SYSTEM DYNAMICS AS A TOOL FOR EXPLORING GREENHOUSE GAS EMISSION MITIGATION POTENTIAL IN FREIGHT TRANSPORT

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ABSTRACT

In this study, system dynamics modelling is used to evaluate the impacts of decisions made by different decision makers in the freight subsector on the performance of the sector, as measured in terms of greenhouse gas (GHG) emissions, direct job creation, water usage and various externality costs. The focus is on gaining a deeper understanding of opportunities for reducing GHGs, and particularly on the shift of freight from road to rail. Transport of processed food along the Cape Town-Gauteng corridor is used as a case study. Decision makers considered include the freight owners and those responsible for decisions around the vehicle fleet. In the model, decision makers respond to a number of aspects of system performance, including cost, system reliability and taxes. These aspects inform their decision to shift freight on or off rail, or to invest in efficiency interventions. Decisions made in one year impact on overall system performance, which may change a decision maker's actions in the following year. This paper describes in detail the structure of the model and how it functions. It also discusses the necessary input data, and how this was gathered. Finally, simulation results are presented and discussed.

1 INTRODUCTION

The latest South African Greenhouse Gas Inventory indicates that the transport sector contributed a total of 47.4 Mt CO_2e, or 8.4% of South Africa's greenhouse gas (GHG) emissions in 2010 (DEA, 2013). Freight transport is thought to account for about half of these emissions. The National Climate Change Response Policy requires significant GHG emitting sectors, including transport, to define "bottom up" carbon budgets (Republic of South Africa, 2011). The DEROs (Desired Emission Reduction Outcomes) process currently underway aims to define DEROs for the transport sector (and possibly companies and subsectors within this) for which detailed mitigation plans will be required.

It is widely recognised that a significant, but challenging, opportunity to reduce emissions in the freight transport sector is the shift from road to rail (IPCC, 2014). The primary aim of this work is to create a better understanding of the complexities of the freight transport system, in particular mode shift decisions, and interrogate the effectiveness and implications of GHG mitigation measures available to this subsector. This is to support and inform WWF’s broader work on low carbon frameworks for the transport sector.

This paper presents the development and outcomes of a system dynamics model of freight transport in South Africa. Using processed food freight along a major corridor as a case study, the model explores different decision-making behaviour by both freight owners and freight transporters as they respond to mitigation measures that impact on system costs and reliability. The focus of the paper is on describing in detail the structure of the model and how it functions, the input data requirements and data sources as well as presenting simulation results for the base case.

2 DEVELOPING A FREIGHT TRANSPORT SYSTEM DYNAMICS MODEL

In this work, System Dynamics (SD) was selected as the modelling approach as it allows for the exploration of the evolution of a complex system over time, through consideration of the feedback loops and dynamic behaviour of the system. SD has been successfully applied to investigate the implications of policy decisions on transport systems elsewhere, for example, by the French Ministry of Transport (Salini & Karsky, 2003) and for the EU15 countries via the ASTRA model (IWW, 2000). A further advantage of SD modelling is that it lends itself to collaborative model building, and interfaces can be easily built which allow for exploration by stakeholders of the impact of changing individual parameters and relationships on the overall system performance.

The conceptual model structure for the freight transport model was developed based on an understanding of the South African freight transport system gained from literature and extensive stakeholder interaction. The conceptual model was programmed in a system dynamics software package called STELLA (www.iseesystems.com). The model structure was further refined through consultation with experts, and the model populated with data from literature and that received from stakeholders. The overall model structure and main components of the model are presented in Figure 1.

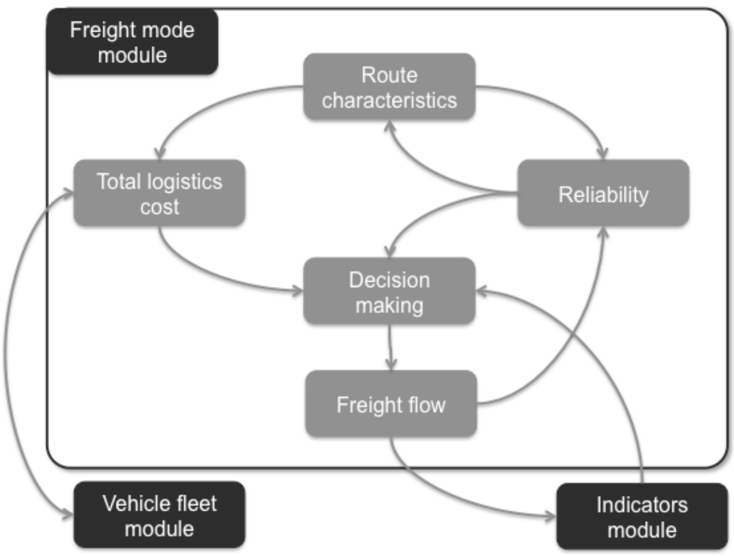

Figure 1: Freight model structure and main model components

2.1 Model scope

The model is simulated for the period of 2012 to 2050, to align with the National Climate Change Response Policy timeframe. Only one commodity group on one corridor with a single origin-destination was simulated to avoid introducing unnecessary complexity that could detract from the core objective of the model. Processed food was selected as the commodity group due to the large volumes transported on corridors (van Eeden & Havenga, 2010). The nature of processed food and the distance of the selected corridor (the Cape-Town Gauteng corridor) also make it suitable for intermodal transport solutions. Currently, however, most of this freight is transported by road (Transnet, 2012). It thus represents a potentially ideal candidate for a road to rail shift.

The limitations of this reduced scope are that the effects of congestion and capacity constraints cannot be considered explicitly. Further, given that only a small subset of the freight system is modelled, the impact of mitigation measures on output indicators (GHG emissions, jobs, water etc.) can only be determined relative to this subset, and will not reflect the impacts on the system as a whole.

2.1.1 Freight characteristics

Processed food freight transport along the Cape Town to Gauteng corridor is anticipated to grow. The freight demand forecast used in this model is obtained from Transnet's Rail Forecast from April 2013[1], which informed their Long Term Planning Framework (LTPF) (Transnet, 2014a). Under this framework, processed food freight is segregated into a number of different classifications as follows:

- **Rail suitable:** typically containerised or palletised freight transported in bulk to a single destination;
- **Competing:** freight that can be transported on either rail or road. Freight might be boxed and packaged, but can require additional palatalization or have more stringent storage and handling requirements. Possibly smaller quantities transported to many destinations; and
- **Road suitable:** freight that is most suitable for road transport due to the type of packaging, volumes and dispersed destinations.

Transnet refers to the rail suitable freight and competing freight together as the Rail Addressable Market (RAM). This is the maximum volume of processed food freight that can theoretically be transported by rail and represents a constraint in the model. Figure 2 graphically illustrates the cumulative projected demand for the different types of freight. The RAM is the total area of rail (solid area) and competing (dotted area) freight. Transnet projections only run up to 2042; the last 10 years of data (2033-2042) were projected linearly to estimate values up to 2050.

[1] Data obtained from Transnet, not publicly available.

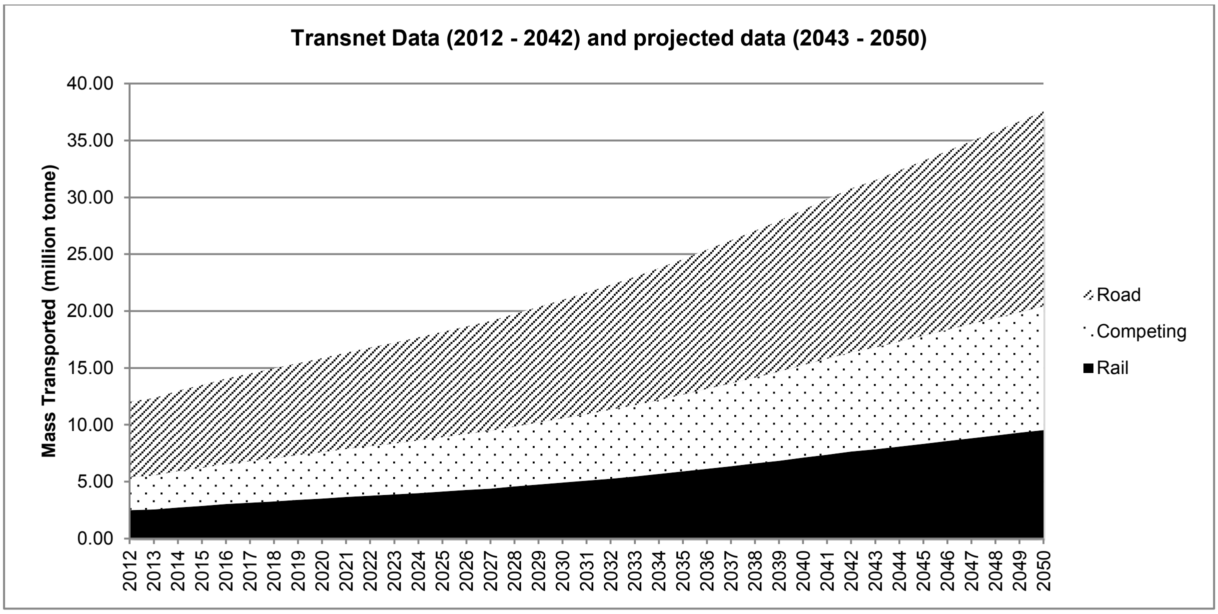

Figure 2: Processed food freight demand to 2050 along the Cape Town – Gauteng corridor

2.1.2 Route characteristics

Freight moved by rail was modelled to include a road leg at either end of the rail corridor to account for the fact that rail links are often not located directly adjacent to the origin or final destination of the freight. In contrast, road freight was assumed to take place as one trip. This is represented in Figure 3.

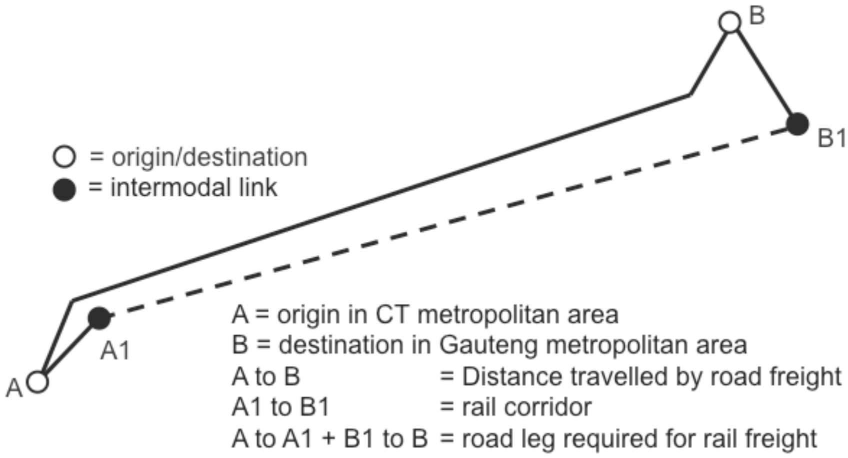

Figure 3: Routes modelled for transport of freight by road and rail

In the base case, both the rail corridor and road corridor distance are set at 1,400 kilometres, with an additional 50 kilometre road leg required at each end of the rail corridor.

2.2 Defining decision makers

From stakeholder consultation, two different decision makers were identified in the freight sector:

- Freight owners; and
- Vehicle fleet owners.

Freight owners determine the mode of transport for their freight based on a number of mode characteristics (e.g. cost, reliability, emissions, etc.). The vehicle fleet owner makes decisions on truck technology improvements, which in turn influence transport cost and emissions associated with the movement of the freight owner's goods. It is noted that this distinction between freight owners and vehicle fleet owners is not always clear-cut as certain players may both own and transport their freight.

Within both the freight owners and vehicle fleet owners, individual organisations are seen to have different priorities in decision-making. For the purposes of constructing the model, three freight owner decision maker types were distinguished:

- **Cost focused:** Cost is identified as the main driver for this type of decision maker. Typical companies have large volume products that serve the majority of consumers;
- **Reputation focused:** Reliability is the main driver for this decision maker. Environmental issues are also considered to enhance the brand value. Typical companies cater for a higher-end market with consumers willing to pay more for better quality and consistent availability of products; and
- **Sustainability focused:** This a "fictional" decision maker that makes decisions for the greater good. Priorities are to reduce emissions, increase employment and reduce externality costs. This may represent the focus of a government decision maker attempting to drive more of a development agenda.

Within vehicle fleet companies, a distinction was made between two types of decision makers:

- **First adopters:** Typically larger freight logistics companies with more stringent maintenance and driver training programs. At the forefront of adopting new technologies to improve vehicle efficiency and have more capital, which therefore allow for longer payback periods.
- **Late adopters:** Smaller companies or one-man driver and truck operations. Sometimes utilise second-hand trucks and drivers don't receive driver training. Capital is limited, therefore these types of fleet owners rarely consider adopting new technologies if not required by law.

2.2.1 Market share and fleet composition in the base case

The market share is the percentage of the total freight in the model that belongs to a freight owner. Without a detailed understanding of the processed food freight market, as a starting point it was assumed that the base case (current market) is assumed to consist of 90% cost focused decision makers with the remainder being reputation focused. Sustainability focused decision makers are not considered in the base case. Further assumptions were required to define the composition of the fleet that services each freight owner type. First adopter fleets are assumed to be large logistics companies and late adopters are one-man one-truck operators or selfoperated fleets. The default values are presented in Table 1 and were estimated based on stakeholder consultations.

Table 1: Assumed fleet composition for processed food freight owner types

	Reputation focused	Cost focused	Sustainability focused	Comments
First adopters	90%	30%	50%	Reputation focused freight owners predominantly use first adopter fleets. Occasionally make use of late adopter trucks during times of high demand. Cost focused decision makers utilise a far greater percentage of late adopter fleets.
Late adopters	10%	70%	50%	

2.3 Decision making criteria

Stakeholder interviews have suggested that cost and reliability are the main criteria by which mode shift decisions are currently made. Additional decision-making criteria (including jobs, emissions and externality costs) were added to the model to investigate possible changes in behaviour through scenarios.

The decision making process and how this is effected in the model is detailed in another paper (Lewis *et al.*, 2015), but the weightings given to these criteria by the different decision makers is presented in the Table 2. Weightings for reputation and cost focussed decision makers were determined in consultation with stakeholders.

Table 2: Weightings for decision-making by decision maker type

Variable	Reputation focused	Cost focused	Sustainability focused
Cost	40%	70%	10%
Reliability	55%	30%	10%
Jobs	0%	0%	27%
Emissions	5%	0%	26%
Externality cost	0%	0%	27%

2.3.1 Timing

Freight is shifted between road and rail transport depending on the demand for rail in a specific year. Based on stakeholder input, it is understood that the mode shift is not immediate, but rather phased in. This is to account for the likelihood of there being binding contracts with a transport provider or the freight owner might be utilising in-house trucks for transport that might also result in a delay to shift. To simulate this, a first-order material delay with delay duration of two years is built into the model.

2.3.2 Total Logistics Cost

The model aims to capture the total logistics cost to the freight owner (price paid per tonne kilometre), as this is the cost used in the decision making process as one of the criteria for selecting a mode of transport. The initial total logistics cost for road and rail were based on data from 2007 that is both corridor and commodity specific (de Jager, 2009). Costs were escalated to the base year (2012 values) and broken down into transport, warehousing, inventory carrying and management and admin cost based on the 10th State of Logistics (SoL) report (CSIR, 2014).

Transport cost for road was further disaggregated in accordance with the SoL to capture impacts of projected increasing fuel costs[2], fuel levies, carbon tax (as proposed in the South African Carbon Tax Policy Paper (National Treasury, 2013)), increasing driver wages, toll fees and the impact of deteriorating road surfaces on vehicle maintenance costs. Rail transport cost is affected by the electricity price and labour cost increases. The electricity price forecast is based on the anticipated average electricity price path from the Integrated Resource Plan (IRP) (DoE, 2011). The base case price path is linked to the "Revised Balanced Scenario" build plan with the maximum price path linked to the "Emission 3" build plan.

Warehousing cost depends on the punctuality of fleets (less punctual fleets require more goods in storage as a buffer), inventory carrying cost is determined largely by travel time, and management and administration cost is influenced by increasing labour cost. The main parameters influencing travel time are listed in Table 3 together with the default assumptions for the base case.

Table 3: Route characteristics sector input parameters

Input parameter	**Value**	**Comments and references**
Rail speed	70 km/h	Based on current average Transnet freight rail speed (Frost & Sullivan, 2012). Assumed to remain unchanged throughout simulation period.
Road corridor speed	2012: 75 km/h 2050: 60 km/h	Value in 2012 is that used in the SoL (de Jager, 2009). Assumed to drop to 60 km/h by 2050 due to congestion. The projection is linear.
Road metropolitan speed	2012: 46 km/h 2050: 30 km/h	Assumed that travel on metropolitan roads is 30% on freeways (at 75 km/h), 50% on major roads with more than 1 lane per direction (at 35 km/h) and 20% on major roads with only 1 lane per direction (at 30 km/h). The assumed speeds are based on stakeholder input that trucks are limited to travel no faster than 40 km/h in urban areas. Future average road speed values were derived from data from the Gauteng 25-year ITMP (Gauteng Roads and Transport, 2013). The projection is linear.
Additional planned stoppage time	Rail: 24 hours Road: 4 hours	Additional time added to the "travel time". For trucks merely a few hours on a long trip for weighbridge, food, toilet and rest purposes. For rail, can vary between a few hours to 10 days (based on stakeholder input).
Improved rail operational performance	0%-50%	A linear improvement in rail operational performance was introduced in the model. This impacts on reliability and costs.

[2] Future fuel price fluctuations are governed by the projected crude oil price (U.S. EIA, 2013).

2.3.3 Reliability

Reliability is the probability of a transport system failing over time. Punctuality is the indicator used in this model to simulate reliability. It is a measure of how "on time" the mode of transport is and is expressed as a percentage of shipments that is perceived to be on time by the freight owner. For road transport, the punctuality is linked to the vehicle fleet and informed by stakeholders. For the model it is assumed that the average punctuality for first adopter truck owners is 98%, and that of the late adopter fleet is 92%. For rail transport, the punctuality was determined from the average time delay per train, which was calculated from mostly Transnet data (see Table 4), and the tolerance levels for delays of European freight owners (BSL Management Consultants, 2008).

Table 4: Input parameters used for calculating rail punctuality

Input parameter	Value	Comments
Utilisation [%]	Increase linearly from 80% (2012) to 100% (2050)	Indication of how hard the infrastructure is working. A percentage of the installed infrastructure capacity used to satisfy demand (Transnet, 2014b).
Optimum mass transported per train trip [tonne]	Increase linearly from 6,000 (2012) to 9,000 (2050) tonnes	The value for 2012 is based on Transnet data (Transnet, 2014b). The 2050 value is assumed. Used to calculate the number of train trips in order to obtain the time delay per train.
Initial failure rate [minutes/million.tonne.km]	5.8	Infrastructure related failures on the simulated route (Transnet, 2014b).
Target failure rate [minutes/million.tonne.km]	1.4	
Initial additional delays not related to failures [hours]	5	Assumed values based on delays for Transnet coal and iron ore lines (Business Report, 2011). Captures other delays not related to infrastructure failures.
Additional delays target [hours]	2	

2.4 Model output indicators

As well as predicting the amount of each type of freight on each mode, other output indicators include:

- **GHG emissions** (of fuels and electricity): Based on emission factors from Defra and the IRP (Defra, 2013; DoE, 2011)
- **Other life cycle GHG emissions**: For emission sources associated with the life cycle of the transport services (upstream and downstream of the service), emission factors from the ecoinvent database (http://www.ecoinvent.org/database/) were applied.
- **Water consumption**: Water requirements only calculated for the production of the main energy sources: diesel, biodiesel and electricity (Omni Tech International, 2010; DoE, 2011).

- **Externality costs**: These are additional costs incurred by society when a private party utilises a service. Costs for accidents, emissions, congestion, noise, roadway land availability and policing simulated based on data contained in Swarts *et al.* (2012).
- **Jobs**: The data used to derive the jobs indicator is taken from Barrett (2011).

To compare model outcomes, a Business As Usual (BAU) case was defined and output indicators expressed relative to the BAU case. The BAU case is fixed in the model and assumes that the ratio of freight (tonnes) on rail to road as in 2012 stays fixed throughout simulation period, the baseline fuel consumption is used for calculating road transport indicators and the revised balanced scenario is used as the electricity grid emissions factor.

3 MODEL RESULTS

The base case assumes that the only mitigation measures in place are the proposed carbon tax and assumed governmental biodiesel blending regulations. A 50% increase in rail operational performance is also assumed. Figure 4 illustrates when what volumes of the rail suitable and competing freight, collectively known as the Rail Addressable Market (RAM), starts to shift from road to rail. In this figure, the “rail suitable freight on rail” starts shifting to rail in large volumes between 2014 and 2017, and then stays on rail transport up to 2050. After 2017 the competing freight starts to shift from road to rail, which causes a large increase in the “total freight on rail” between 2017 and 2020. Despite the shifts to rail, there is still a gap between the “RAM” and the “total freight on rail” after 2020, which means that not all types of freight owners shifted their RAM to rail.

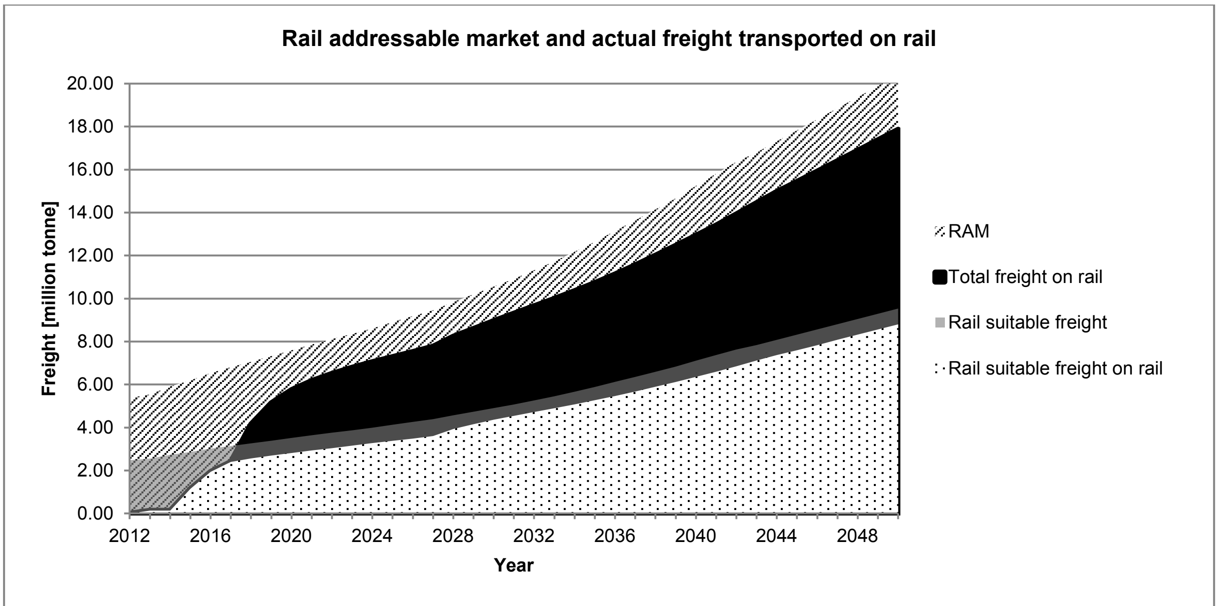

Figure 4: Freight on rail in base case compared to the Rail addressable market

Figure 5 shows the timing of mode shifts for each type of freight and freight owner. The shifting of freight from road to rail of the cost focussed freight owners, and their 90% market share, are clearly the reason for the bulk of the freight movement as discussed for Figure 4. “Cost focussed, rail suitable” freight starts to shift after 2014 and “cost focussed, competing” freight after 2017. Both these types of freight stay on rail transport up to 2050. “Reputation focussed, rail suitable” freight briefly moves on to rail in 2016, only to move back off in 2017. In 2027 it again moves on to rail, with this mode remaining the preferred mode to the end of the modelling period. “Reputation focussed, competing” freight never moves on to rail within the simulated timeframe.

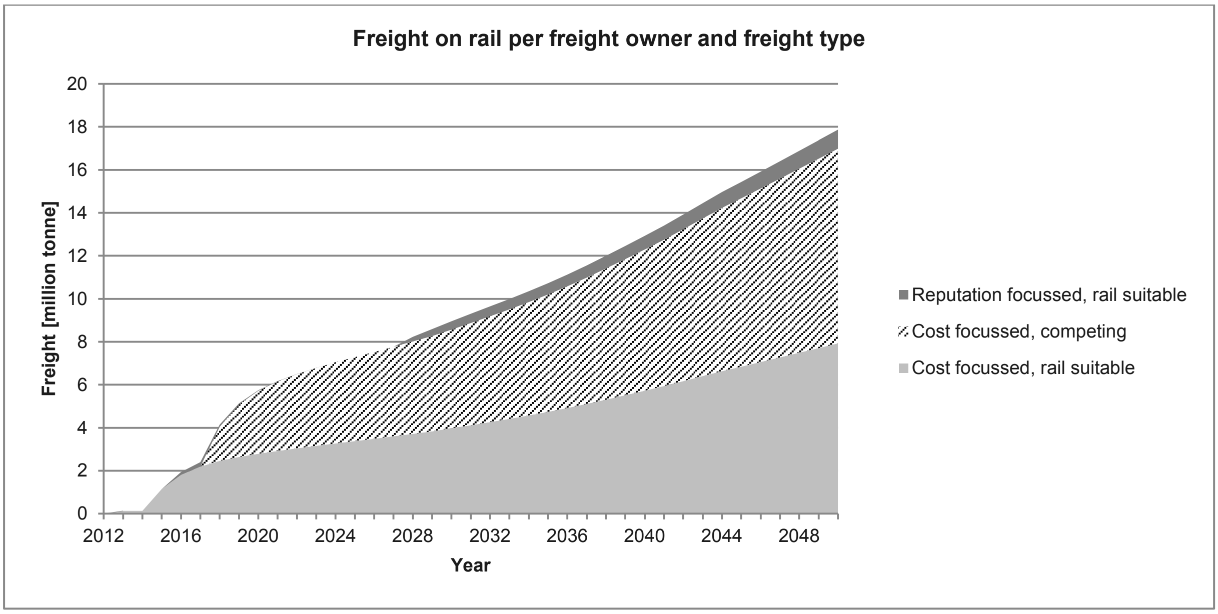

Figure 5: Rail freight per freight owner and freight classification

For presenting other model outputs, a comparison is made with the BAU case, as described above. The mode split is presented in Table 5 and the change in the main outputs in Figure 6.

Table 5: Mode split per freight owner

Output		Reputation focused	Cost focused	Total
Percentage RAM on rail in 2050 [% freight on rail]	BAU value	0	2.3%	0*
	BC value	47%	100%	95%
Percentage of total freight on rail in 2050 [% freight on rail]	BAU value	0	1.2%	0*
	BC value	23%	50%	48%

*Insignificantly small

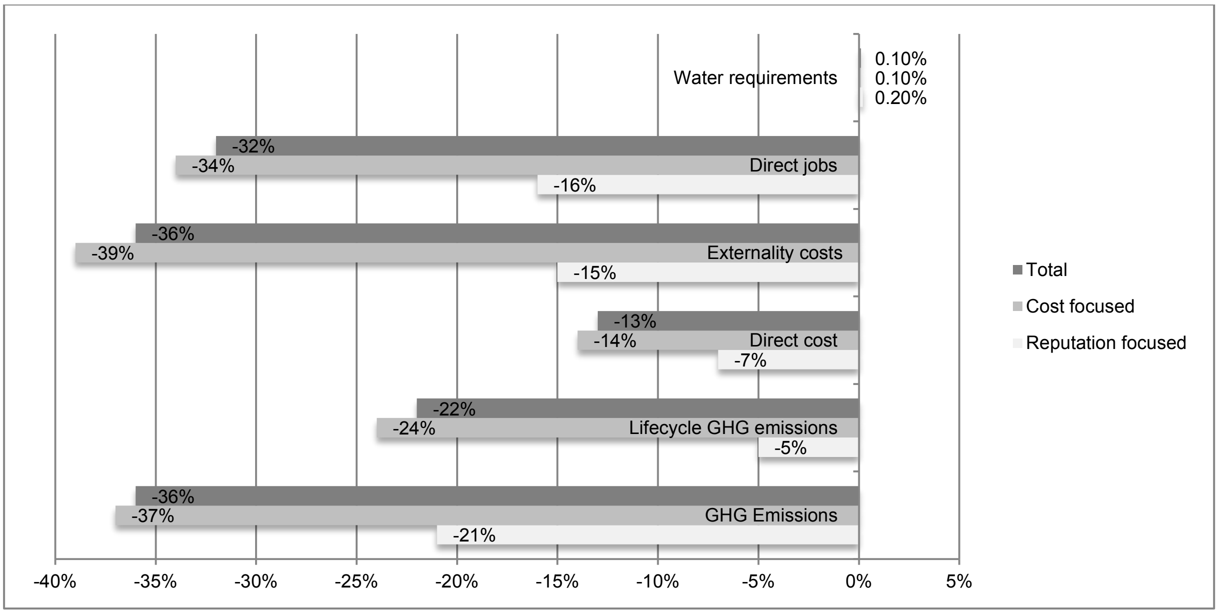

Figure 6: Change in outputs for base case simulation compared to the BAU

With the increased volume of freight on rail in the base case, the only negative impacts are the reduction in direct jobs and a slight increase in water requirements. The latter is as a result of increased water requirements for producing biodiesel. All other outputs are positive, with large reductions in GHG emissions and externality costs.

4 CONCLUSIONS AND RECOMMENDATIONS

The system dynamics model presented here provides a tool to better understand decision-making behaviour in the freight transport sector, particularly regarding mode choice. Using data and assumptions to reflect the processed food freight market a projection of mode share is made up to 2050 for transport on the Cape Town-Gauteng corridor. The model shows that a significant shift of the RAM from road to rail is possible for decision makers who prioritise cost over reliability. However, reputation focussed decision makers (who prioritise reliability) are only seen to shift a fraction of their RAM onto rail and only do so much later, even though rail operational performance is improved over time.

The accuracies of the model outputs are largely dependent on the inputs. Through a sensitivity analysis, input parameters were identified that cause large variation in outputs and that were based on assumptions, old data, or questionable data. These parameters are recommended for further research to refine the model, and include data related to:

- Characterization of the processed food market in terms of percentage of each type of decision maker as well as their decision-making priorities;
- Current rail and road transport costs;
- Utilisation of the rail infrastructure, available capacity, planned future capacity and the impact of capacity constraints on mode shifts;
- Additional rail delays not related to failures on the Cape Town to Gauteng corridor; and
- Rail infrastructure improvements and its impact on reliability and intermodal point upgrades.

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