IMPLICATIONS OF VEHICLE DESIGN
TO HEAVY TRUCK PERFORMANCE

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ABSTRACT

Improvements in productivity, efficiency, and safety are the primary motivating forces behind improvements in the design of components of heavy vehicles. Vehicle designers and operators require estimates of the productivity and efficiency implications of changes in vehicle design in order to evaluate the effectiveness of design improvements. For example, a vehicle designer may be able to reduce the tare weight of a vehicle chassis by using a new high strength alloy. While this reduced tare weight would increase the potential payload and, therefore, the overall productivity and efficiency of the vehicle, this increased productivity is only available at some cost; namely, the increased cost associated with using the new high strength alloy. The fundamental question faced by the vehicle designer and the operator is whether the increased productivity associated with the use of the new alloy more than offsets the increased costs. Numerous other similar examples could be cited relating to vehicle design and vehicle performance.

This paper presents a microcomputer based methodology capable of determining productivity and efficiency implications associated with change in vehicle design elements, and illustrates the application of this methodology by analyzing the implications of: 1) decreased vehicle tare weights, 2) increased allowable gross vehicle weights, 3) increased mechanical efficiency, 4) decreased rolling resistance, 5) decreased aerodynamic drag, and 6) decreased operating speed, for a fleet of petroleum tankers operating in western Canada.

The conclusions include: 1) the magnitude of productivity gains possible vary substantially relative to changes in various design elements (i.e. the potential productivity gains associated with increasing allowable vehicle gross weights are larger than those associated with decreased aerodynamic drag, 2) actual productivity gains attained are a function of both the design of vehicle components and the nature of the trucking operations (i.e. not all operators would reap the same benefits from a particular design feature), and 3) an understanding of the full implications of various design alternatives are necessary to optimize vehicle designs.

1.0 Introduction

There has been considerable interest in recent years in methods to increase the productivity/efficiency of transportation systems. Much of this interest was initiated by the energy crisis in the 1970's. Some of this interest has been focused on productivity/efficiency improvements associated with large trucks involved in freight transportation.

Efforts at increasing the productivity of large trucks have been focused on two specific areas; the first, increasing the size of trucks allowed to operate on public roads; and the second, improving the performance of existing designs.

A number of other papers presented at this conference, in particular, the other papers from Canada, focus on the issue of increasing vehicle weights and sizes. These types of changes have had a dramatic impact on the productivity of the trucking industry in Canada. There may be further room for increases in productivity if some of the current proposals to increase allowable gross vehicle weights are implemented. It is now routine to operate trucks with gross vehicle weights in excess of 60 tonne with payloads of 50 tonne on Canadian highways. Increases in productivity and efficiency of 15-30% have been observed with these larger vehicles. (1)

Allowing larger and heavier trucks to operate on public roads is an obvious way to increase productivity of these vehicles. Improving on existing designs to get more for less, while not being nearly as obvious, can also reap significant returns in productivity.

No matter which thrust is taken to increase vehicle productivity, it is highly desireable to be able to analyze and evaluate proposed methods of increasing vehicle productivity. This, as will be demonstrated below, can be done using modeling techniques.

2.0 Modeling Methods

Previous work {1} has described how vehicle operational productivity/efficiency determinations related to the trucking industry essentially become a costing exercise. It was also shown that appropriate measures of productivity, from an operations point of view, include .$/tonne km of payload, or for a particular vehicle, $/loaded km or $/running km.

Figure 1 illustrates the structure of a previously developed deterministic motor carrier costing model. As illustrated in Figure 1, productivity (as measured in cents/tonne km) is a function of a large number of inputs and/or assumptions about a relatively large number of variables. This results in a situation wherein the productivity as determined by the model can be highly variable, depending upon the value of inputs and/or basic assumptions made. This is indeed a reasonable representation of the real world. This high variability in results does however present a difficult situation for those attempting to make general comments about productivity. The usual approach has been to determine the productivity (cents/tonne km) for a number of typical situations to provide a "feel for" the various situations. This approach is clearly helpful however it does have its limitations because of the large number of variables and the large range in potential values for many of these parameters. (This point will be illustrated in the examples later in the paper.)

There is another approach which is possible which can contribute to a more complete understanding of the relationships between the various parameters and productivity. This approach involves the use of a model to carry out a deterministic sensitivity analysis.

3.0 Deterministic Sensitivity

In order to determine the relative importance of various variables in determining productivity as measured by cents/tonne km, a sensitivity analysis is undertaken using the deterministic model illustrated in Figure 1.

This is done as illustrated in Table 1 for a 5 axle tanker unit by specifying three values for each parameter. These values represent a minimum value, a maximum value and a most likely value for each parameter. (Observed values would be expected to fall inside the range defined by the minimum and maximum values about 98% of the time, i.e. ± 2 standard deviations from the mean.) The deterministic model is then used to evaluate the sensitivity of productivity to individual parameters by setting the value of all parameters equal to their most likely value except for one which is evaluated at its maximum and minimum value. The results of such a sensitivity analysis for a 5 axle tanker using the deterministic costing model illustrated in Figure 1 are summarized in Table 1 and illustrated in Figure 2. (Note: No allowance has been made for administration costs and profits. The analysis therefore allows for only vehicle operating costs as opposed to total operating costs. This is appropriate for our purposes herein because we are primarily concerned with the impact of changes in vehicle design on vehicle productivity.)

From Figure 2 it is noted that the various parameters can be generally categorized relative to the sensitivity of productivity to changes in values of their individual parameters (i.e. % variation column in Table 1). They might be generally classified as relatively insensitive, moderately sensitive and very sensitive. (The parameters to which productivity is highly sensitive are identifed in Table 1 by ** and moderately sensitive by *).

Given the results of the sensitivity analysis, it is possible to conclude that issues related to vehicle productivity will be primarily determined by the values of parameters to which productivity is very sensitive, to a lesser extent to those to which productivity is moderately sensitive and largely unaffected by those to which productivity is relatively insensitive.

For the example illustrated in Table 1 and Figure 2 it is possible to conclude that productivity is:

1) highly sensitive to:

- vehicle capacity and utilization as measured by vehicle gross and tare weight and total annual distance, and
- tractor cost as measured by distance wage rate;

2) moderately sensitive to:

- average fuel price,
- mechanical efficiency,
- coefficient of rolling resistance,
- speed,
- tractor costs of repair,
- capital costs of tractor, and
- trailer costs of repair;

3) relatively insensitive to all other parameters.

It is important to note that this analysis represents a particular operating scenario. This scenario is described by the values assigned to the individual costing variables. The costs (productivity) would be substantially different if the scenario changed. To illustrate, it has been assumed that a new tractor costing between $80,000 - $110,000 with a service life of 7-10 years and a salvage value of $20,000 - $30,000 was used on the haul. If a used tractor with a capital cost of $25,000 were used, the costs incurred and therefore the productivity would be substantially different. It is for these reasons that it is very difficult to generalize when dealing with costing and therefore productivity measures. Each vehicle has its own specific cost base associated with each particular operation.

4.0 Observations

Vehicle Gross Weights

In reviewing Table 1 and Figure 1, it is noted that a variation in vehicle gross weight from 37,500 kg to 43,000 kg results in a 17% change in productivity. This range in gross vehicle weight is the current difference between the allowed maximum for a 5 axle semi-trailer in Saskatchewan relative to Ontario, two provinces in Canada. This difference in "regulation" accounts for up to 17% difference in productivity for the same vehicle operating in the two different jurisdictions.

Vehicle Tare Weights

From Table 1 and Figure 1, it is noted that the vehicle tare weight was varied for analysis purposes from 11,500 to 14,500 kg. This range represents the variation in tare between typical 5 axle tanker units operating in Canada. This observed variation is associated with the type of tractor, type of trailer, equipment, accessories and the types of materials used in manufacture. It is noted that a "light" unit could be up to 15% more productive than its heavier counterpart in the typical Canadian operation described herein.

Total Annual Distance

The overwhelming productivity determinant is utilization as measured in our example by annual distance travelled. As noted, variations in productivity of up to 26% could be attributable to variations in annual utilization. Little wonder that it is the operator with high vehicle utilization that tends to set the pace in a competitive market.

Distance Wage Rate

Labor costs make up a significant portion of the costs of operating a truck. It is therefore not suprising that relatively small variations in the level of wages can make a marked difference in overall costs. From Table 1 it is noted that observed variations in wage rates can account for variations in productivity up to 13%.

Fuel Price and Consumption

The price of fuel and the consumption rate can have significant impacts on overall costs. Fuel prices are dictated by the market place and/or governments. On the otherhand, fuel consumption rates are to at least some extent, under the control of individual operators by way of how they select their equipment and maintain and operate it. As will be illustrated later, these decisions can have a dramatic impact on overall vehicle productivity.

Overall fuel consumption rates are dictated by mechanical efficiency, rolling resistance, density of air, coefficient of drag of the vehicle, the frontal area and operating speed. {2}

Mechanical efficiency is dictated largely by engine design and engine tune. Rolling resistance is a function of wheel bearings, type of tires and the type of road surface and structure. The only parameter under the control of the operator is the selection of tires. This alone can result in reducing the rolling coefficient from .0085 to .0047 {2}. This variation could be as simple as selecting good radial tires over standard bias ply tires.

Trucks and tractors are still being designed as general "box" shapes with wheels underneath {2}. It is only in the last few years that any obvious attempt has been made by vehicle manufacturers to decrease the aerodynamic drag of the vehicle through vehicle design modifications. The usual approach to date, at least in North America, has been to design the vehicle without consideration to aerodynamics and then let the operator try to improve the operation with drag reducing add-ons. Usually not more than 10% improvement is achieved in fuel efficieny with these add-on devices. On the otherhand, if aircraft technology were applied to trucks, drag coefficients could be reduced from 1.0 down to the 0.3 region {2}. In this context, it is also important to note that the drag coefficient used in the model varied from .8 to 1.0 (see Table 1) and the density of air was assumed to be constant at .0024. The range for the coefficient of drag (i.e. .8 to 1.0) more accurately represents the range for calm air conditions than it does for possible real world conditions. If there is a crosswind for example, the actual coefficient of drag experienced by the vehicle could vary more in a range from .6 to 1.2. This would obviously make the coefficient of drag an even more important parameter than is suggested by our (conservative) analysis. Further, the density of air actually varies as a function of barometer pressure and temperature. In western Canada where temperatures at the road surface can vary from -40° C to +40° C, the density of the air could vary from .0030 to .0022 which accounts for much of the 5-10% variation in operating costs observed between summer and winter conditions. This additional factor has not been included but could be significant in some cases.

Speed not only kills in the context of vehicle safety, but it can also have signficiant effects in overall costs of operating a vehicle. First increased speed increases fuel consumption. As noted from Table 1, a modest increase in speed from 80 km/hr to 110 km/hr can decrease overall vehicle productivity by 5%.

Speed also indirectly influences the cost of repairs for the tractor and the trailer. These costs which are partially attributable to operating speed, can contribute 5-7% variation in the overall productivity of large trucks.

Capital Cost of Tractor

The cost of equipment, in particular the tractor, can be an important part of overall costs and therefore an important determinant in productivity. In general, the less capital required to do the job, the more productive the operation. This when applied to the trucking industry, means "no chrome" and "no frills".

5.0 Conclusions

Figure 1, Table 1 and the above discussion has illustrated that a large number of variables go into determining the overall productivity of a large truck in providing transport service. Some of these parameters are more important than others in determining productivity. Some are a function of the operation (i.e. utilization), some a function of the equipment selected (i.e. vehicle tare weight), and some a function of the manner in which the vehicle is operated (i.e. speed).

The impact of operator decisions upon productivity can be demonstrated. Table 2 summarizes the expected results if an operator were to do everything "right" with respect to the parameters under his control (i.e. minimum values for the parameters summarized in column 1 in Table 2), relative to doing everything "wrong" in terms of these parameters (i.e. maximum values for parameters in column 1 in Table 2). It is noted that the overall productivities of doing things "right" relative to doing them "wrong" could be up to 50% difference. This is clearly beyond the margin of profitability within any significant trucking operation. It also is interesting to note that the difference between doing it wrong and doing it right translates to decisions like buying a relatively heavy, expensive (overequipped) vehicle with bias ply tires operated at relatively (but in many ways, typical) speeds.

In short, while increasing vehicle sizes and weights can increase vehicle operation productivity by 15-30%, similar improvements in productivity are attainable by doing more with less through design improvements to existing vehicles.

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2. Hertz, P.B., Technical Aspects of Transport Energy Efficiency, Internal Working Paper, Mechanical Engineering Department, University of Saskatchewan, July 1982.

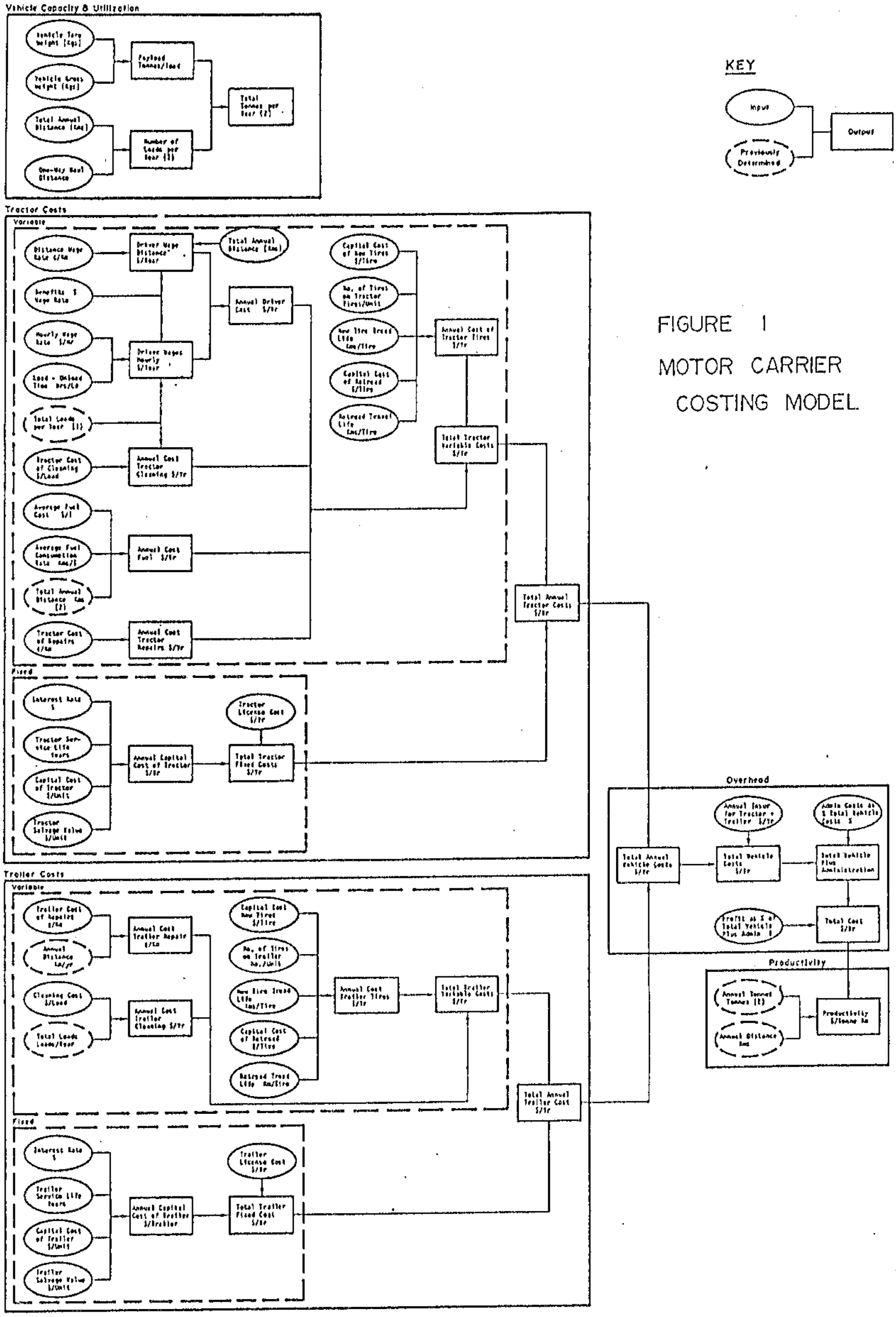

FIGURE 1
MOTOR CARRIER COSTING MODEL

TABLE 1

DETERMINISTIC SENSITIVITY 5 AXLE-TANKER

INPUT PARAMETER	TYPICAL VALUE - INPUTS			ASSOCIATED PRODUCTIVITY (CENTS/TONNE KM)			% VARIATION
	MINIMUM	MAXIMUM	MOST LIKELY	MINIMUM	MAXIMUM	MOST LIKELY	
VEHICLE CAPACITY AND UTILIZATION							
PAYLOAD (KGS PER LOAD)							
VEHICLE GROSS WEIGHT (KGS)	37500	43000	37500	2.11	2.53	2.53	17
VEHICLE TARE WEIGHT (KGS)	11500	14500	13000	2.39	2.78	2.53	15
TOTAL LOADS PER YEAR							
TOTAL ANNUAL DISTANCE (KMS)	90000	240000	170000	2.37	3.02	2.53	26
ONE WAY HAUL DISTANCE (KMS)	500	900	700	2.49	2.61	2.53	5
TRACTOR COSTS							
VARIABLE COSTS							
DISTANCE WAGE RATE ($/KM) (2)	0.12	0.18	0.15	2.37	2.7	2.53	13
HOURLY WAGE RATE ($/HR) (2)	6.5	12.5	9.75	2.48	2.59	2.53	4
BENEFITS AS % OF WAGE RATE (%)	25	40	32	2.48	2.59	2.53	4
LOAD-UNLOAD TIME (HRS/LOAD)	0.5	1.5	1	2.46	2.61	2.53	6
AVERAGE FUEL PRICE (CENTS/L)	25	35	30	2.45	2.62	2.53	7
AVERAGE FUEL CONSUMPTION RATE (KMS/L)							
MECHANICAL EFFICIENCY	23	33	28	2.46	2.65	2.53	8
COEF OF ROLLING RESISTANCE	0.0047	0.0085	0.0066	2.45	2.62	2.53	7
DENSITY OF AIR (slugs/cu.ft.)	0.0024	0.0024	0.0024	2.53	2.53	2.53	0
COEFFICIENT OF DRAG	0.8	1	0.9	2.51	2.56	2.53	2
FRONTAL AREA (sq.ft.)	80	100	90	2.51	2.56	2.53	2
SPEED (km/h)	80	110	100	2.46	2.58	2.53	5
TRACTOR COSTS OF REPAIR ($/KM)	0.02	0.06	0.04	2.45	2.62	2.53	7
TRACTOR COST OF CLEANING ($/LOAD)	1	5	3	2.52	2.55	2.53	1
NO. OF TIRES ON TRACTOR (TIRES/UNIT)	10	10	10	2.53	2.53	2.53	0
CAPITAL COST OF NEW TIRES ($/TIRE)	260	460	360	2.52	2.55	2.53	1

TABLE 1 (CONTINUED)

DETERMINISTIC SENSITIVITY 5 AXLE-TANKER

INPUT PARAMETER	TYPICAL VALUE - INPUTS			ASSOCIATED PRODUCTIVITY (CENTS/TONNE KM)			% VARIATION
	MINIMUM	MAXIMUM	MOST LIKELY	MINIMUM	MAXIMUM	MOST LIKELY	
TRACTOR COSTS (CONT'D)							
NEW TIRE TREAD LIFE (KMS/TIRE)	100000	320000	200000	2.52	2.55	2.53	1
CAPITAL COST OF RETREAD ($/TIRE)	240	330	280	2.53	2.54	2.53	0
RETREAD TREAD LIFE (KMS/TIRE)	160000	600000	360000	2.51	2.58	2.53	3
FIXED COSTS							
CAPITAL COST OF TRACTOR ($/UNIT)	80000	110000	90000	2.49	2.62	2.53	5 *
TRACTOR SERVICE LIFE (YRS)	7	10	8.5	2.51	2.57	2.53	2
TRACTOR SALVAGE VALUE ($/UNIT)	20000	33000	27000	2.51	2.57	2.53	2
INTEREST RATE (%)	8	14	10	2.5	2.6	2.53	4
TRACTOR LICENSE COST ($/YR)	1500	2200	2000	2.52	2.54	2.53	1
TRAILER COSTS							
VARIABLE COSTS							
TRAILER COST OF REPAIRS ($/KM)	0.04	0.07	0.055	2.47	2.6	2.53	5 *
CLEANING COST ($/LOAD)	1	5	3	2.52	2.55	2.53	1
NO. OF TIRES ON TRAILER (NO./UNIT)	8	8	8	2.53	2.53	2.53	0
FIXED COSTS							
CAPITAL COST OF TRAILER ($/UNIT)	30000	50000	40000	2.49	2.58	2.53	4
TRAILER SERVICE LIFE (YRS)	6	10	8	2.52	2.57	2.53	2
TRAILER SALVAGE VALUE ($/UNIT)	5000	13000	10000	2.52	2.56	2.53	2
TRAILER LICENSE COST ($/YR)	22	22	22	2.53	2.53	2.53	0
OVERHEAD							
ANNUAL INSURANCE - TRACTOR & TRAILER ($/YR)	3300	4400	3900	2.52	2.55	2.53	1
ADMIN. COSTS % OF TOTAL VEHICLE COSTS (%)	0	0	0	2.53	2.53	2.53	0
PROFITS AS % TOTAL VEHICLE PLUS ADMIN. (%)	0	0	0	2.53	2.53	2.53	0

FIGURE 2 DETERMINISTIC SENSITIVITY
5 AXLE TANKER

		% VARIATION
VEHICLE CAPACITY & UTILIZATION	PAYLOAD	
	VEHICLE GROSS WEIGHT	17
	VEHICLE TARE WEIGHT	15
	TOTAL LOADS PER YEAR	
	ANNUAL DISTANCE	26
	ONE WAY HAUL DIST.	5
TRACTOR COSTS	VARIABLE COSTS	
	DISTANCE WAGE RATE	13
	HOURLY WAGE RATE	4
	BENEFITS	4
	LOAD/UNLOAD TIME	6
	FUEL PRICE	7
	FUEL CONSUMPTION	
	MECH. EFFICIENCY	8
	ROLLING RESISTANCE	7
	DENSITY OF AIR	0
	COEF. OF DRAG	2
	FRONTAL AREA	2
	SPEED	5
	REPAIR COSTS	7
	CLEANING COSTS	1
	CAPITAL COST- TIRES	1
	NEW TIRE LIFE	1
	CAPITAL COST-RETREAD	0
	RETREAD LIFE	3
	FIXED COSTS	
	CAPITAL COST-TRACTOR	5
	SERVICE LIFE	2
	SALVAGE VALUE	2
	INTEREST RATE	4
	LICENSE COST	1
TRAILER COSTS	VARIABLE COSTS	
	REPAIR COST	5
	CLEANING COST	1
	FIXED COSTS	
	CAPITAL COST-TRAILER	4
	SERVICE LIFE	2
	SALVAGE VALUE	2
	LICENSE COST	0
OVERHEAD	INSURANCE	1
	ADMINISTRATION	0
	PROFITS	0

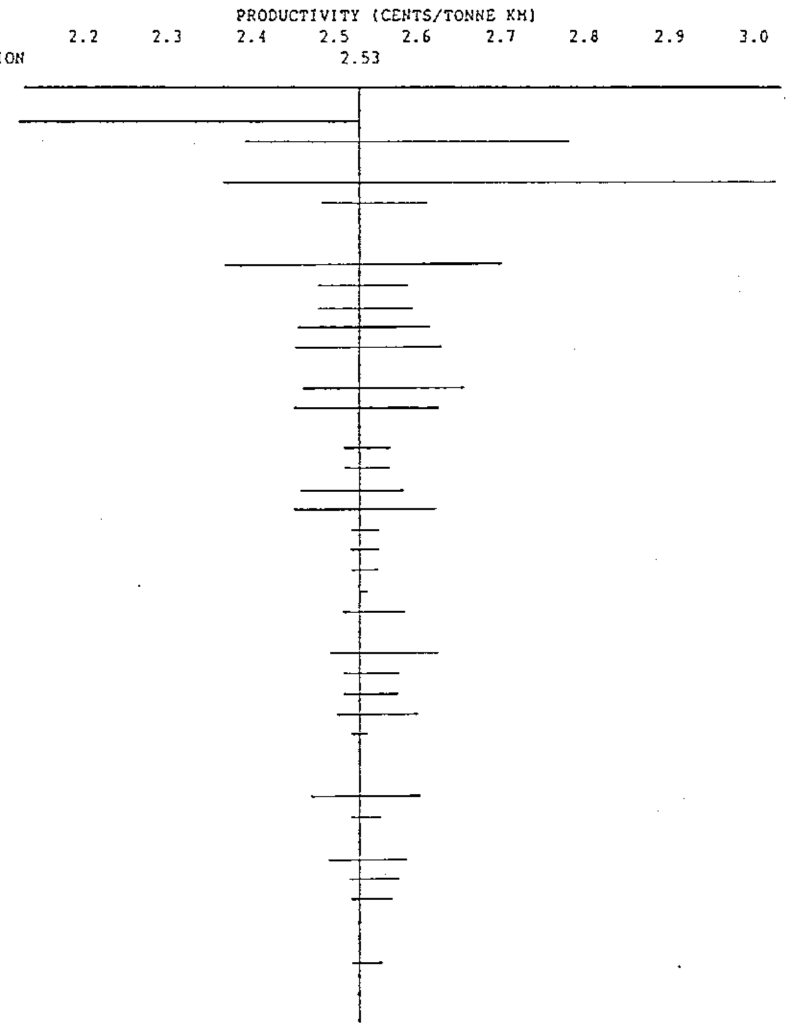

TABLE 2

PARAMETERS UNDER OPERATORS CONTROL

PARAMETER	EXPECTED VALUES		
	MINIMUM	MAXIMUM	MOST LIKELY
VEHICLE TARE WEIGHT (kg)	11,500	14,500	13,000
SPEED (km/h)	80	110	100
COEFFICIENT OF ROLLING RESISTANCE (choice of tires)	0.0047	0.0085	0.0066
TRACTOR COST OF REPAIR ($/km) (speed related)	0.02	0.06	0.04
CAPITAL COST OF TRACTOR ($) (no chrome)	80,000	110,000	90,000
TRAILER COST OF REPAIR ($/km) (speed related)	0.04	0.07	0.055

PRODUCTIVITY WITH PARAMETERS AT MOST LIKELY VALUES = 2.53 cents/tonne km

PRODUCTIVITY WITH PARAMETERS AT MAXIMUM VALUES = 3.09 cents/tonne km

PRODUCTIVITY WITH PARAMETERS AT MINIMUM VALUES = 2.06 cents/tonne km