Road network analysis of sugar cane haulage in the Sunshine Coast region, Queensland

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Abstract

The expansion of sugar cane cropping into new localities requires an assessment of economic viability combined with biophysical suitability modelling. A key determinant of the viability is the cost of transport, measured in time, of the voluminous sugar cane to the processing mill. Modelling the times across a large region can provide guidance to the localities that would be economically marginal given a particular transport scenario. The Sunshine Coast region is presently undergoing an expansion program into areas that are not traditionally sugar cane growing localities. The proposed transport network model described in this paper predicts travel times using only a roads coverage, digital elevation model and cadastral coverage. Five main impediments to travel time were considered; road slope, road class, urban zoning, road length, intersection delay and mill departure delay. Comparison with recorded travel time for existing sugar cane plantations showed a highly significant correlation to predicted. Potential areas located in the ranges are shown to be too distant while areas to the north are considered suitable.

Introduction

The expansion of sugar cane cropping into new localities requires an assessment of economic viability combined with biophysical suitability modelling. A key determinant of the viability is the cost of transport of the voluminous sugar cane to the processing mill. In an agricultural system dominated by trucks, using public road networks, the *time* to haul from the farm to the mill forms the basis of the transport costs. Modelling the times across a large region can provide guidance to the localities that would be economically marginal given a particular transport scenario.

Sugar cane is transported across the Sunshine Coast region where gently undulating coastal plains are backed by rugged ranges interspersed with river valleys (figure 1). The existing sugar cane industry occupies the central flood plains around the city of Nambour. Urbanisation and a diverse range of intensive horticulture are rapidly displacing the sugar cane plantations. Combined with an economic requirement to increase production volume, the cane growers and the processing mill operators have united to promote the uptake of cane growing in the region. The full extent of the land available is determined by the economic viability of the transport coverage.

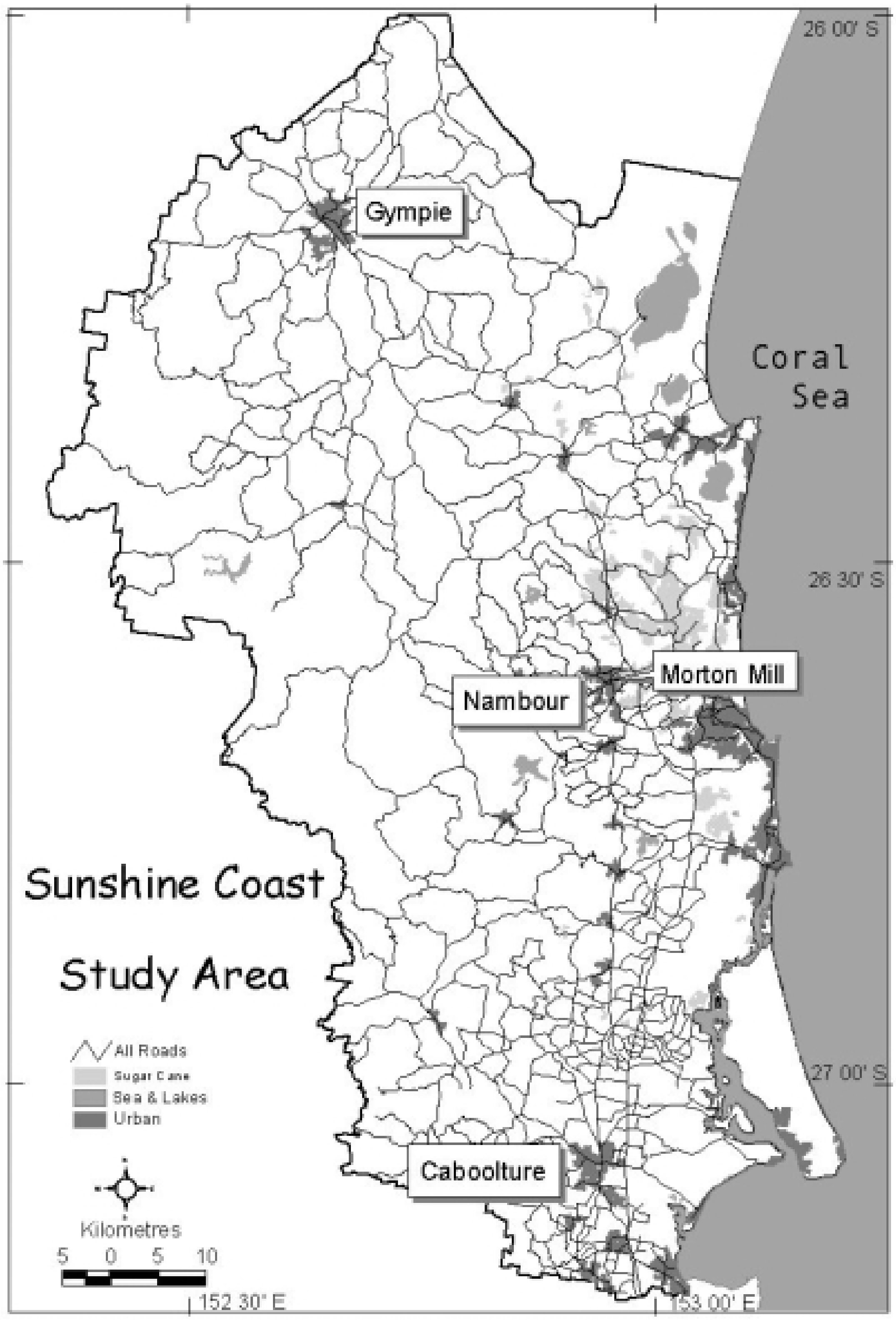

Figure 1. Sunshine Coast regional road network

The road network, in general, is being upgraded to cope with the increased traffic loads from continued urban development. However the trucks have to contend with urban speed and traffic flows, variable road gradients and mixed road surfaces. Dedicated rail transport is being phased out due to the cost of infrastructure maintenance and limited ability to cope with expansion to new areas. This paper describes a quantitative network model of a road transport infrastructure using only a limited set of spatial data sets.

The application of network modeling for regional transport systems appears limited to the freight and people commuting sector rather than for the primary production industry (Pursula 1999). The estimation of cost for freight transport is the key focus for several authors. Goods transport across the trans-European network is modeled by Jourquin and Beuthe (1996). Using data for the loading, moving, unloading, transshipping and transiting components Jourquin and Beuthe are able to derive efficiency-cost functions. Each network section and node is costed using a function of vehicle fixed costs, time to handle the goods, truck capacity, energy consumption and average speed. The model indicates that the level of taxation for road transport is the primary determinant for the use of railways and, to a lesser extent, waterways (Jourquin & Beuthe 1996). This model comprehensively determines the cost when using established transport routes between major centres but is unsuitable for an agricultural region with variable travel times caused by mixed road classes and slope changes.

Crossley (1998) outlines an expert system called RANE that predicts total road and vehicle costs. The road type, gradient, curvature, roughness, rolling resistance, traction and width are recorded for each road section. For each type of vehicle traveling on the various road classes the cost is estimated. The vehicle demand for each road class is assessed. Thus the total cost package of road infrastructure and vehicle fleet maintenance can be estimated. In the Kilimanjaro region of Tanzania where this model was applied, insufficient funding is causing the road system to deteriorate disproportionately. Rural feeder roads are being sacrificed financially to maintain the major arterial roads (Crossley 1998). This system introduces some excellent uses of the road conditions for economic modeling but does not incorporate a spatial network function that facilitates the derivation of optimum travel routes given the road and vehicle infrastructure.

Johansson (1997) also models the cost of road use with a bias towards optimal road use charging due to congestion and emissions. As the level of congestion increases the fuel consumption and emissions increase and this is a function of a speed-flow relationship. Using the linear speed-flow and the speed-density relationships this model indicates that users should pay a road charge corresponding to the vehicle emissions and additionally pay for the increased emissions of other road users (Johansson 1997). Although this model is not directly related to the derivation of transport times in the Sunshine Coast the implications concerning the cost and increased congestion are worth noting.

Optimal commuting travel routes are modeled in a similar approach to freight transport. Thériault et al (1999) used maximum speed for each road class, network route optimization, distance to nearest school, turn and transfer penalties to model congestion and related travel patterns. The outputs can then be used for strategic allocation of resources and planning for the amelioration of congestion points (Thériault et al. 1999). This model comprehensively accommodates an array of demographic and route data to produce travel estimates for an urban environment. In a rural environment the restrictions of speed vary more with localized conditions rather than congestion for the majority of the network (Pursula 1999). Managing traffic flows in real-time models provide a method of managing the congestion restrictions (Kosonen & Bargiela 1999) but are unlikely to impact on the Sunshine Coast for some period. However the road upgrades for a region can create induced traffic issues through increased usage (Hills 1996). Increases in truck-based transport can impact heavily on a regions transport infrastructure and subtle influences such as tightening customer service requirements and the just-in-time imperatives can increase the transport load to critical levels (McKinnon & Woodburn 1996).

The switch from rail to road transport in particular can place additional stress on infrastructure beyond planning expectations (McKinnon & Woodburn 1996). In India the growth of freight traffic has been 9.5% for the period 1980–94 and infrastructure bottlenecks are creating considerable congestion (Ramanathan & Parikh 1999). The switch from rail transport to road transport for the Sunshine Coast will create a stress on the Nambour city streets which may mimic the Indian bottlenecks (Nierat 1997). Population growth of 2.1% (Queensland Department of Local Government and Planning 1996) in the region will exacerbate the congestion. The subsidization of rail transport as a means of reducing the infrastructure stress is promoted by Ramanathan and Parikh (1999). The proposed model does not address the use of railways but only minor modification would be required to make the network more inclusive.

Stress caused by increased energy demands from the road transport sector has been modeled world wide (Samimi 1995, Johansson 1997, Ramanathan 2000). In Australia the transport sector is the largest consumer of energy with road transport being responsible for 79% of consumption (Samimi 1995). The impact of fuel shortages on sugar cane haulage are not included in this model but should be investigated. In particular the use of alternative fuels and strategic planning require more attention (Ramanathan 2000).

Method

Derivation of accurate travel times relies on detailed data on a wide variety of traffic conditions. At a regional scale the information for intersection delays and traffic peaks is not available for all roads in the Sunshine Coast (QLD Department of Main Roads 1999). Instead the network model utilised a roads layer and digital elevation model (DEM) at 1:100,000 scale and a cadastre layer at 1:25,000 scale to accommodate the various restrictions on truck transport. Five main impediments to travel time were considered; road slope, road class, urban zoning, road length, intersection delay and mill departure delay. Note that several assumptions are used. Firstly that there is a direct relationship between speed and network flow (Johansson 1997). Secondly the times taken to drive a fully laden truck from a farm to the processing mill are the same as the return unladen journey. Thirdly the time to offload and load the sugar cane for each farm is identical. Fourthly, the speed of a truck is identical when going up or down a slope.

The effects of road slope on the speed of a truck were calculated for each road segment. Slope, derived from a DEM, was classified into 2 degree slices up to 16 degrees. These slices were then used to cut up the road network into discrete arcs of minimal slope variation. Each node, defining the start (from) and finish (to) of an arc, is attributed for elevation from the DEM. The slope of each arc is then determined from the trigonometric relationship between the 'from' and 'to' node using the Euclidean distance instead of the arc length. This laborious process was necessary since many roads are engineered to minimize road gradient by tracking across steep slopes. This method of slicing arcs at slope changes and then calculating the change in node elevations was able to estimate the gradient independent of the DEM-derived slope values.

Using the slope value the effect on the speed of a truck was estimated. To derive an exact effect that a slope would have on truck speed would involve very detailed knowledge of gear ratios, engine power and torque curves for each truck. This was not possible and an approximate solution was adopted with the information available.

The major determinants of velocity on a slope are the weight of the truck and the power of the engine. Truck gross weight ranges from 42.5 to 59 tonnes fully laden (Jorgensen 1995) depending on the configuration of trailers. A central figure of 50 tonnes was chosen as the average weight however modelling the network for optimum capacity and truck configuration could be informative. Engine power based on the standard Caterpillar C-15 engine is maximized at 265 kW (Caterpillar 2001). Advice from Morton Mill engineer Peter Harders (pers comm.) outlines a range from 209 to 317kW for the existing transport fleet. Derivation of a velocity function with slope involved several stages. The individual components of the force equation (1) are firstly calculated (figure 2).

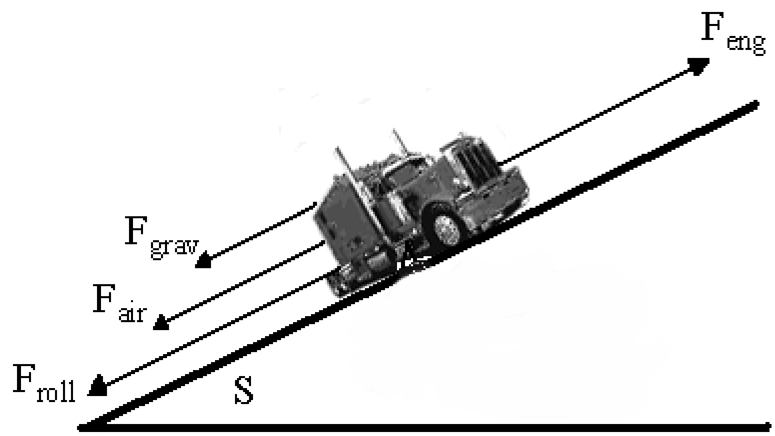

Figure 2. Forces operating on a truck traveling up a slope where F_{grav} is the gravitational forces, F_{air} is the air resistance, F_{roll} is the rolling resistance and F_{eng} is the engine force.

The net forces acting in figure 2 result in equation 1 where F_{eng} is the engine force, F_{air} is the air resistance, F_{roll} is the frictional force of rolling a tire along a surface and F_{grav} is the gravitational force.

$$Force_{nett} = F_{eng} - F_{air} - F_{roll} - F_{grav} \quad (1)$$

Rolling resistance:

$$F_{roll} = \mu.M.g.\cos(S) \quad (2)$$

Where µ is the coefficient of the object's rolling friction, M is the Gross Vehicle Mass, g is gravitational force and S is the slope of the road. The specific values for the sugar cane transport are input. The coefficient of friction for a truck tyre on a asphalt is 0.008 (Bosch 1996).

$$F_{roll} = 0.008 \text{ x } 50{,}000 \text{ x } 9.8 \text{ x } \cos(S)$$
$$= 3.92\cos(S) \text{ kN}$$

Gravitational force:

$$F_{grav} = M.g.\sin(S) \quad (3)$$

Substituting for a 50 tonne truck.

$$F_{grav} = 50{,}000 \text{ x } 9.8 \text{ x } \sin(S)$$
$$= 490\sin(S) \text{ kN}$$

Air Resistance:

$F_{air} = 0.5.\rho.\ Cw.A.(V + V_0)^2$ (4)

Where ρ is the viscosity of air, Cw is the coefficient of drag, A is the frontal area, V_0 is the headwind and V is the velocity. Given that headwind is assumed to be zero the formulae can be reduced to;

$F_{air} = \kappa V^2$ where $\kappa = 0.5.\ \rho.\ Cw.A$ (5)

Substituting into equation 1.

$F_{nett} = F_{eng} - \kappa V^2 - 3.92\cos(S) - 490\sin(S)$ (6)

To determine κ the formulae $F_{eng} = Power_{eng}/Velocity$ (7) is used. Maximum power (265 kW) is assumed to be applied when velocity is 100km/hr (27 ms^{-1}) on flat road (ie. S = 0). Substituting into equation 6.

$F_{nett} = 0 = F_{eng} - \kappa V^2 - 3.92\cos(0) - 490\sin(0)$
$= (265/27) - \kappa 27^2 - 3.92$

$\therefore\ \kappa = 0.008$

For a truck traveling at constant velocity up a slope equation 6 needs to be solved for $F_{nett} = 0$. Assume that in first gear the maximum torque occurs at 10km/hr (2.77 ms^{-1}) where the power is less than the maximum power and is nominally 10% less at 238 kW.

$F_{eng} = 238/2.77 = 86$ kN

Solving for $F_{nett} = 0$

$0 = 86 – 0.008V^2 - 3.92\cos(S) - 490\sin(S)$

$V = \sqrt{[(86 – 490\sin(S) – 3.92\cos(S))/0.008]}$ (7)

Equation 7 then describes the rough estimate of velocity as a function of slope. Figure 3 shows the curve of the function. Although the assumptions used to derive the velocity function ensure the results are very approximate the creation of a mathematical framework facilitates the input of specific truck performance data. Possibly the allocation of a specific truck to particular farms could optimize efficiency by matching power availability to physical terrain characteristics of the collection area.

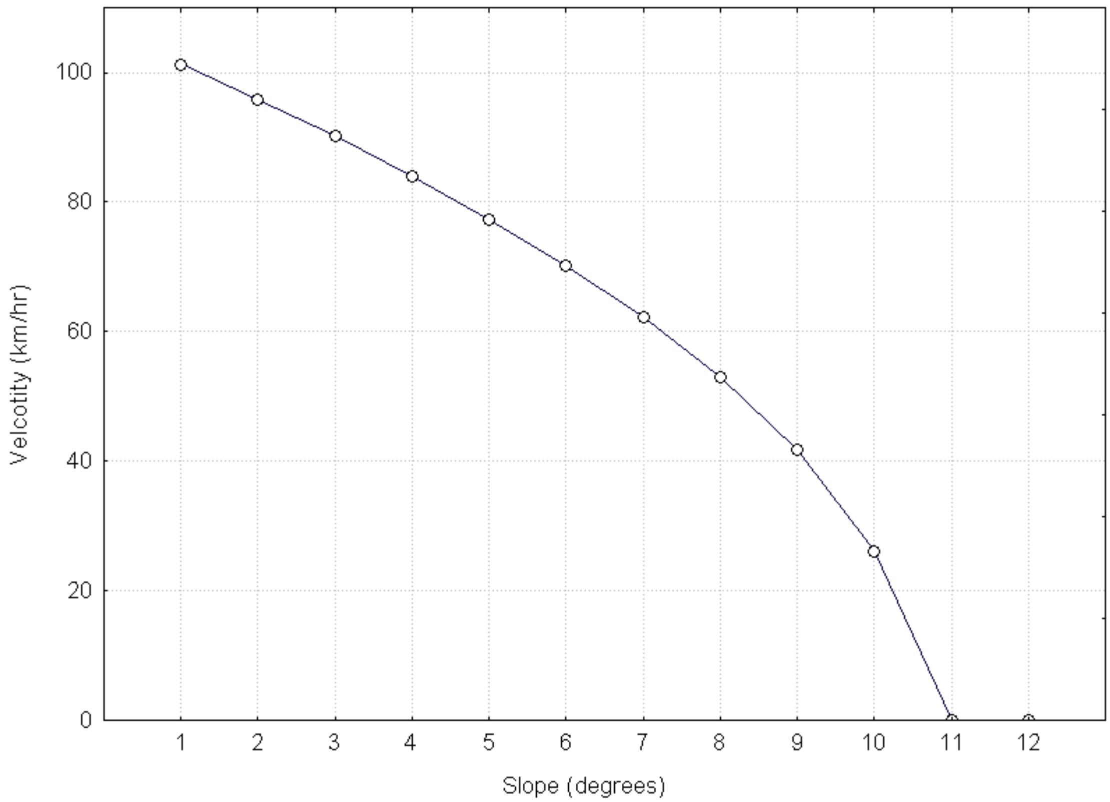

Figure 3. Plot of equation 7

The road class describes the state and inherent restrictions for the particular road section. For instance a class 1 road is a freeway and has a speed limit of 110km/hr, minimal gradients and no intersection delays. Trucks can essentially cruise at 100 km/hr with out modification for various spatial features. Class 3 describes most country roads and incurs speed restrictions from gradients, intersections and a speed limit of 100km/hr. Each class is processed individually with respect to speed limit, slope calculation and intersection penalties.

Urban zoning impacts significantly on the network traffic flow with traffic lights and speed limits. As a result the average speed for a truck in an urban zone is set at 10 km/hr. The exact location of traffic lights or speed zones was unknown and so cadastral data was used. Cadastral blocks of 3000 metres square or less are buffered by 50 metres which clumps adjoining house blocks into polygons. If these polygons exceed 300,000 metres square then the roads in these areas are considered to be urban. Freeways and highways are exempt from this restriction.

Road length is derived from the arc length and may show inaccuracies when the digital line work does not follow the actual road path. Intersection delays are calculated as 6 seconds for left turns, 12 second for right turns and no delays for driving strait through. Thériault et al (1999) used the values of 24 seconds for left turn, 12 seconds for right turn and 6 seconds for passing through an intersection. Allowing for the reversed Canadian driving rules the increase in delays reflect complexity of the intersections in an urban environment. Departure and arrival at the mill is delayed by 5 minutes, which accommodates delays in driving out of the mill and increased traffic caused by the Morton Mill being located in the centre of Nambour city.

Comparison of the predicted times was conducted with times recorded by the Morton Mill for existing cane farm transports. The Morton Mill recorded complete round trip times and so to compare against the single trip times generated by the model the recorded times were halved then 4 minutes deducted for loading (Peter Harders pers comm.). There was no possibility to analysis the variability of the recorded data as the times were indicative only. Recorded data was not available for areas outside of the existing cane growing areas and thus the comparison will contain bias towards the coastal road network attributes.

Results

A region wide map showing roads with indicative travel times was produced (figure 4). Travel times within the study area reached 86 minutes to the west, 78 minutes to the north and 70 minutes to the south.

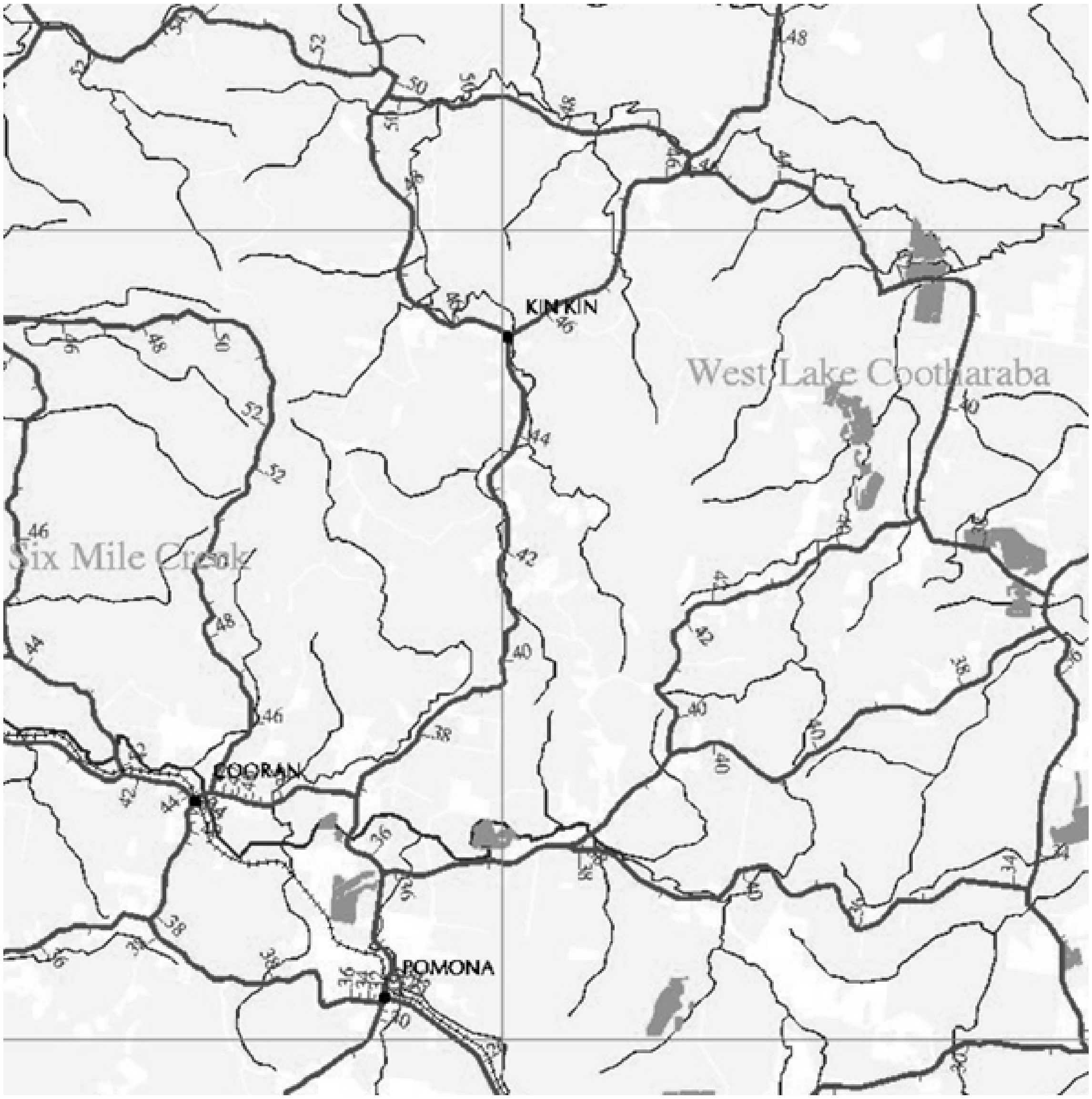

Figure 4 Section of network model output showing travel times to processing mill

Regression analysis showed a significant correlation to the recorded data ($R^2_{adj} = 0.78$, $F(1, 15) = 57.87$, $p < 0.001$; figure 5). Two recorded times were omitted from the study since the urban and roads data for the specific locality were considerably outdated following recent urban developments.

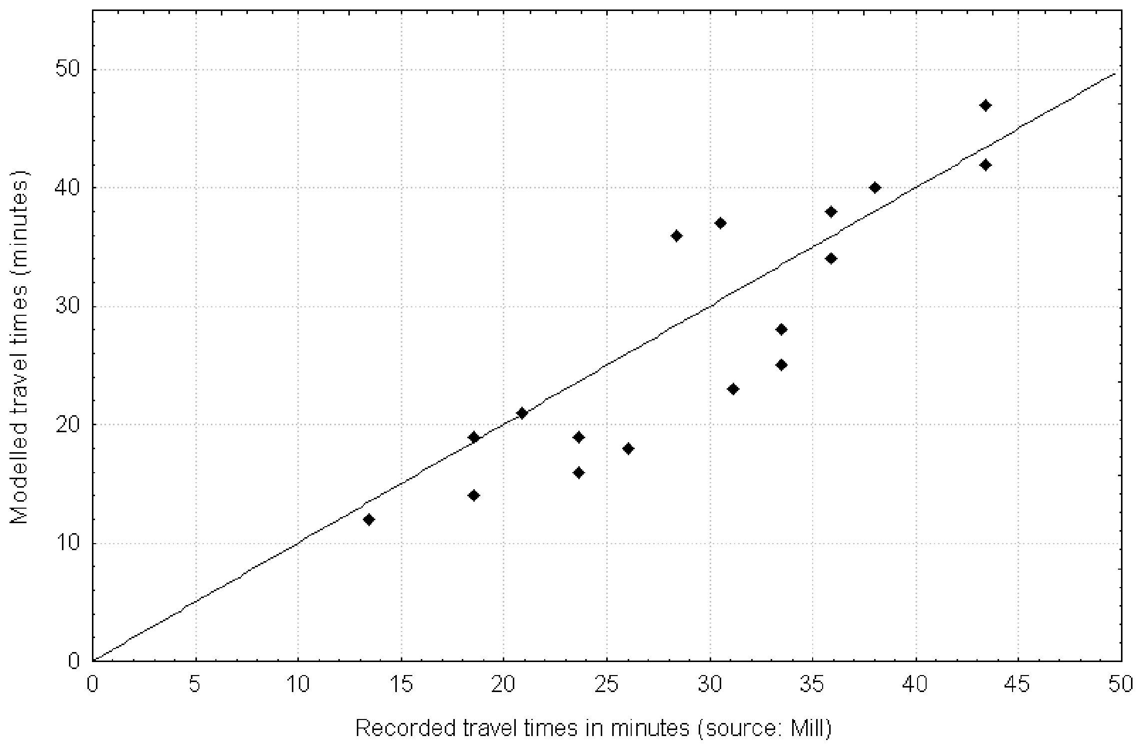

Figure 5 Graph of recorded verses modeled travel times

Discussion

The application of network modelling to regional transport issues can provide a perspective that is informative to regional resource utilisation. Although most land owners considering adopting sugar cane cropping would have an accurate idea of the transport times this style of modelling offers several additional benefits. Firstly the entire region is presented in a map format and zones of potential can be identified for further investigation and marketing. Secondly the issues relating to the restrictions on road transport, such as urbanization, road conditions and network utility, can be prioritized and quantified in the regional planning schemes. Thirdly the ability to enhance the model with rail transport could facilitate economic optimization of regional transport systems.

From the Sunshine Coast cane growers perspective the model clearly showed that the areas in the hills (Woodford and Conondale) are out of transport range (> 50 minutes) while areas in the north (Lake Cootharaba and Mary River Valley) show potential. There is no definitive travel time limit since the size of the cropping area combined with productivity factors can influence the economic decision to proceed with sugar cane cropping.

Acknowledgements

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