery in a way that even at end of life it still fulfills the usable energy requirement.

- $\boldsymbol{f_{reserve} = 0.9}$ (assumption)
  $f_{reserve}$ is an intentional margin beyond calculated demand that covers variations in duty cycles, unexpected delays, heating cycle behavior, non-ideal field conditions and control inaccuracies.

- $\boldsymbol{f_{temperature}} = \mathbf{0.9}$ (assumption)
  A temperature decreasing factor is need because the available energy and power of a battery reduce at low temperatures.

Combining the factors considered, the equation for calculating nominal energy of battery can be written as,

$$E_{battery,nominal} = \frac{E_{battery,usable}}{f_{DoD} \cdot f_{ageing} \cdot f_{reserve} \cdot f_{temperature}} = \frac{E_{battery,usable}}{0.5508} \tag{5.12}$$

Table 5.3 presents the usable and nominal battery energy values for the previously defined scenarios.

Table 5.3: Usable and Nominal battery energy estimates for the defined scenarios

Heating Scenario	**Usable battery energy**	**Nominal battery energy**
A	$\frac{23.12}{0.92} = 25.13$ kWh	$\frac{25.13}{0.5508} = 45.62$ kWh
B	$\frac{26.98}{0.92} = 29.33$ kWh	$\frac{29.33}{0.5508} = 53.24$ kWh
C	$\frac{46.24}{0.92} = 50.26$ kWh	$\frac{50.26}{0.5508} = 91.25$ kWh
D	$\frac{66.06}{0.92} = 71.80$ kWh	$\frac{71.80}{0.5508} = 130.36$ kWh

Based on the above hypothesis, even Scenario A, which represents an idealised heat-requirement case, would require an approximately 50 kWh battery pack. Rather than introducing a dedicated standalone battery for the heater system, the traction battery of the BEV hauler could be considered as a potential primary energy source for the heaters. The available JA40 BEV specification sheet indicates a 600 V electrical architecture with a total battery capacity of 540 kWh and usable battery energy of 432 kWh. However, drawing power directly from the traction battery would increase vehicle energy consumption and reduce its operating range. This approach could become more suitable in the future if a larger traction-battery capacity can be accommodated or if improved energy-harvesting and recovery techniques increase the energy available on the vehicle.

6
Assessment of Approaches

This chapter assesses the two solution approaches investigated in this thesis, reflects on the main findings from each approach, discusses their practical potential and limitations, and considers the assumptions that influence the reliability of the results.

6.1 Material-based approach

The material-based approach was explored as a practical way of reducing carry-back without relying on an external energy source. The main idea was to improve the interaction between the bulk material and the dumper-body surface by applying UHMW-PE liners in areas where material is likely to remain after tipping. This type of solution could potentially be introduced into existing dumper-body designs without major changes to the overall structure.

The simulation results along with practical application examples indicate that UHMW-PE could be a promising liner material for reducing carry-back. The DEM simulations suggest that lining selected areas of an existing dumper body may support better material discharge. A simplified DEM model was used to represent the main features of the unloading process while keeping the simulation time manageable for comparing several design alternatives. However, the results are influenced by the assumptions used in the particle model and by the limited field data available to describe carry-back behavior. Further work involving more detailed particle models, physical testing, and data from a wider range of materials and operating conditions would improve confidence in the predicted carry-back patterns.

6.2 Energy-based approach

The energy-based approach was explored because material-based solutions may not fully address carry-back in wet or cold conditions, where the material can strongly adhere to or freeze against the dumper-body surface. The idea behind this approach was to heat selected internal surfaces of the dumper body to reduce the conditions that promote sticking and thereby support more complete unloading.

The investigation provides a framework for estimating the energy required to heat selected dumper-body surfaces. It expands the carry-back analysis beyond the amount of retained material by also considering the energy needed to influence material adhesion. Even for the lowest heater-use scenario considered, the estimated battery capacity was too large to be practically installed outside the available engine-bay space. Nevertheless, the approach may become more feasible in future haulers if additional battery capacity is available and part of it can be allocated to dumper-body heating. The calculated values should be considered preliminary because the analysis relies on several simplifying assumptions, particularly the assumption of steady-state heat transfer. Actual temperature distributions and energy requirements may therefore differ during real operating cycles.

6.3 Feasbility study

The two approaches address carry-back in different ways, but their practical feasibility can still be compared. The material-based approach appears to be easier to apply to the current dumper configuration because it could be introduced in selected areas of the existing body and does not require an additional onboard energy source. Before it can be implemented, further work is needed to assess liner attachment, durability, wear, and performance under representative operating conditions.

The energy-based approach would require more changes to the vehicle, including heating components, electrical power, control systems, and suitable installation space. Based on the battery capacity estimated in this study, it does not appear practical for the current dumper configuration, as the required capacity cannot be accommodated within the available engine-bay space. However, the concept could become more relevant for future haulers with larger battery capacity and electrical systems designed to support additional heating loads.

7
Conclusion

This thesis examined the carry-back problem in dumper bodies and explored potential ways to reduce the material remaining after unloading. The work first developed an understanding of the problem by considering the influence of bulk-material characteristics, operating conditions, and dumper-body geometry. This provided the basis for screening different solution concepts and selecting the most relevant options for further investigation. The selected concepts were then assessed using simulation-based and calculation-based methods. The work demonstrated how DEM can be used to study the influence of surface and geometric changes on material discharge, while the energy-based assessment provided an initial understanding of the requirements and practical constraints associated with heating selected dumper-body surfaces. Together, the investigations show that carry-back should be addressed through solutions tailored to the operating conditions and vehicle constraints rather than through a single general measure.

The study provides a foundation for continuing the development of carry-back mitigation concepts. It also highlights the importance of validating analytical and simulation-based findings through representative physical testing before drawing conclusions about real-world implementation.

7.1 Future development

The next step is to move the promising concepts from simulation and calculation into practical testing. Discussions on using UHMW-PE as a liner material are already ongoing, and physical trials under representative operating conditions would help confirm whether the carry-back reduction predicted by the DEM simulations can be achieved in practice. These trials could also be used to evaluate practical aspects of the liner, including its attachment method, durability, and wear behavior. For the energy-based approach, the current calculations should be refined and validated, as they are based on assumptions such as steady-state heat transfer. Transient thermal analysis, together with temperature and power measurements during operation, could provide a clearer picture of how the dumper body responds to heating and how much power is actually required. This work would support the further development of a practical solution for reducing carry-back.

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