MEASURING AND EVALUATING LOG TRUCK PERFORMANCE IN A VARIETY OF OPERATING CONDITIONS

by

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(ABSTRACT)

Studies of log truck speeds and fuel consumption were made at four location in the south eastern United States. Execution of the study necessitated the development and testing of a microprocessor based data logger capable of withstanding the harsh operating environment found in forest harvesting and transport equipment.

The first study investigated the normal operating pattern for a truck in a logging contractors fleet. The truck was found to be highly utilized and to incur considerable distances of unloaded running to service the contractor's widely separated operations. A second study highlighted the fuel and speed penalties associated with operations on sand and gravel roads.

The third study documented significant performance differences between routes delivering to one location even where road surface differences were minimal. A fourth, detailed study illustrated speed and fuel consumption differences between urban and rural operations. Tests on a group of five experienced drivers demonstrated considerable differences in speed and fuel usage. Some drivers appeared to have a driving style which delivered higher speed with low fuel consumption. A detailed analysis of individual speed profiles indicated that as much as 1/3 to 1/2 of the recorded fuel consumption on one section was associated with air resistance.

In conclusion the studies noted that for the trucks and conditions evaluated:

(1) there are significant performance losses and increased costs associated with operations on low standard road sections. Road roughness was a significant factor determining speed.

(2) performance and cost differences between routes were demonstrated even for roads of comparable road surface type. This indicated that inter-route costs differences may be pervasive. These differences would require acknowledgement and evaluation if equitable route payment schedules were to be constructed.

(3) All the trucks studied operated for at least part of the time at high speeds and may be incurring unnecessary fuel and maintenance expenses. Application of aerodynamic deflectors might be beneficial and their applicability should be tested.

(4) Some driving styles appear more efficient and deserve further investigation and documentation. Changing driver behavior might present the most cost effective means of improvement in fleet performance.

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CHAPTER 1 INTRODUCTION

Road transport is an important component of forest industry operations. The forests of the Southern states of the USA yield more than 200 million tons of roundwood a year, almost all of it carried by road for at least part of it's journey to the mill. Reliance on road transport grew with closure of rail lines, changes in relative rail/road freight costs and continuous improvement in road infrastructure. These factors have favored an increase in the zones around mills receiving wood directly by truck.

Trucking itself has undergone considerable changes. Trucks are becoming more efficient. Newer, lighter materials allow increased payloads. Newer, more fuel efficient engines and improved aerodynamics allow better road mileage. At the same time newer, more powerful engines and better roads appear to be allowing higher travel speeds, and increased truck productivity.

Taken over 30 years these changes have moved the primary focus of log transport from a 1950's short haul / single drive axle truck predominance to the use of tractor trailers on 50 - 70 mile long hauls common today.

However, the increased round trip times associated with longer distances place a stress on the management of the trucking system. The longer the trip, the less predictable the truck's return time becomes and the greater the chance that breakdown or mill delay will cause the truck to lose the opportunity to make another load that day.

Increased crew productivity also contributes to increased management stress. A typical 1950's crew with four men producing two four cord loads had less concern with truck availability than a 1980's crew of six producing 10 nine cord loads a day. The modem crew, with a deck capacity of only one or two loads under the loader and high throughput is affected by even a few hours delay in truck arrival. In many operations trucking has become the critical logging phase. Stop the trucks and the operation stops.

Although trucks are becoming more efficient they are not necessarily becoming less expensive to operate. Primary inputs into trucking such as truck purchase cost, driver's wages, fuel, tire and insurance costs have all been rising in recent years and offsetting the gains in fuel economy, productivity and reliability. Taken together with longer haul distances, trucking may now comprise as much as 50% of the delivered costs of wood.

Trucking Efficiency

Effective fleet management is required for efficient trucking. In the longer term, fleet managers worry about purchasing the right trucks, hiring the right drivers, getting value for money in truck maintenance, and finally getting the limited supply of trucks to the right place at the right time. With effective management, these translate into safe driving, tolerable insurance rates, low operating costs and freedom from breakdown. Typically, log transport operations are part of a contractor logging operation and these longer term management decisions are often made on the spot by the contractor.

The crucial phase of the log trucking (and overall logging) business is delivering the loads and earning the revenue. The rapidly changing circumstances of this business places a premium on effective day to day management. Equipment breakdown, inclement weather, and varying demand for the loggers product all require decision on a day by day basis. Trucking, however often demands almost continuous decisionmaking to rearrange work assignment to maximize crew production and meet delivery targets. This rapid response requires a sharing of responsibility between the contractor, his crew bosses and the drivers.

Some factors such as mill unloading delay and weather are beyond the control of the manager and although they have a dramatic effect on operations, prior planning for them is at best restricted to developing some sort of contingency plan. Some other factors, though less dramatic in immediate impact, may have a considerably greater long term effect on trucking costs and longer term profitability. Immediate knowledge of these would allow better management.

Two such factors are the effects of road conditions (surface and alignment), and the influence of driving skill and style on truck performance. Knowledge of the former would allow better estimation of truck productivity and haul cost, perhaps leading to more effective and fairer price negotiation. Better knowledge of effective driver style could allow better training and monitoring of driver performance.

Truck Productivity

Truck productivity is a function of delivered payload, average speed and delays. Considerable recent effort has gone into studying and ameliorating the effects of poor loading practice (Beardsel, 1986) and mill delays are an ongoing concern of woodyard managers. Less effort has been placed on studying the determinants of average truck speed, although driving time represents some 60 - 70 % of the truck cycle. Truck speed is a function of truck characteristics, road surface and condition and driver skill and style. As managers seek to better understand the way their systems function, they need information on the interrelationships of these factors. Important questions are *How much do poor roads effect truck speed?* , *How do driving styles and skill impact truck productivity?*

Direct Truck Operating Cost

Some of the consequences of road condition and driving style are reflected in trucking costs, particularly the consumption of fuel, tires and brakes. Of these fuel is the major component. High fuel consumption is also an indicator of driving styles which increase engine, drive train, tire and brake wear. In most fleets these factors are so intermixed that managers can seldom separate one cause from the other. *How do driving styles differ in effect on cost?* Fuel is subject to considerable price volatility and may rise in price in coming years. Therefore, knowledge of the magnitude of fuel consumption levels as a major component of operating cost and how they vary with differences in road and driver style provides a better basis for management.

Measuring Performance

While improved knowledge of factors such as equipment and operator performance in forest harvesting would be valuable, collection of the information needed to establish the insights is difficult. Principal difficulties are the extremely varied and harsh operating environment. A varied environment requires very large samples to obtain representative data. Indeed conditions vary so much from site to site that representative sampling of work performance as a basis for prediction may be impossible. The harsh nature of the environment often prevents accurate measurement of these widely varying operating conditions. Methods that rely on human observation and recording are often too time consuming, expensive or inaccurate.

Developments in electronic technology afford new possibilities for data collection. These devices can obtain and store (and immediately summarize to reduce data storage requirement) large quantities of information. Furthermore, construction, assembly and the use of highly integrated electronics have permitted the development of compact robust electronic data collection systems capable of withstanding the harsh environment presented by most logging and trucking equipment.

Use of accurate electronic measuring devices coupled with a large sample storage capability of data logging equipment makes the monitoring of numerous performance factors feasible. While economical *off the shelf* commercial packages are not yet available, assembly of components into an operating data capture system suitable for forest harvesting machine study is feasible. Development of these systems is of considerable practical importance in expanding the range of data which can be collected by researchers and managers to better understand and manage harvesting systems.

Project Objectives

Exploratory information from many areas is required to better understand the operational factors influencing log trucking. While collection of all relevant data in one study is impossible, selected investigation can highlight areas of importance such as the overall pattern of work assignment experienced by log trucks, the influence of roads (alignment and surface) on truck performance and differences between drivers. The influence of the road could be expected to vary section by section with changes in alignment and surface condition.

The lack of suitable *off the shelf* data collection equipment capable of obtaining and storing the detailed data needed to fulfill these objectives necessitates the development and assembly of a data logging system.

Thus the objectives of this research are two fold:

1) To construct and program a general purpose data logging system capable of monitoring the performance of both truck and other forest harvesting equipment.

2) Study and evaluate the effects of work assignment, road surface, route, and driver on truck performance with particular emphasis on speed and fuel consumption.

CHAPTER 2 LITERATURE REVIEW

Information on trucking is commonly reported at one of two levels, averages concerning performance of trucks and fleets *on the job*, and predictions about individual truck capability. Information on driver performance is infrequently reported.

On-the-Job performance

Estimating on-the-job performance for trucks and fleets has long relied on combinations of work study and accounting methods; work measurement techniques are applied to issues of productivity, while production and cost data combine to predict economic performance. These typically reflect the interest of those managing the existing truck fleet, the effects of particular job / road conditions or operational constraints on daily or weekly delivery.

Road gradient is one of the most important determinants of truck performance. Pope (1950) extended an approach first credited to the US Highway Research Board (Highway Research Board, 1948), which tried specifically to account for road gradient. The method was called the "Rise and Fall" and involved estimation of the total elevation change (up + down) per unit distance and a recording of travel time over these various study sections. From this a table of expected travel time was developed. Pope's work in the Western USA extended the procedure by applying it to a number of surfaces. Unfortunately these studies were specific to the types of truck and the region where it was developed and were soon rendered technologically out of date.

Clark (1988) applied direct work study principles to the evaluation of the performance of a new truck configuration, recording and summarizing trip and delay times. Martin (1970) worked from a similar work study base to project and an economic ranking of factors influencing log hauling cost. Ker and Solomon (1976) reported an experimental approach to establishing truck operating costs. They concluded that there were severe difficulties in short time period experimental measurement and greater reliance should be placed on longer term fleet records.

Individual Truck Performance

Predicting specific truck performance parameters is a major input to truck purchase decisions. Performance is usually compared on the basis of a number of indicators (ie. gradability and geared speed). Transport engineers developed a standard for calculating values for these values, the SAE J688 Truck Ability Prediction Procedure,(1951). A set of 12 related equations described a calculation procedure for derivation of effective net HP for a specific road speed based on the estimated magnitude of resisting forces (air resistance, grade resistance, road surface rolling resistance) and available engine power. This allowed ready estimation of factors such as maximum gradeability, maximum restart grade, maximum geared speed and gradeability in each gear. These performance parameters have long provided important yardsticks in the selecting and matching engines, transmissions, rear axles and tires, because of their interaction in determining effective gearing and power availability. For example, desired top speed influences engine maximum RPM, rear axle ratio, and tire selection. Maximum gradeability simultaneously influences low gear transmission reduction as well as rear axle ratio, tire size and engine power. Gradability at cruise speed is largely determined by engine power curve and effective total driveline reduction (rear axle and tires). Deciding among the many combinations presents a formidable task.

These calculations require assumed values for several basis parameters. A considerable amount of testing has been undertaken to determine effective operational values for such factors as tire rolling resistance, (Smith, 1970). Engine accessory losses and engine torque and fuel consumption relationships have been provided by testing and reporting by manufacturers under standard conditions (SAE J816B).

Static performance predictions do not consider the complex interaction effects of changing gradient and driver performance, or changing road load demands and engine power production. A greater appreciation of their limitation came with proposals for truck regulations based on gross power to weight, a static measure, in the early 1970's. Donnelly (1970) of Mack Trucks Inc. demonstrated the problem of determining the appropriate power measure for input to the proposed factor when comparing *constant horsepower* engines such as those produced by his company to conventional engines. Paul(1972) used the newly emerging dynamic simulation methodology in a test of the proposed gross power to weight static measure. He concluded that the more general framework of the dynamic simulation model was required to properly evaluate the capability of truck configurations and simple static performance measures (eg. power to weight) were of limited use in realistically comparing alternatives.

Computerizing the Calculations - Dynamic Simulation

Developments in digital computer technology led to computer implementation of the J688 calculation procedure. This allowed dynamic simulations of vehicle's performance response to changing external parameters (ie. cornering, changing grade etc.). Perhaps the best known of these is the CUMMINS VMS model (Schutz, Klokkenga and Stattenfield, 1970). Other major truck manufacturers have developed similar programs. Barta (1976) describes his company's product under the description *Paper Trucks on Paper Roads*. These computer programs are most often used to predict the performance of truck configurations of interest to the potential customer over some of the many road and trip profile descriptions stored in the vendor companies computer data library.

Applications of computer technology to problems of wider interest are also reported. Boyd and Easterly (1974) combined empirical testing with the CUMMINS VMS model to evaluate the fuel savings possible with coolant temperature switched fan drives. An application in the forest harvesting area was made by Smith (1981) where he used the Cummins VMS program to compare the potential performance of alternative truck and trailer / axle combinations. Another application was the development by the author of a simplified truck performance program (TRUCKSIM) as a basis for the study of both truck specification and forest road designs as well as their interaction (McCormack, 1986).

Dynamic Truck Simulation Methodology

The core calculations of these programs are derived directly from the J688 static procedures. Smith (1970) describes the state of the art as it had been extended from the J688. The major groups of power related factors considered remain:

Air resistance

Road rolling resistance

Road gradient loss (or gain)

Drive train losses

Engine accessory losses

Engine power output, fuel flow and load

Transmission, rear axle and tire rolling resistances.

These factors are coupled by first deriving for a particular instant in time (current velocity, road gradient and surface), the effective net power demand to maintain truck speed in the face of the air, road and gradient losses. This is then compared to the power available at the wheel for the specific RPM indicated by road speed and total geared reduction, after accounting for drivetrain and engine accessory losses. Net available power is then applied to accelerate (decelerate) the truck for one time step where the new road position (gradient and surface) and velocity are used to repeat the cycle. Given a short enough time step (0.1 - 1.0 seconds) dynamic response is assumed to approach the continuous case.

The functionality and credibility of these programs differs in two important ways from their ancestor, the 1951 SAE J688 procedure.

The adoption of a close interval dynamic simulation approach provides a new type of information about vehicle response. Statistics such as the number of gear changes required on a given route, the minute by minute engine RPM and power levels, and most importantly, a prediction of fuel economy are all possible (and included) in most manufacturer's simulations.

Dynamic Simulation Limitations

However, this wealth of predicted performance data brings with it a sometimes dangerous aura of believability. The problem that arises is not how accurately the program predicts, but whether it's predictions are based on assumed inputs similar to the user's real world problem. Crucial assumptions include:

The true air resistance of the real world load (Coefficient of Drag).

The true surface roughness and surface strength (Rolling Resistance) of the user's roads.

The complexities of driver behavior, particularly the interaction between driver, road alignment and geometry and sight distance.

A major difficulty is that the user (the decision making customer) has no readily available means of collecting data to describe his problem accurately, or checking the applicability of the values used by the vendor's sales engineers.

These programs also face a difficulty in modelling driver behavior. This means that input specification and output interpretation are exacerbated when the programs are applied to conditions differing markedly from the higher quality roads where driver influence is minimized. High quality (Interstate) roads have predominantly moderate grades, excellent alignment and a relatively uniform concrete surface, leaving less room for driver variation. The considerable variations apparent in forest road conditions is therefore a major factor limiting applicability.

Information which would allow better guidance for application in log hauling is limited. Garner (1978) conducted a series of wind tunnel tests of truck trailer configurations to determine effective aerodynamic drag. Ljubic (1982, 1984, 1985) has developed and applied a methodology for isolating and determining values for truck performance parameters. His technique relied on the use of accurate instrumentation and very high capacity computer based digital recording technology which allowed the ready recording and analysis of very detailed experiments. When used with coast down testing, he was able to determine performance factors including air drag, rolling resistance and drivetrain losses for the particular instrumented truck and studied forest road conditions. As an example, Ljubic used his instrumentation and methodology to investigate the influence of oil viscosity on truck fuel consumption (Feric, 1986). Application to cover a wider range of road and vehicle types is required.

Data Gathering

Evaluation and specification of components for new trucks has been the focus for the development of most analytical techniques and testing procedures. Reports on the performance of trucks in service (particularly log trucks and fleets) are few as are studies of the interaction of truck performance with forest road hauling conditions. The approach of using an instrumented truck as the basis of study was reported by Ljubic (1982) but the initial emphasis has been on an elaborate instrumentation and detailed experiments.

Early applications of electronic data collection techniques to forest harvesting studies were much simpler. Cotell et al (1979) developed a combination of custom designed and commercially available equipment to evaluate man - machine interaction and system performance. A more robust harvest machinery data logger was developed by the author during the 1970's. This unit was based on a modular, small board wire wrap construction technique was aimed at producing a robust device capable of withstanding the harsh operating environment on mobile equipment. Initial application of the device was successful but reliance on user written assembler control software prevented it's widespread application. The custom design approach was superseded by commercial systems for industrial control which were based on similar design requirements (robustness, small size, reconfigurability) and employing robust small board, modular formats (eg. STD BUS). Zhang, Perumpral and Byler (1987) described the application of an STD BUS system to farm tractor engine control. The measurement and recording capabilities required for industrial control are very similar to those needed for data logging and STD BUS technologies now enjoy wide application.

Summary

Attempts to better understand forest harvesting and transport processes have been following two major paths. Techniques based on empirical measurement are commonly applied at the management level, but have hitherto been constrained by the capabilities of the measurer and the adversity of the environment. Developments of theoretical understanding, however, while relatively advanced in some areas, (eg. truck simulation) are constrained by lack of information on many important facets of operational performance (eg. details of the operational environment, accurate knowledge of human control and response capability).

Newly emerging microcomputer based data collection capabilities provide a bridge between these fields of development.. They make possible the recording of information on performance with sufficient detail and accuracy to be useful in developing better theoretical understanding, while at the same time permitting recording under operational conditions capturing the variety and diversity of the forest harvesting environment.

CHAPTER 3 STUDY METHODS AND PROCEDURES

Introduction

Three phases were undertaken to meet the project objectives:

1. Assembly, programming and testing of the data logging equipment and associated transducers.
2. Development of data retrieval, storage, processing and analysis programs.
3. Planning and execution of the Field Studies.

Development of Data Logging Equipment

Project objectives called for the development of a general purpose data logging system for forest harvesting research and it's application in monitoring the speed and fuel consumption of log trucks. Important criteria used in equipment selection included:

1 - Tolerance for heat, vibration and dust.

2 - Operation at modest current and voltage levels and tolerance of fluctuations.

3 - Small physical size and ease of fitting to forestry equipment.

4 - High data collection and storage capacity.

5 - Ease of reconfiguration for new tasks.

6 - Compatibility in programming and data exchange with existing equipment and user skills.

Data logging equipment involves two major groups of components:

1. external environmental sensors (transducers) which produce the signals to be measured, and a
2. data logger which monitors the signals produced by the transducers, then measures, processes and subsequently stores the readings.

Transducers (eg. measurement devices for vehicle speed, fuel flow) are usually purpose manufactured sensors which produce a voltage or frequency output signal. Selection depends on desired accuracy and required service environmental tolerance.

Data loggers currently being used in research are of several types. Ready made systems are commonly available for most major laboratory monitoring functions, but are not suitable for forest harvesting application because of size and power requirement. Newer more compact "single board" devices are now readily available which are robust, low power and small, and capable of measuring and storing significant volumes of data. However, data retrieval and flexibility in application remain a difficulty.

A more common solution is to use an intermediate sized multi-board micro computer system. This has the advantage of greater capacity for data collection and storage and ready inclusion of common data exchange media (eg. floppy disk or tape systems). Some systems (such as the STD bus) were developed for industrial process control and conform to internationally recognized size and interconnection standards. This permits ready configuration of specialized measurement and processing boards from different manufacturers to meet user needs. Such systems are readily reconfigured to meet new needs. Some of these manufacturers produce subsystems which emulate popular microcomputers (eg. IBM PC). These have an important advantage in capitalizing on programming skills often already present in an organization. It also allows for common data exchange format (eg. 3 1/2" IBM format floppy disk).

Assembly of the Data Logger and Transducers

Major components of the data logging system assembled for this project were:

1 STD BUS Data Logging computer

2 System monitor and control console

3 Speed transducer

4 Fuel Flow Transducer

5 Fuel Temperature Transducer

6 Engine RPM transducer

7 Brake Monitor

The general layout of the complete data logging system in presented in Figure 3.1. Detailed description of each element follows.

Data Logging Computer

An STD BUS computer system was selected for the main data logging computer. STD BUS systems are widely used in data collection and industrial control and were developed for harsh and demanding environments.

The computer system assembled for this project comprised:

ZIATECH ZT8809 80186 Microprocessor Board including 256 K Byte memory

ZIATECH ZT8825 Extended Memory Board

ZIATECH ZT8853 3 1/2 Floppy Disk Drive

Robotrol 7728 Analog - Digital Converter (16 Channel)

MSI C730 21 Channel Counter and Digital I/O

MATRIX 8 slot card cage and backplane.

The system emulated an IBM PC - XT and operated under a ROM based DOS 3.3. Voltage requirements were +/- 12 and 5 volts. Component boards were all designed for a high vibration and wide temperature extreme environment. The final system dimensions after mounting on a foam vibration isolation base were 12" X 12" X 8" and met the size requirement for mounting under the passenger seat of the test trucks.

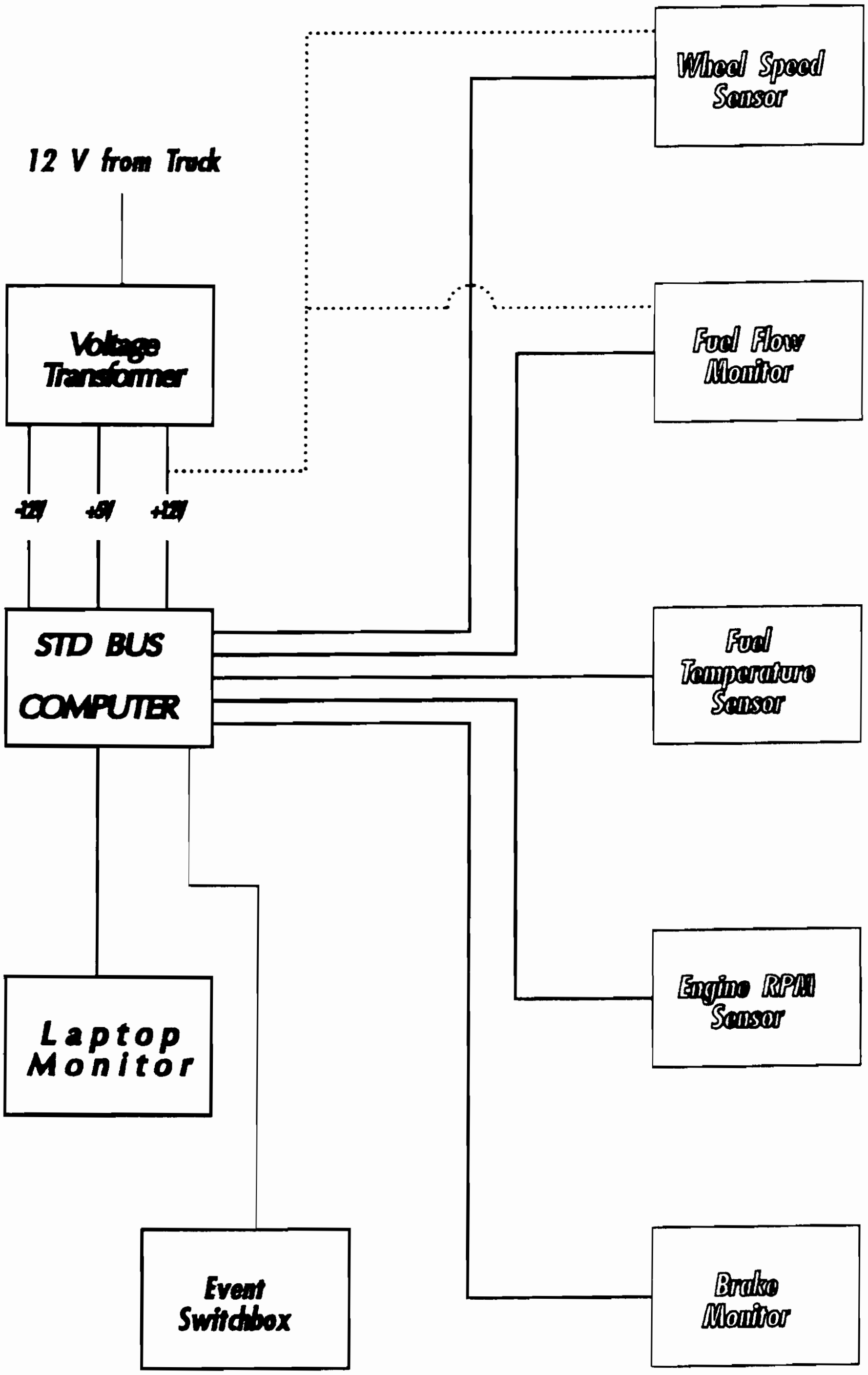


Figure 3.1 Data Logger System Interconnection Schematic

A controller program was written in Quick Basic to :

- Monitor and read the voltage and counter channels at user defined intervals (usually 2 seconds),
- Monitor the switch box for user event data,
- Display incoming data on the Laptop monitor,
- Compact and store data in RAM DISK.

Approximately 3 hours data storage was available with the 384 kByte RAM DISK implemented for this project. Up to 1 Mbyte of data storage capacity could be provided on the existing memory card and a number of cards could be added if required. At the conclusion of each run, and while the truck was stationary, the data were transferred from RAM DISK to 3 1/2" floppy disk using the disk drive installed in the system.

Voltage Transformer

A Melcher AM3000 DC-DC inverter power supply was used to generate the voltage levels (+/- 12 V and +5 V) required by the computer and transducers. Voltage input was supplied from the truck 12 volt system. The output supplies were fully isolated from the input although a common ground with the truck system was used because of the requirements of several of the transducers.

Wheel Speed Sender

A 360 count per revolution optical encoder was used to measure wheel rotation. The encoder was mounted on an outboard stub axle assembly attached to the wheel hub oil seal bolt circle of the driver side front wheel of each of the test trucks (Figure 3.2). The front wheel was used as it was not subject to the power induced wheel slip experienced by the drive wheels and was less sensitive to weight transfer induced rolling radius changes between loaded and unloaded condition. The driver side wheel was used as it would normally experience better road surface conditions than the offside wheel. The bearing mounted encoder housing was restrained from turning by a PVC pipe extension slip mounted in a ring attached to the truck fender. This mounting allowed for the vertical movement of the truck wheel suspension and horizontal rotation with steering. Encoder output was a 5 V pulse train, about 36 counts per foot of distance.

Accuracy in distance measurement relies on constant tire rolling radius which was determined by comparing encoder output with measured distances for each truck.

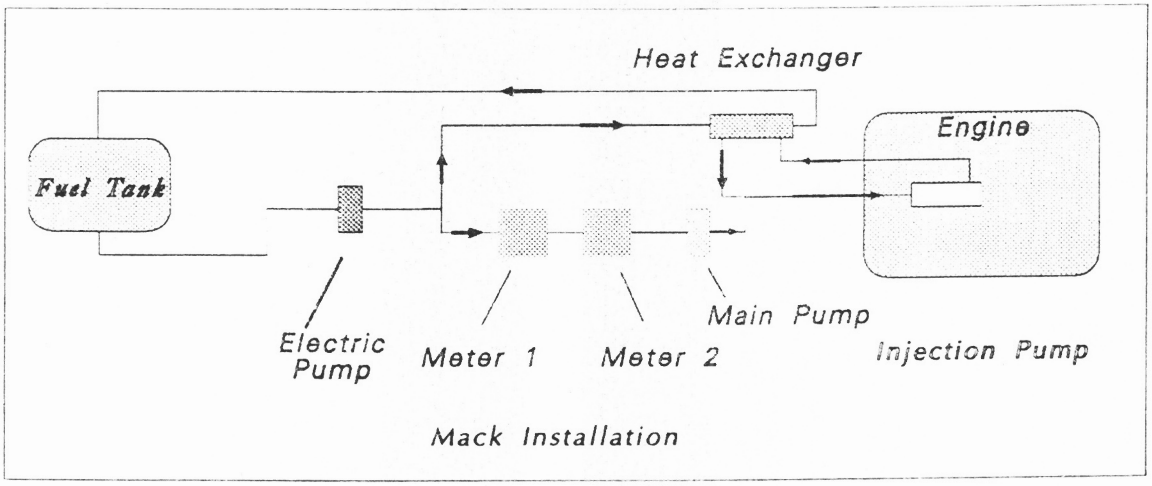
Fuel Flow Monitor

Two fuel flow transducers were used throughout this study:

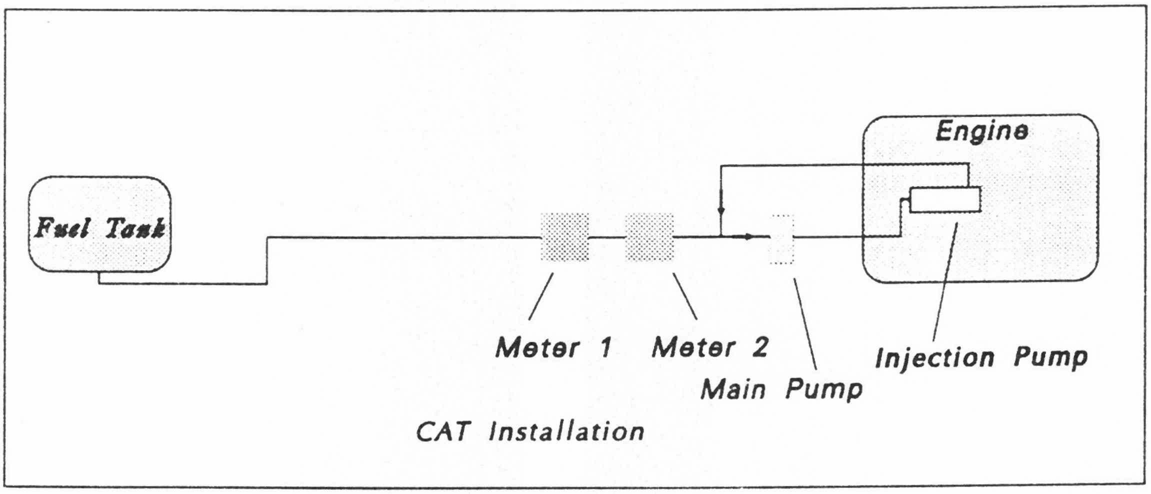
> a Pierburg PLU116H unit, with output of about 290,000 pulses per gallon (77.5 pulses per ml),
>
> and an ARGO Fuel Monitor with about 11,000 pulses per gallon. (3 pulses per ml.)
>
> Both of these units were volumetric displacement types and certified for accuracy.

Installing the fuel flowmeters required considerable reorganization of the fuel supply, return hoses and fittings on each of the engines. The three configurations used are diagrammed in Figure 3.3. The ARGO meter was used in all studies, the Pierburg unit was used in addition in Studies 1, 3 and 4.

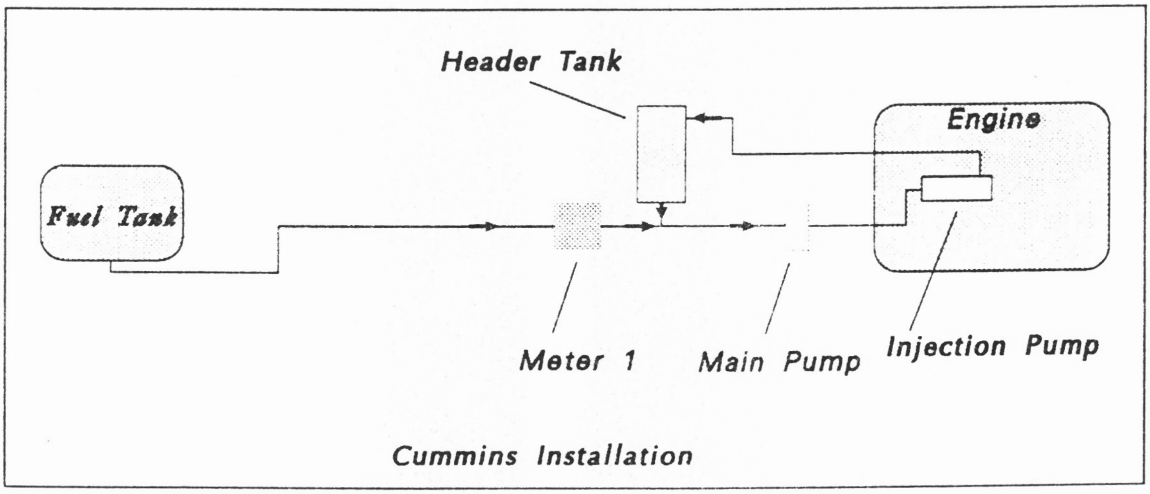
Figure 3.2 Wheel Encoder and Mounting



Mack Installation



CAT Installation



Cummins Installation

Figure 3.3 Fuel Flow Meter Installation Schematics

Study 2 required fitting of an intermediate float controlled *header* tank which nullified the value of the extremely high precision of the Pierburg unit.

Fuel Temperature

Fuel temperature was monitored at the fuel flow meter inlet using a LM34CZ semiconductor temperature sensor. This device produces a 1mv signal for each degree Fahrenheit.

Engine RPM

An ARGO Model 1310 sending unit attached to the tachometer drive shaft was used to measure RPM with the MACK and Caterpillar installations. The Cummins engine was monitored electronically from the engine tacho-generator.

Brake Usage

Brake application was monitored from the brake lamp circuit. This provided indication that the brakes were being applied, but no indication of the braking intensity. The usage of the engine brake (where fitted) cannot be measured by this method. In Study 4, the engine brake, although fitted to the truck, was not used for the duration of the study. Braking information was analyzed only for Study 4.

User Switch Box

An eight switch panel was monitored by the computer at one second intervals. Different panel switches were allocated to record events such as speed zone type (25, 35 and 45 mph), traffic interference, a major road alignment speed restriction (tight corner) and an event marker.

This latter *push to contact* button inserted a sequence number in the data set. The event was also entered in a trip log with a short description associated with the sequence number.

Data Logger Operations and Testing

For the initial implementation, the data logging system was fitted to a Mack log truck operating in Pennsylvania for a trial period of two weeks to debug the system and make all the transducers operational.

Fuel transducers operated on a volumetric principle and were therefore of reliable performance. The more exact of the pair was certified for accuracy by the factory in an individual test before delivery. The correspondence between readings of the two devices was checked from data collected in the startup tests.

The wheel encoder produced a fixed output(360 pulses) per wheel revolution. Calibration was required on each truck to determine the number of wheel revolutions per mile. This was done by comparing encoder output with known route segment distances. Calibration was repeated in each study to determine the appropriate factor for each truck installation.

A two second data collection interval was accepted after trial in Pennsylvania. This interval was a balance between excessive data collection and accuracy. Closer intervals were within data logger capability, but were not desirable. Individual diesel engine types have a period of latency in fuel flow adjusting to meet engine demand with excess fuel being recycled in the return flow. This process involves large volumes of fuel and relatively long periods in some engines (eg. CUMMINS). Monitoring of input data on the laptop computer as they were being collected suggested periods of 1 - 2 seconds. A closer interval simply generated excess data which tracked fuel flow adjustment rather than underlying consumption, and needed to be averaged to represent actual fuel usage. The data collection period was adjusted to 5 seconds on the Cummins installation and considerable fluctuations were still noticed in the data from fuel dumping when engine load was suddenly reduced.

Data Analysis

Computer Processing

Field data were transferred to floppy disk at the end of each trip. These data required several stages of processing before analysis could begin. Major steps included:

1. Reduction of input data to a standard random access computer file storage format.
2. Processing of RPM and road speed data to derive gear ratio including a visual edit of change points.
3. Insertion of section markers using imbedded sequence numbers, distance data and a visual edit of shift pattern and speed trace.
4. Preparation of section summaries and plotting of trip data traces.

Ten graphics and data manipulation programs were written to achieve these steps.

Definition of Terms and Statistics

The two important quantities recorded and analyzed during these studies were vehicle speed and fuel usage. Road speed was analyzed and reported in miles per hour units (m.p.h). Fuel usage was analyzed and reported in units of **gallons per 100 miles (abbreviated as g/100).** This form of the ratio presents quantity consumed per unit of output and is in the correct form for a consumption ratio. It presents a convenient numerical index because it varies directly with fuel usage; higher fuel usage is reflected in a higher numerical ratio. The more traditional miles per gallon (a productivity ratio) can readily be obtained by inversion (mpg = 100 / (g/100)).

The primary product produced by transport systems is the quantity delivered times the distance moved, commonly expressed as ton - miles. Two productivity ratios based on ton - miles were used, ton - miles per hour and ton - miles per gallon. The ton quantity used was the net delivered payload and distance was measured as the trip length was taken from landing to delivery point. The use of payload in the measure provides sensitivity to effective loading and reduction of tare weight.

The Ton - mile / hour ratio describes overall truck productivity and was defined as:

Ton - mile / hour (t-m/h) = (delivered payload * one way trip distance) / (round trip driving time).

Total round trip driving time was used as the time measure. Use of round trip input quantities better reflects overall productivity. One way measures are often used in traditional road transport where backloading is common. Backloading is rare in log transport. Indicative maximum values for this ratio are about 700 t-m/h for log transport (55 mph and 25 tons loaded one way). with typical line haul freight values about 1500 t-m/h where loaded backhaul is available.

A fuel productivity ratio describing the efficiency of fuel usage in producing revenue was defined as:

Ton - mile / gallon (t-m/g) = (tons delivered * one way trip distance) / (round trip fuel)

Round trip fuel values are used making the ratio sensitive to both loaded and unloaded fuel consumption. Indicative maximum values for this index are about 70 t-m/g.

Comparison between fuel usage while loaded and while running empty was made using the Loaded/Unloaded Fuel Consumption Ratio, defined as:

Loaded / Unloaded Fuel Consumption Ratio = (g/100 Loaded) / (g/100 Unloaded).

The measure is influenced by differences in weight and driving habits between unloaded and loaded state, and by direction based differences in road conditions. The major factor is road gradient, with an adverse unloaded grade being a favorable loaded grade.

Considerable distances of unloaded travel from a logger's maintenance base to job site and return are a common part of log transport. A measure based on the percentage of loaded miles in daily total miles was developed and applied in the project. The statistic is defined as:

Loaded mile percentage = (loaded mile per day / total miles per day) * 100

Data Trace Example and Description

An example of a trip data trace for one 3 mile route section is included (Figure 3.4). This plot is produced against a distance base on the X axis. The selected section is a four lane urban city bypass with 5 traffic lights. This truck was stopped at four of them. Gear change patterns are evident in the RPM trace. The pull off from the initial stop was up hill and the truck spent a considerable period in 5 th., 6 th. and 7 th. gears. In contrast the second stop is on a down grade and the truck climbs to 8 th. gear (top) quickly.

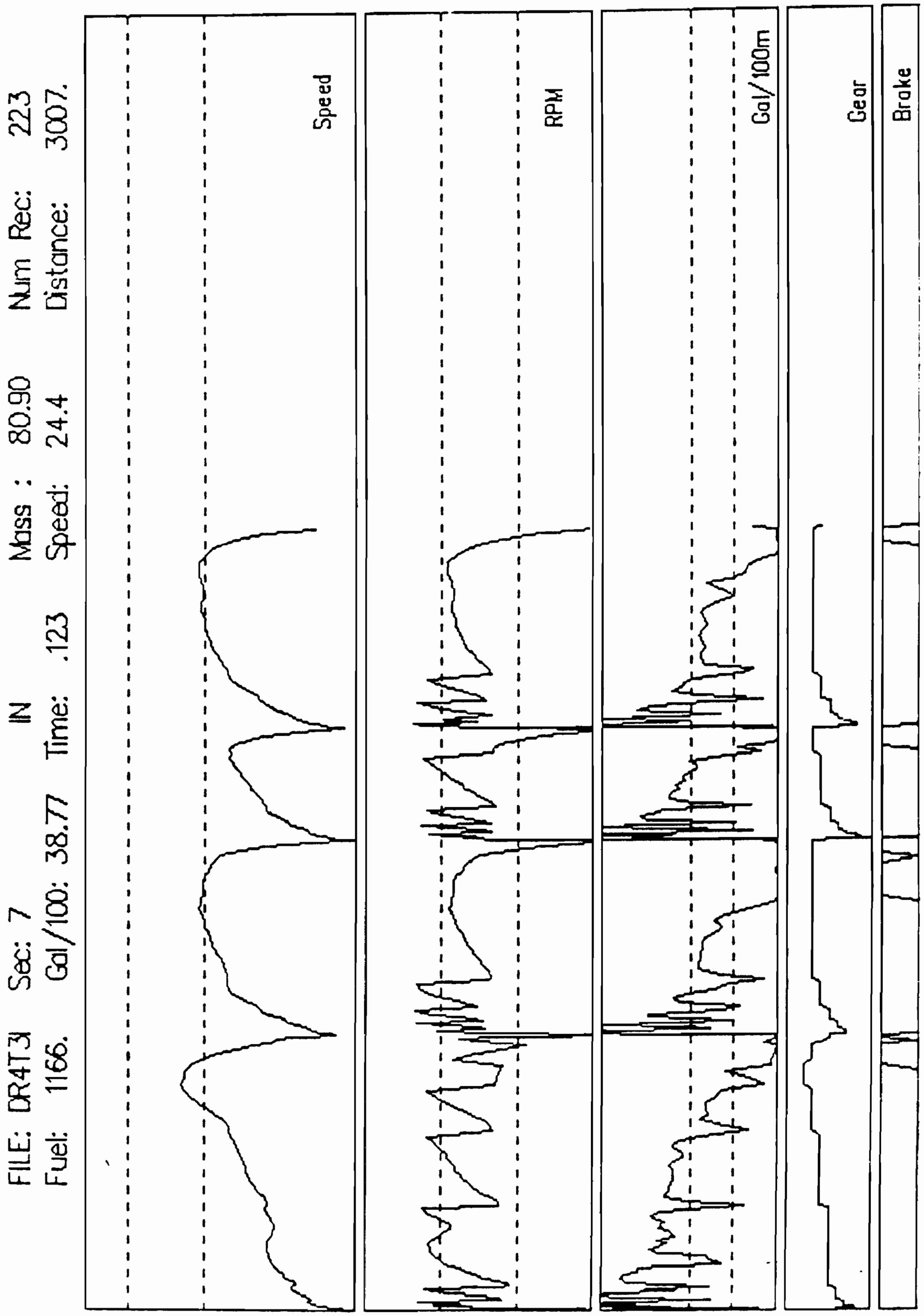


Figure 3.4 Sample Data Trace for One Route Segment

The fuel flow trace displays fuel consumption per unit distance (Gallons per 100 miles). Note the improving (ie. reduced) fuel consumption as the truck climbs through the gears (particularly evident from the first stop). The brake trace simply indicates application of the brake pedal. Notice the extensive brake periods preceding each of the red lights.

Records such as these could be used for considerably more detailed testing, and the data logger has the capacity to record at much closer intervals. Acceleration and deceleration traces such as these, already in digital form, provide the basis of the *Coast Down* methodologies, as applied by Ljubic in Canada.

Similar plots were prepared for all sections and checked for sensor or computer malfunction. Some anomalies were detected as a result of electrical interference. These anomalies were usually in the form of *spikes* most commonly one or two observations wide. The spike data was deleted and replaced with an average of adjoining cells. The interference was ultimately traced to the CB radio, and the remainder of the study conducted without use of the radio.

Study Description

General Outline

Following initial testing, four formal trials were conducted using trucks drawn from contractors' fleets operating in South Carolina and Florida. These trials were:

Study 1 Contractor Operations

The normal daily work pattern of a six month old Freightliner (Table 3.1) in a logging contractor's fleet was monitored for a week. The truck operated in central and eastern North Carolina. The study purpose was to gain insight into work and route mix patterns for contractor hauling operations.

Study 2 Road Surfaces

The influence of road surfaces of particular interest to log truckers was evaluated by monitoring the performance of a Ford 9000 (Table 3.1) operating on sand and gravelled roads in Northern Florida.

Study 3 Route Comparison

Data for a comparison of performance of a truck and driver combination on different routes was collected by monitoring the operations of a Mack SuperChief (Table 3.1) hauling from seven different woodyards in North and South Carolina.

Study 4 Road Sections and Drivers

A detailed study of performance on one route using five different drivers was undertaken to obtain more detailed information on (a) variations in performance between road sections and (b) variations between drivers. All test data was collected using the same truck as Study 3.

All studies were completed during summer of 1989. Weather conditions throughout were hot and dry.

Table 3.1 Truck Specifications

Study 1

Truck Make:	Freightliner
Engine:	Cat 3406B
Engine Power	350 HP at 1900 RPM
Transmission:	Fuller RTO11609B (Overdrive 0.73)
Rear Ratio	4.44
Tires:	11R24.5

Study 2

Truck Make:	Ford 9000
Engine:	Cummins LT310
Engine Power	310 HP at 2100 RPM
Transmission:	Fuller RTO 11609B (Overdrive 0.73)
Rear Ratio	5.20
Tires:	11R22.5

Study 3 & 4

Truck Make:	Mack Super Chief
Engine:	Mack E6-350-4VH
Engine Power	350 HP at 1800 RPM
Transmission:	MACK T2090 (Overdrive 0.71 top)
Rear Ratio	5.02
Tires:	11R22.5

CHAPTER 4 CONTRACTOR OPERATIONS

To obtain some indication of the levels of utilization and the pattern of work assignment associated with contractor trucking operations, one of a contractor's fleet of twelve trucks was instrumented, and it's normal operations monitored for a week. The selected truck and driver were responsible for both log delivery and equipment transport (lowboy). The contractor ran two sawlog and one whole tree chip operation. The load target weight for log hauling was 80,000 pounds. Hauling was mostly over lower standard state and county roads. No loaded hauling on interstate was recorded during the study. Trucks were assigned to either log or chip hauling for the day. Log loads were assigned from either or both of the log crews within one day.

Normal Operations

A Weekly Trip Log

A daily log of all trips made is presented in Table 4.1 a,b,c. Normal log hauling operations were monitored on the first three study days during which time 10 loads were delivered. On the fourth day the truck was engaged in moving one of the logging crews to a new site 77 miles away. Six separate loaded journeys were made. The fifth day was a mixture of chip hauling and equipment moving with two chip loads and three loaded equipment shifts

Table 4.1 a Daily Trip Log for Contractor Log Truck on Days 1 and 2

Day 1

Trip	Start	Distance (miles)	Fuel	Speed	Load	
	Time	Empty	Loaded	(gal)	(mph)	
1	05:49	55		9.3	42.5	Empty Log Trailer
2	07:41		14	3.9	41.9	Loaded Logs
3	08:24	14		2.0	48.7	Empty Log Trailer
4	09:32		48	11.8	46.0	Loaded Logs
5	11:38	48		7.5	46.1	Empty Log Trailer
6	13:02		48	12.3	41.1	Loaded Logs
7	15:01	48		7.1	50.2	Empty Log Trailer
8	16:24	55		10.2	48.4	Empty Log Trailer
Total		**220**	**110**	**64.1**		

Day 2

Trip	Start	Distance (miles)		Fuel	Speed	Load
	Time	Empty	Loaded	(gal)	(mph)	
1	05:38	55		9.9	45.0	Empty Log Trailer
2	07:33		48	11.2	42.3	Loaded Logs
3	09:06	26		4.8	52.3	Empty Log Trailer
4	10:16		103	24.5	48.1	Loaded Logs
5	12:43	98		17.4	50.9	Empty Log Trailer
6	14:54		48	12.4	45.3	Loaded Logs
7	16:42	26		4.6	45.4	Empty Log Trailer
8	17:54		26	5.4	44.9	Loaded Logs
9	18:22	39		4.4	46.3	No Trailer(Bobtail)
Total		**244**	**225**	**94.6**		

Table 4.1 b Daily Trip Log for Contractor Log Truck on Days 3 and 4

Day 3

Trip	Start Time	Distance (miles) Empty	Distance (miles) Loaded	Fuel (gal)	Speed (mph)	Load
1	05:59	66		13.8	53.1	Empty Chip Van
2	07:20	36		4.5	42.0	No Trailer (Bobtail)
3	08:22		77	16.9	48.0	Loaded Logs
4	10:31	97		16.8	51.3	Empty Log Trailer
5	12:39		48	11.5	45.4	Loaded Logs
6	14:40	26		4.4	46.1	Empty Log Trailer
7	16:19		90	20.1	48.8	Loaded Logs
8	18:46	55		8.7	55.0	Empty Log Trailer
Total		**280**	**215**	**96.7**		

Day 4

Trip	Start Time	Distance (miles) Empty	Distance (miles) Loaded	Fuel (gal)	Speed (mph)	Load
1	06:02	67		12.7	54.1	Empty Log Trailer
2	09:21		6	1.8	15.6	Delimber
3	10:05		67	15.5	43.6	Loaded Lowboy
4	12:47	21		4.1	48.1	Unloaded Lowboy
5	13:19		27	7.5	46.6	Loaded Lowboy
6	14:10	77		14.6	55.9	Unloaded Lowboy
7	16:08		77	17.7	46.8	Loaded Lowboy
8	18:03	28		4.5	50.3	Unloaded Lowboy
9	18:49		28	7.1	50.2	Loaded Lowboy
10	20:00	67		12.8	52.2	Unloaded Lowboy
11	22:40		67	16.6	40.3	Loaded Lowboy
Total		**260**	**272**	**114.9**		

Table 4.1 c Daily Trip Log for Contractor Log Truck on Day 5

Trip	Start Time	Distance (miles) Empty	Distance (miles) Loaded	Fuel (gal)	Speed (mph)	Load
			Day 5			
1	06:00		28	6.7	40.9	Loaded Lowboy
2	07:29	67		9.8	40.6	Unloaded Lowboy
3	09:31		30	6.7	39.9	Loaded Chip Van
4	11:09	30		5.0	41.7	Unloaded Chip Van
5	12:02		23	5.1	36.4	Loaded Lowboy
6	13:05		23	5.2	37.1	Loaded Lowboy
7	14:24	15		1.6	39.1	No Trailer (Bobtail)
8	15:01	15		2.6	36.3	Empty Chip Van
9	15:32		30	6.8	39.0	Loaded Chip Van
10	17:14	30		5.4	30.6	Empty Chip Van
11	18:12	66		9.3	49.2	Empty Lowboy
Total		**217**	**134**	**64.2**		

Summary data for daily performance is presented in Table 4.2. Daily fuel consumption is similar on days 1 to 3 at about 20 G/100 miles (5 mpg) although the percentage of loaded miles varied from 33 to 47%.

The low percentage of loaded miles on Days 1 and 3 is indicative of some of the difficulty contractors face in running logging operations at longer distances (> 50 miles) from their maintenance base. This separation incurs considerable dead running in the morning and evenings.

The higher percent productive results for day 2 (47%) were obtained by hauling the last load of the day to an intermediate location, dropping the trailer and returning to base without a trailer (bobtail). Equipment relocation (Day 4) had both a higher fuel consumption and a higher percentage of productive miles. The larger percentage of loaded miles contributed to higher average fuel usage. Increased fuel usage could also have been caused by greater air resistance associated with large frontal area of the equipment transported. The mixed chip and equipment hauling on Day 5 produced the best fuel economy. A combination of a light weight and small size of the equipment transported, some bobtail running and lower loaded mile percentage is presumed to have reduced consumption for this day.

The scheduled work day for the truck when hauling logs (Day 1 to 3) was over 12 hours. Using the truck as primary transporter to move a logging operation resulted in a 16 hour day. This high working time can be partly attributed to the several hours of dead running needed each day to get the truck to the job site to get the first load and to return to base at the end of the day. This becomes critical as operations move further away from the labor and equipment base.

Table 4.2 Daily Performance Totals for Contractor Truck Operation.

Day	Work Time *(hours)*	Total Fuel *(gal)*	Fuel Usage *(G/100)*	Miles	% Productive
1	12.3	64.1	19.4	330	33
2	14.0	94.6	20.1	469	47
3	13.8	96.7	19.5	495	43
4	18.1	114.9	21.6	532	51
5	14.1	64.2	17.9	351	38

Round Trip Performance Results for the Three Operations

Round trip truck performance data for deliveries from each of the contractor's three operations is summarized in Table 4.3. Average fuel usage and speeds are presented for unloaded and loaded legs and the combined round trip. Haul distances for the three operations, listed in Table 4.3, were 48, 97 and 30 miles for Log Operation 1 (Sawlog), Log Operation 2 (Chip and Saw) and the Chipping Operation (Whole tree chips) respectively. Average loaded weights were high for two of these operations, which was expected to increase fuel consumption. The high unloaded fuel usage recorded for the chipping operation resulted from the high frontal area of the unloaded chip van. Unloaded fuel consumption was high for all operations leading to a comparatively small loaded / unloaded fuel consumption ratio of 1.3 for this truck. This high unloaded consumption rate points to considerable additional cost associated with the dead running recorded during this week.

The highest truck productivity (t-m/h) was achieved for deliveries from Log Operation 2. Delivered loads were the lightest and trips from this operation to it's mill were the fastest. The influence of the route from the chipping operation to it's mill is evident in the 15% decline in truck productivity associated with the slower haul. Surprisingly, fuel productivities between these operations did not vary in the same way. Log Operation 1 produced the best ton-mile/gallon result, with the much slower hauls from the chipping operation the next best. These ratios indicate that with current fuel prices, the level of fuel cost is somewhat more than 1 cent per delivered ton - mile.

Additional data from Contractor Study

Data collected during this week also provided information on specific aspects of truck operation. Observations include :

Table 4.3 Average Truck Performance from the Three Operations in the Contractor Study

		Unloaded		Loaded			Round Trip				
Trip	Loads	Fuel (g/100)	Speed (mph)	Fuel (g/100)	Speed (mph)	Load (,000lb)	Fuel (g/100)	Speed (mph)	Ratio*	t-m/h	t-m/g
Log 1	2	15.3	49.7	23.9	46.3	86.0	19.5	48.0	1.5	604	73
Log 2	3	16.9	52.4	22.4	48.0	79.8	19.6	50.2	1.3	632	64
Chip	2	17.2	41.6	22.4	39.0	85.2	19.8	40.3	1.3	530	66

* Ratio is Loaded / Unloaded Fuel Consumption Ratio

1) The effect of load on truck performance

2) Fuel efficiency with and without unloaded trailer (bobtail)

3) Truck performance on stand access roads

Studies of Different Load Levels

A set of five trips varying widely in load size were obtained from one logging operation to the receiving mill. A description of the 48 mile route is presented in Table 4.4.

Analysis is restricted to the loaded journey because the truck returned directly to the same landing only twice in this series. Data for these loaded journeys is presented in Table 4.5.

In this set of trips, gross vehicle weight rose 23% from trip 1 to trip 5, with a corresponding 35% increase in delivered payload. Truck speeds for this series were variable, but do not appear to have declined substantially with the increase in gross vehicle weight. This indicates considerable excess reserve power for this engine / transmission combination on the flatter roads of the lower coastal plain. In consequence the truck productivity measure (ton-mile/hour) increases in direct relationship with the payload. Fuel consumption rose only 12 % with the 35% increase in payload. Overall fuel productivity (t-m/g) improved by about 26% .

Fuel Efficiency with and without Unloaded Trailer

Evaluation of the daily log indicated about 12% of the mileage was associated with dead running (mostly moving from base to the job site and return in the evening). On three occasions this was done without a trailer (bobtail).

Table 4.4 Road Segment Description for the Log Hauling Study

Segment	Length	Description
1	0.86	Farmers access track - sandy loam, dry, level
2	0.99	Farm to market - narrow, paved, poor surface
3	2.20	Farm to Market - narrow, paved, fair surface
4	6.74	State Highway, 2 lane, flat, good visibility
5	11.14	State Highway, 2 lane, flat, good visibility
6	20.43	Federal Highway, wide 2 lane, rolling, good visibility
7	5.33	Urban Highway, 4 lane not divided

Table 4.5 Comparison of Different Loads on One Haul Route

Trip	GVW (,000lb)	Load (,000lb)	Fuel (G/100)	Speed (mph)	t-m/h	t-m/g
1	83.0	53.4	23.1	42.4	599	74
2	89.0	59.4	24.6	46.2	695	79
3	91.7	62.2	23.7	45.5	722	85
4	96.9	67.2	25.3	41.1	741	88
5	102.0	72.4	25.8	45.3	816	91

Trips arranged in order of increasing load.

The first occasion occurred when a loaded trailer was dropped at an intermediate point between logging site and mill because delivery could not be made before woodyard closing time. The other occasions arose after the delivery of a repaired trailer and before recovery of the defective unit.

Fuel performance results for these trips are contrasted with four other normal unloaded trips (Table 4.6). A considerable reduction in fuel consumption is associated with bobtail running. Possible reasons for this are the reduction in air resistance associated with the frame trailer and axle set, the reduction in drag associated with the rolling resistance of the trailer tires, and the 35% reduction in gross weight. These results indicate that consideration should be given to trailer parking arrangements which permit travelling to and from the maintenance base bobtail.

Truck Performance on a Sandy Track

A total of 11 trips over a 0.4 mile section of sandy track used as landing access from a sand/gravel county road were collected for the chipping operation (Table 4.7). A combined total of six trips were recorded in the loaded direction (from the landing). These included three vehicle configurations, loaded, unloaded and bobtail (no trailer). Five trips with two configurations were recorded in the return direction. The track included sections of deep sand and slight adverse grade (1-2% in loaded direction).

The severe effects of loose sand in reducing both fuel consumption and speed are evident. There is also considerable difference between the fuel consumption associated with the three loading conditions. Average fuel consumptions for each configuration were 62, 40 and 22 g/100 miles respectively, although travel speed was about the same in all cases. The marked reduced consumption when not pulling a trailer as compared to pulling the empty trailer is an indication of the cost of towing the additional set of axles as well as the additional weight. Better fuel economy was obtained in the return direction, due to the assistance of the moderate favorable grade.

Table 4.6 Fuel Usage with and without Unloaded Log Trailer (Bobtail)

Unloaded Log Trailer

Trip	Distance (miles)	Speed (mph)	Fuel (g/100)
1	54.5	45.0	18.2
2	97.5	51.4	17.3
3	47.5	50.2	15.0
4	48.4	49.1	15.6

Bobtail

Trip	Distance (miles)	Speed (mph)	Fuel (g/100)
1	41.7	46.3	10.7
2	15.7	32.6	10.5
3	36.4	42.0	12.5

Table 4.7 Truck Performance on Sandy Access Track

Trip Type	Fuel (G/100	Speed (mph)	Gross Vehicle Weight (,000lbs)
Loaded			
Chip 1	65.32	10.6	85.02
Chip 2	64.94	8.8	85.42
Lowboy 1	56.20	8.0	55.00
Average	62.07	9.1	75.15
Unloaded Forward			
Lowboy 2	40.19	10.2	34.00
Bobtail Forward			
Truck 1	23.53	8.38	16.50
Truck 2	19.93	7.89	16.50
Average	22.08	8.13	16.50
Unloaded Return			
Chip 1	19.78	7.38	31.50
Chip 2	13.21	9.05	33.80
Chip 3	21.90	8.15	29.25
Chip 4	17.38	8.19	32.00
Lowboy 3	19.16	7.22	34.30
Average	18.44	8.64	32.17

Distance was 0.37 miles
Road Type was Sand Compartment trail
Loaded / Unloaded Fuel Consumption Ratio for chip hauling was 1.6

Summary

The selected log truck was heavily scheduled. The truck travelled over 2000 miles and worked over 70 hours in the five day week of which 846 miles were loaded, 1200 miles unloaded with trailer and 90 miles were bobtail (without trailer). Truck utilization for productive work (loaded mile percentage) was influenced by the distance from base to the logging operations. Additional running of about 12 % of the direct return distance from the logging operations to their respective delivery points was incurred during this week. Fuel consumption varied with application. Transporter operations involved greater fuel consumption than log delivery.

Investigation of the detailed data indicated that additional weight could be carried with little or no speed penalty and low fuel penalty. Examination of data from three trips without trailer (bobtail) indicated that considerable fuel savings might be made by dropping trailers wherever possible and ferrying the tractor only (bobtail). Analysis of data from a sandy access road indicated considerable increase in fuel consumption and decrease in speed associated with poor road surface. This pointed to the need for more data on the effect of road surface. A trial was conducted in Florida to address this need.

CHAPTER 5 THE EFFECTS OF DIFFERENT ROAD SURFACE

The wide variety of road surfaces encountered during log hauling is a particular problem for loggers, not shared by traditional transport operations. The need to operate on this wide variety of surfaces influences both the initial choice of truck, and it's subsequent performance. The previously described contractor study found that sandy roads considerably reduced speed and increased fuel consumption.

The objective of the second trial was to investigate the effect of widely differing road surfaces on truck speed and fuel usage. The chosen study area was centered on a lower coastal plain logging operation south of Perry, Florida supplying Proctor and Gamble's Foley pulp mill. The truck selected for study was one of a logging contractor's fleet of seven. The Ford 9000 tractor (Table 3.1) had a higher ratio rear drive to provide better performance on the more demanding sand and gravel sections. It was pulling a locally constructed full tree trailer, which carried a cage to contain tree limbs on the rear. This resulted in a tare weight for the combination of about 32,000 lbs. Target gross weight was 80,000 lbs. The payload loss due to the heavier trailer reduced truck and fuel productivity when measured in ton-mile units by about 4% when compared to the lighter trailers used in the other studies.

The logging operation was located about 60 miles south of the mill. The haul route was about 1/3 sand and gravel road. The route had very little elevation change in any of it's sections and road alignment was generally straight with excellent sight distance throughout. Eighteen sections were identified in the 60 mile haul route, covering the range from unprepared sand track to four lane divided highway. Descriptions of the road sections are presented in Table 5.1 - 5.5. A classification (1 - 5) is used to aid in interpretation of the results. The Class 5 classification is applied to the lowest standard unformed sand trails within the compartment used for access to the landing. Class 4 was applied to permanent formed sand compartment roads used for compartment access. These were maintained infrequently, or as required for harvesting. Class 3 was applied to formed, mostly gravelled roads used as major, all-weather access to the forest block. These roads were in semi-continuous use and received more regular maintenance. Class 2 roads were paved county and two lane state roads. Class 1 was reserved for divided four lane highway. The Class 1 roads were effectively comparable to interstate for truck performance considerations. They were essentially flat which would compensate for the slightly increased rolling resistance associated with bitumen surface.

Results by Road Class

Class 5 - Unimproved Sand

Truck speeds while operating within the compartment, were very low, at between 4 and 8 mph (Table 5.1). This resulted in a low ton-mile productivity of 60 - 100 t-m/h, about 1/7 of the observed level for Class 1 Highway sections. Two factors appeared to be limiting truck speed, (1) the roughness of the trail and (2) the rolling resistance of the sand. The first section within this compartment was a minor trail leading to the loader. The second section was a more heavily used trail which ran through the center of the compartment with the minor trails leading to the loading sites, such as Section 1, branching off as spurs. Stumps were removed from the major trail, but since it had experienced considerably more traffic, several softer *sand hole* sections had developed. The minor trail had experienced less preparation but also much less traffic, and the original ground surface was largely undisturbed, if uneven. Stump holes and uneven ground surface caused drivers to limit travel speed to avoid truck damage and being tossed around the cab.

Table 5.1 Section Description and Performance Results for Class 5 Unimproved Sand Tracks

Class 5 - Unformed Sand Tracks

Section	Length *(miles)*	Description
1	0.2	Unprepared sand track in Compartment
2	0.2	Heavily trafficked sand track within compartment

Speed

Section	Loaded *(mph)*	Unloaded *(mph)*	Round Trip *(mph)*		Productivity *t-m/h*
1	6.16	4.70	5.43		65
2	8.55	8.79	8.67		104

Fuel Consumption

Section	Loaded *(g/100)*	Unloaded *(g/100)*	Roundtrip *(g/100)*	Fuel Ratio*	Efficiency *t-m/g*
1	72.50	26.63	49.60	2.7	24
2	79.37	42.76	61.07	1.9	20

* Loaded Unloaded Fuel Consumption Ratio

The truck and trailer suspension were stiffer unloaded as compared to loaded and lower speeds were recorded on the rougher minor trail (Section 1). However it's firmer surface led to comparatively reduced fuel consumption both unloaded and loaded. The softer *chopped up* sand surface of the major trail exerted a greater rolling resistance and resulted in lower fuel productivity (20 t-m/g) for a slightly higher level of overall truck productivity (104 t-m/h).

Another factor noted while riding as an observer in this trial was the high level of driver skill and judgement needed for operation on these soft sand road sections (Class 4 and 5). Gear changing while crossing soft areas was either very difficult or not possible due to the loss of truck momentum experienced while the clutch was disengaged. Therefore the driver needed to select a gear that would provide maximum speed and momentum while at the same time retaining sufficient reserve power to pull through the softer area.

Fuel consumption levels on the Class 5 trails were 50-70 g/100 (1-2 mpg). These were the highest recorded during the whole project. The sand access road studied in the previous contractor trial produced similar consumption levels. Fuel efficiency was about 20 t-m/g which was 1/3 of the highway levels recorded for this truck.

Class 4 - Formed Sand Roads

Travel speeds of about 20 mph on the smoother formed sand roads were considerably faster than those on the unprepared roads (Table 5.2). Truck productivity at 250 t-m/h was about 1/3 of Class 1 highway levels.

Table 5.2 Section Description and Performance Results for Class 4 Formed Sand Roads

Class 4 - Formed sand roads

Section	Length *(miles)*	Description
3	1.3	Compartment access road - limited gravel in some *sand holes*
16	1.5	Compartment access road - no gravel

Speed

Section	Loaded *(mph)*	Unloaded *(mph)*	Round Trip *(mph)*		Productivity *t-m/h*
3	19.00	21.28	20.14		242
16	21.77	25.24	23.51		282

Fuel Consumption

Section	Loaded *(g/100)*	Unloaded *(g/100)*	Roundtrip *(g/100)*	Fuel Ratio*	Efficiency *t-m/g*
3	54.18	27.58	40.88	2.0	29
16	56.48	31.82	44.15	1.8	27

* Loaded Unloaded Fuel Consumption Ratio

Driving on these roads presented similar level of driver challenge as the compartment trails with the existence of very soft *holes*. These became more difficult to pass with continued traffic. Selection of correct gear and approach speed were critical.

Fuel usage at about 55 g/100 loaded and 30 g/100 unloaded were still very high when compared to highway levels (25 g/100 and 17 g/100 respectively). This high fuel consumption is attributed to the high rolling resistance of the soft sandy surface. The fuel efficiency factor of about 28 t-m/g was about 1/2 the class 1 highway level

Class 3 - Gravelled Main Access Roads

Speed over the gravel road at about 35 mph were 60% of highway levels (Table 5.3). These roads had a much firmer surface than the sand roads, but rolling resistance levels were still much higher than bitumen or concrete. Surface corrugation was present in some sections which caused severe truck vibration at particular speeds. Both factors limited travel speed. Productivity levels were about 400 t-m/h as compared to about 750 t-m/h for highway operation. These gravelled road sections comprised a substantial part of the haul and consequently had a great impact on daily truck productivity.

Fuel consumption was not as severely affected as travel speed, about 25 g/100 as compared to the 20 g/100 highway level. The extra power required to overcome rolling resistance was offset by the reduced air resistance at the lower travel speeds.

Table 5.3 Section Description and Performance Results for Class 3 Gravelled Roads

Class 3 - Gravel main access

Section	Length (miles)	Description
9	2.7	Gravelled, Company maintained
15	5.0	Gravelled, Company maintained
18	7.1	Gravelled, Company maintained
17	0.8	Gravelled, County maintained
13	6.5	Gravelled, Company maintained

Speed

Section	Loaded (mph)	Unloaded (mph)	Round Trip (mph)		Productivity t-m/h
9	27.40	29.98	28.69		344
15	41.16	41.77	41.46		498
18	31.17	35.17	33.17		398
17	30.68	36.43	33.56		403
13	34.98	38.33	36.65		440

Fuel Consumption

Section	Loaded (g/100)	Unloaded (g/100)	Roundtrip (g/100)	Fuel Ratio*	Efficiency t-m/g
9	37.32	19.30	28.31	1.9	42
15	30.64	18.00	24.32	1.7	49
18	37.32	17.60	25.50	2.1	47
17	34.28	16.53	25.40	2.1	47
13	25.46	18.03	21.74	1.4	55

* Loaded Unloaded Fuel Consumption Ratio

Class 2b - Shorter Paved Roads

This class contained short sections of paved two lane roadway atypical of the class as a whole because of speed limits, acceleration or braking requirements. These sections were therefore separated from the longer and more important Class 2a sections to aid evaluation.

Section 8 (Table 5.4) provides an interesting case where unloaded consumption exceeds loaded consumption. Unusually low loaded consumption was a result of the coast down of the loaded truck to stop at the weight scales leading to low loaded consumption. High unloaded consumption was caused by hard acceleration of the unloaded truck leaving the scales.

The slow speed on section 14 was associated with the full stop required at the start and finish of the section and it's short length. This resulted in higher fuel consumption due to the need to accelerate the truck from rest.

Class 2a - Longer Paved Two Lane Roads

Speeds recorded on these longer paved two lane sections about 50% faster than those on gravelled Class 3 roads (Table 5.5) but still slower than the Class 1 divided highway, because of posted speed limits, narrower roadway and alignment. Thus truck productivity was slightly lower (600 t-m/h). Fuel consumption and efficiency levels (about 20 g/100 and 60 t-m/g) were about the same as the four lane divided road.

Table 5.4 Section Description and Performance Results for Class 2(b) Paved Two Lane Roads with Short Section Length

Class 2b Short paved two lane

Section	Length *(miles)*	Description
7	1.2	Urban
8	0.5	Mill entrance
14	0.4	County

Speed

Section	Loaded *(mph)*	Unloaded *(mph)*	Round Trip *(mph)*		Productivity *t-m/h*
7	32.70	38.10	35.40		425
8	22.98	28.13	25.56		307
14	22.30	22.90	13.03		156

Fuel Consumption

Section	Loaded *(g/100)*	Unloaded *(g/100)*	Roundtrip *(g/100)*	Fuel Ratio*	Efficiency *t-m/g*
7	20.64	19.55	20.09	1.1	60
8	22.50	34.28	28.39	0.7	42
14	49.36	21.79	35.57	2.3	34

* Loaded Unloaded Fuel Consumption Ratio

Table 5.5 Section Description and Performance Results for Class 2(a) Paved Two Lane Roads with Longer Section Length

Class 2a - Two Lane Roads

Section	Length (*miles*)	Description
6	2.1	Urban
10	5.3	County
11	7.7	County

Speed

Section	Loaded (*mph*)	Unloaded (*mph*)	Round Trip (*mph*)		Productivity *t-m/h*
6	42.50	44.69	43.59		523
10	51.62	58.17	54.89		659
11	48.54	56.35	52.45		629

Fuel Consumption

Section	Loaded (*g/100*)	Unloaded (*g/100*)	Roundtrip (*g/100*)	Fuel Ratio*	Efficiency *t-m/g*
6	28.70	15.07	21.90	1.9	55
10	23.11	17.82	20.47	1.3	59
11	23.23	16.78	20.01	1.4	60

* Loaded Unloaded Fuel Consumption Ratio

Class 1 - Four Lane Highway

Highway levels of fuel consumption and fuel efficiency (20 g/100, 60 t-m/g - Table 5.6) were similar to those in the previous contractor study. High average speed on the four lane sections resulted in a high 750 t-m/h truck productivity level.

Summary

Truck performance was strongly affected by road class which was primarily determined by surface type in this level terrain. Fuel consumption increased considerably on the softer sands, but less so on the firmer gravel roads. Of perhaps more concern were the large speed reductions on the gravelled and sandy roads. Performance data revealed in Figures 5.1 and 5.2 demonstrate the levels of these reductions graphically.

Recognition of these differences raises an important issue for both the truck operators and log purchasers. Haul routes composed of varying proportions of these road classes could experience very different levels of truck productivity and operating cost. The important question is then *How much does truck performance vary between routes?* This issue was addressed in the third trial.

Table 5.6 Section Description and Performance Results for Class 1 Divided 4 Lane Road

Class 1 - Four Lane Road

Section	Length	Description
12	16.6	State Highway
4	9.5	State Highway
5	16.1	State Highway

Speed

Section	Loaded (mph)	Unloaded (mph)	Round Trip (mph)		Productivity t-m/h
12	60.29	61.88	61.08		733
4	59.96	63.90	61.93		743
5	62.94	61.40	62.17		746

Fuel Consumption

Section	Loaded (g/100)	Unloaded (g/100)	Roundtrip (g/100)	Fuel Ratio*	Efficiency t-m/g
12	24.91	16.57	20.74	1.5	58
4	25.04	17.68	21.36	1.4	56
5	23.34	17.97	20.65	1.3	58

* Loaded Unloaded Fuel Consumption Ratio

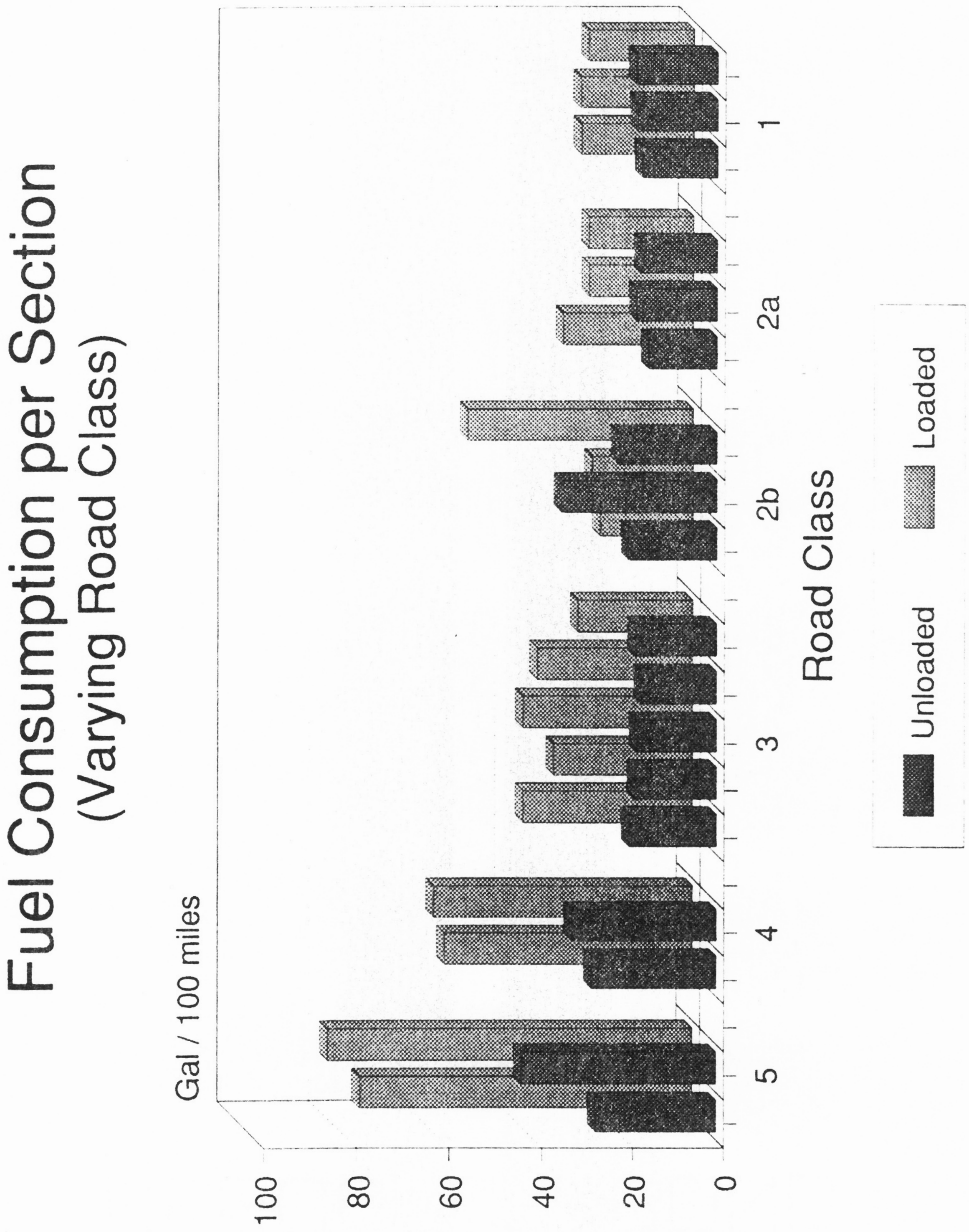


Figure 5.1 Unloaded and Loaded Fuel Consumption by Section

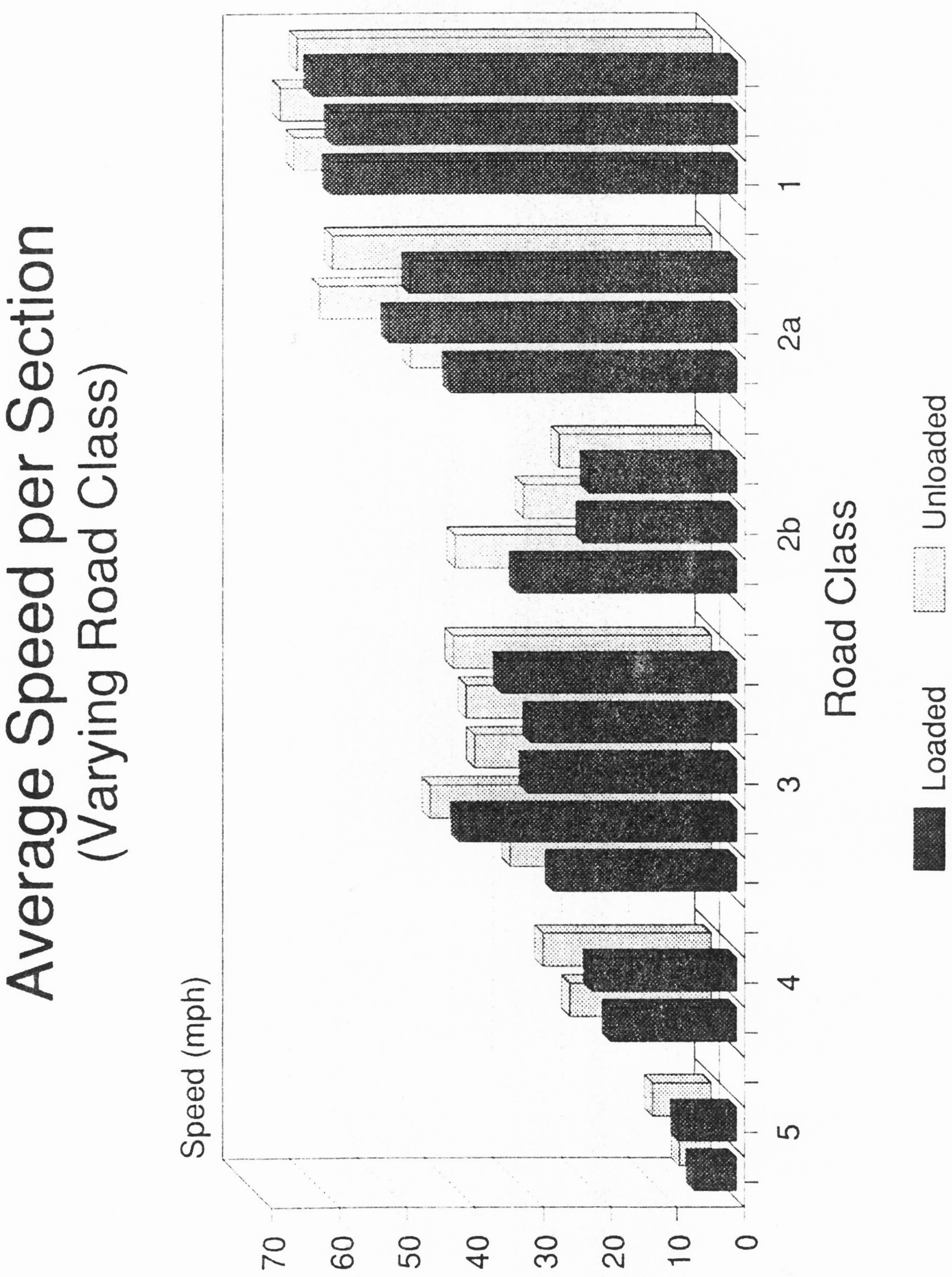


Figure 5.2 Travel Speed by Section

CHAPTER 6 COMPARISON OF ROUTES

Road sections were considered as lengths of road with common characteristics. Road surface type and condition, a major factor in section classification, was shown to have a major impact on truck performance. Because a haul route is just a collection of sections, it is possible that the combined effects of inter - sectional performance variations could lead to a smaller, but still economically important variations in performance over whole routes. An exploratory investigation of performance differences for a set of different routes was undertaken in South Carolina. The objective of the study was to explore the level of variation between routes in the productivity of a single truck and driver.

The experimental design used in the study involved collecting data for three or four trips to each of seven woodyards using one truck and one driver. The trucking company was responsible for moving preloaded trailers from the outlying woodyards to the mill. The seven woodyards were located at distances of between 45 and 80 miles surrounding the pulpmill. Route characteristics for the seven trips are presented in Table 6.1. Most of the haulage distance was on Class 2 roads. The pulpmill was located near the break between the upper coastal plain and piedmont physiographic zones. Hauls to the west (Lattimore, Clinton, Newberry, Hickory Grove) traversed the rolling terrain of the piedmont region. Hauls to the east included considerable distance on the more level or longer, even gradients of the upper coastal plain region (Mt Croghan and Lilesville). Although located in the piedmont to the north of the mill, the Mooresville haul involved almost all interstate with it's associated moderate gradients and excellent alignment. Considering interstate and divided four lane road together as Class 1, these routes were entirely Class 1 and Class 2.

Table 6.1 Study 2 Woodyard Haul Route Characteristics

Yard	Distance (miles)	Interstate	4 Lane	2 Lane	Description
Lattimore	70	5%	7%	88%	Rolling terrain, 26 stop/Traffic lights.
Lilesville	70	-	15%	85%	Flat, 18 stop/traffic lights.
Mt Croghan	47	-	25%	75%	Flat, some sustained grades, 12 Stop/Traffic lights.
Hickory Gr	45	15%	10%	75%	Rolling, 15 Stop/Traffic lights
Newberry	75	-	15%	85%	Rolling, 10 Stop/Traffic lights
Mooresville	62	85	%10%	5%	Flat, 4 Stop/Traffic lights
Clinton	77	-	15%	85%	Rolling, 12 Stop/Traffic lights.

A nine month old MACK Super Chief and it's normal driver were used for this study (see table 3.1 for truck specifications). The driver was very familiar with these routes. The haulage operation was based on exchange of empty trailers for preloaded trailers set out at each yard. Thus while the tractor and driver were fixed, a new trailer was hauled each load. Although different trailers can have different pulling characteristics and tare weights, trailer exchange was an integral part of the operation and elimination of these source of variation was not possible. Loaded trailers were always available at the woodyards during the trial. Loads were weighed and topped off to correct weight before departure from the yard, except for the first load of the day, or hauling on Saturday, when weighbridge staff and loader operator were not available. In these cases loads were hauled as loaded. Loads were not hauled consecutively from the one yard due to scheduling requirement of the haulage operation.

Performance data are presented in Table 6.2. Trip sets are presented in increasing order of average fuel efficiency (decreasing G/100). These data reveal considerable variation in both speed and the fuel consumption for the different routes. Average round trip speeds varied between 44 and 54 mph. Fuel usage ranged from a high of 18.6 g/100 to a low of 16.6 g/100. However, the direct interpretation of these data is made difficult by the variation in loading between yards. Federal interstate restrictions lowered target load weight for the Mooresville haul to 78,000 lbs. Target load weights for operators and supervisors on the other yards also varied. There were several occasions when a loader was not available to top off the load. Two route characteristics of particular significance in interpreting these results are the frequency of traffic lights and stop signs on the Lattimore, Hickory Grove and Lilesville trips and the use of the Interstate on the Mooresville trip.

Table 6.2 Fuel and Speed Performance from Different Woodyards

		Unloaded		Loaded		Round Trip				
Yard	**Load ,000lb**	**Fuel g/100**	**Speed mph**	**Fuel g/100**	**Speed mph**	**Fuel g/100**	**Speed mph**	**Ratio**	**t-m/h**	**t-m/g**
Lattimore	76.6	14.9	49.2	23.7	41.8	19.3	45.5	1.6	508	63
Lattimore	80.1	14.0	46.3	22.1	41.7	18.1	44.0	1.6	543	72
Lattimore	77.6	14.1	47.2	22.6	39.9	18.3	43.5	1.6	495	68
Average	**78.1**	**14.3**	**47.6**	**22.8**	**41.1**	**18.6**	**44.3**	**1.6**	**515**	**68**
Lilesville	76.5	13.7	47.3	21.9	45.5	17.8	46.4	1.6	551	68
Mt Croghan	79.2	13.4	46.2	22.8	43.1	18.1	44.7	1.7	552	71
Mt Croghan	79.1	13.3	46.1	22.9	44.6	18.1	45.4	1.7	570	71
Mt Croghan	77.8	13.6	46.0	21.8	43.6	17.7	44.8	1.6	543	70
Mt Croghan	82.2	11.4	48.4	23.3	43.5	17.4	46.0	2.0	589	78
Average	**79.6**	**12.9**	**46.7**	**22.7**	**43.7**	**17.8**	**45.2**	**1.8**	**564**	**72**
Hickory Gr	81.9	13.9	41.5	21.2	41.1	17.6	41.3	1.5	554	77
Hickory Gr	80.7	14.4	46.1	22.7	36.7	18.6	41.4	1.6	484	71
Hickory Gr	81.2	14.3	46.5	21.2	38.6	17.8	42.6	1.5	513	75
Hickory Gr	82.0	13.3	45.4	22.7	40.5	18.0	43.0	1.7	547	75
Average	**81.5**	**14.0**	**44.9**	**22.0**	**39.2**	**18.0**	**42.1**	**1.6**	**524**	**74**
Newberry	79.4	12.2	48.6	20.2	47.8	16.2	48.2	1.7	614	79
Newberry	79.4	11.6	49.4	21.7	48.6	16.6	49.0	1.9	624	77
Newberry	79.8	15.4	54.9	21.7	50.3	18.6	52.6	1.4	630	75
Average	**79.5**	**13.1**	**51.0**	**21.2**	**48.9**	**17.1**	**49.9**	**1.6**	**630**	**75**
Mooresville	77.3	13.9	57.2	20.4	52.6	17.2	54.9	1.5	649	72
Mooresville	78.1	13.7	53.0	18.5	54.1	16.1	53.6	1.4	678	78
Average	**77.7**	**13.8**	**55.1**	**19.5**	**53.4**	**16.6**	**54.2**	**1.4**	**664**	**75**
Clinton	79.8	12.2	49.0	20.6	49.4	16.4	49.2	1.7	640	79
Clinton	80.6	12.0	51.0	20.2	43.7	16.1	47.4	1.7	575	82
Clinton	83.3	14.3	53.2	22.0	49.5	18.2	51.4	1.5	685	76
Average	**81.3**	**12.8**	**51.1**	**20.9**	**47.5**	**16.9**	**49.3**	**1.6**	**633**	**79**

There appears to be consistency of performance within groups of hauls to individual woodyards. This indicates that interference from other traffic, considered before the study to be a likely major cause of variation, was not a serious cause of delay during this study period. The differences between the first run of the day (usually starting at 5.00 am) and later runs is not apparent.

Variation in loaded weight between trips indicate that greater reliance should be placed on the ton - mile based performance statistics, rather than direct speed and fuel consumption measures. Truck productivity ranged from 515 t-m/h to 664 t-m/h between routes. This is a range of 17% which represents a considerable productivity differential. It is interesting to note that despite the slightly reduced payload, the Mooresville haul on interstate produced the best truck productivity because of the high speeds attained.

A Kruskal-Wallis One Way Analysis of Variance test based on ranks was used to test for the statistical significance of the apparent difference in truck productivity between haul routes. Results indicated a highly significant difference between at least some routes at a probability level of 0.018.

Fuel consumption results ranged from a low of 16.6 g/100 to a high of 18.6 g/100. The fuel productivity between yards ranged from 68 t-m/g to 79 t-m/g. This is a range of about 15% on a mean observed value of 73 t-m/g. Given the average daily fuel consumption for the instrumented truck of about 70 gallons, a 15 % variation in fuel productivity represents about 10 gallons of fuel per day between the best and worst routes.

The statistical significance of the apparent differences between these routes in fuel consumption was tested using the Kruskal-Wallis test. Again the results indicated a significant difference between some of these routes at the 0.067 probability level.

These data indicate some correlation between higher fuel consumption and higher speed (r = 0.49), as would be expected from theoretical considerations of increasing air resistance. Although low, this correlation is statistically significant at between 2.5% and 5% (using Kendal's Rank Correlation, tau = 0.4). The low r value indicates that other factors are influencing fuel consumption and speed. Both driver style and road surface effects are eliminated from this data (only one driver used in the experimental design, and most hauling was on Class 2 bitumen surfaced roads). The remaining major factors are the effects of gradient and traffic control (stop signs and traffic lights).

This trial indicated considerable variation in truck performance between routes even when only one driver was used and significant road surface differences were not present. To provide more information on the nature of the remaining differences, the detailed data for one of the hauls , Mt Croghan, was examined in more detail.

Evaluation of Section Data within One Route

The Mt Croghan haul route was divided into nine homogeneous sections based on easily observed differences in gradient, stop signs and traffic lights. This upper coastal plain route included sections of flat to gentle though sustained grades. Sustained moderate adverse grade (loaded direction) was present in Section 1, 2, 3 and 4. Favorable grade (loaded direction) was present in Section 6. Section 7 was an urban 4 lane highway with three traffic lights. Road surface variation was small.

Section statistics are presented in Table 6.3a. Differences between sections are also presented as percentage divergence from the trip means, each observation weighted by distance, in Table 6.3b. Considerable difference in fuel consumption and achieved speed was recorded between sections. Readily observable factors recorded during data collection explain some of these differences.

Table 6.3a Performance by Section on Coastal Plain Haul (Average of Four Trips)

		Loaded		Unloaded		Round Trip		
Sect.	Dist.	Fuel	Speed	Fuel	Speed	Fuel	Speed	Ratio*
	(mile)	*(G/100)*	*(mph)*	*(G/100)*	*(mph)*	*(G/100)*	*(mph)*	
1	.3	42.87	12.51	12.12	20.21	26.65	16.36	3.54
2	.7	59.97	22.07	4.07	41.54	31.46	31.80	14.67
3	9.0	24.82	46.52	12.16	48.94	18.42	47.73	2.04
4	4.0	28.72	38.58	10.77	42.73	20.02	40.65	2.67
5	10.7	20.58	52.04	13.61	55.47	16.99	53.76	1.51
6	7.0	15.64	47.37	14.69	48.08	15.17	47.72	1.06
7	2.0	23.25	31.68	13.15	33.18	18.21	32.43	1.77
8	7.1	22.08	46.81	12.02	51.83	17.03	49.32	1.84
9	4.9	20.58	51.36	14.56	49.69	17.52	50.52	1.41
Average		**22.48**	**46.56**	**12.92**	**49.33**	**17.66**	**47.94**	**1.74**

* Loaded/Unloaded Fuel Consumption Ratio

Table 6.3b Percentage Divergence in Fuel and Speed for Road Sections based on Column Average

	Loaded		Unloaded		Round Trip		
Section	Fuel	Speed	Fuel	Speed	Fuel	Speed	
1	191	27	94	41	151	34	
2	267	47	32	84	178	66	
3	110	100	94	99	104	100	
4	128	83	83	87	113	85	
5	92	112	105	112	96	112	
6	70	102	114	97	86	100	
7	103	68	102	67	103	68	
8	98	101	93	115	96	103	
9	92	110	113	101	99	105	

A combination of the short section length and adverse grade were responsible for the high consumption and low speed in Sections 1 and 2. Loaded consumption levels in two longer adverse grade sections (3 and 4) are respectively 10 and 28% above the trip distance weighted average. However, these excess consumptions are recovered with lower fuel usage in the average downgrade of Sections 5 and 6 (8% and 30% below average). Average speeds were also higher for these downgrade sections. Another indication of grade is obtained from the Loaded/Unloaded Fuel Consumption Ratio. Adverse grade in the loaded direction will significantly increase this ratio. Sections 3 and 4 consumed more than twice the fuel loaded as unloaded. In contrast, the favorable grade in the six miles of section 6 led to almost the same consumption with gross vehicle weight of near 80,000 lbs as for the unloaded return at about 28,000 lbs. The influence of traffic lights is seen in the lower speeds for Section 7.

Summary

Substantial differences in speed, truck productivity and fuel consumption were established in a comparison of truck performance on seven routes and supported by sectional analysis of one of the routes. Differences attributable to road surface were minimized by the predominant use of paved two lane roads (a uniform Class 2 road surface). The trial used one truck and driver to minimize the effect of driving style. The performance differences must therefore be associated with gradient and traffic control.

The remaining major influence on truck performance not yet explored in these trials is driver skill and style. Driving style is used to describe the pattern of choices of target speed, accelerating and braking intensity employed by individual drivers. Data comparing driving style requires the testing of several drivers.

A detailed experiment was therefore conducted on one haul route with five drivers at the Catawba site to investigate differences in driving style and further analyze the differences in road section due to gradient, alignment and traffic.

CHAPTER 7 RESULTS OF DRIVER STUDY

The objectives for this study were to compare and evaluate truck speed and fuel performance differences:

1) between drivers by comparing both whole trip and between section data (inter-driver study), and

2) between individual sections, minimizing the driver effect by averaging across all trips (inter-section) study.

The previous studies, which investigated the effects of road surface and route on truck performance, minimized the influence of the driver by using only one truck and driver in each trial. This study was primarily designed to explicitly explore the differences between drivers. The experimental design used for this study involved five drivers, each making three return trips from the Catawba mill to the Newberry S.C. woodyard. The same truck was used for all trips.

These data also provided an excellent opportunity to further investigate the differences between road sections. Data presented in Chapter 6 established truck performance differences between road sections even where road surface was similar, but the comparisons were only based on a few trips. Data collected for this study comprised 15 trips over the one route. To facilitate the inter-section study, the route was divided into readily identifiable sections and the passage of the truck from section to section recorded. Where possible the section divisions were selected to contain homogeneous road conditions. The between section comparison is discussed first to provide a background for the driver comparison.

Inter-Section Study

Description of the Route

The 74 mile haul route from the Newberry yard to Catawba S.C. was divided into the 14 sections described in Table 7.1. Section 14 was discarded from analysis because it was not used in all trips. The first trip of the day began at the contractor's depot and did not use section 14. Of the remaining 13 sections nine were rural and four urban. Six of the nine rural sections were two lane rural highway, one (Sec 12) was a four lane divided highway and two (Sec 11 and 13) were narrower two lane county road. The four urban sections comprised two sections of township street/main street and two sections of urban four lane. One of these urban sections, Section 8, had five traffic lights. Sections 1, 2, 7, 8, 10, 11, 12 and 13 each finished with the truck coming to a full stop. Most (nine) of the sections were between two and 10 miles long.

Two sections (1 and 2) were very short (< 1 mile) so the data from these require careful interpretation. These sections required a standing start and a full stop at the end. It takes about 1/2 to 3/4 of a mile to accelerate a laden truck to highway speed. During this period the engine is operating largely at full throttle with correspondingly high fuel consumption. Since the sections began from a standing start, the average speed for this short distance was also low. While these *starting* data are valid and important aspects of truck performance, they represent phenomena different from the grade and alignment influences of normal highway operation.

A data trace for one loaded trip, marked to show the section boundaries, is presented in Figure 7.1. Performance parameters included are speed, engine RPM, fuel flow (as gallons per 100 miles), gear changes and brake usage.

Table 7.1 Section Characteristics

Section	Length (miles)	Description
1	.7	Township street
2	.1	Township main street
3	7.7	Rural two lane highway - rolling down hill
4	7.3	Rural two lane highway - rolling downhill
5	1.6	Township street - speed restricted 4 lane no median
6	9.1	Rural two lane highway - rolling little elevation change
7	16.2	Rural two lane highway - rolling
8	3.0	City bypass highway - four lane no median five stop lights
9	3.5	Rural two lane highway - little grade
10	7.7	Rural two lane highway - little grade but several major intersections
11	6.7	Rural two lane county road - rolling narrow
12	7.3	Rural two/four lane divided state highway - little grade
13	2.9	Rural two lane highway - little grade but poorer alignment
14	.5	Mill entrance

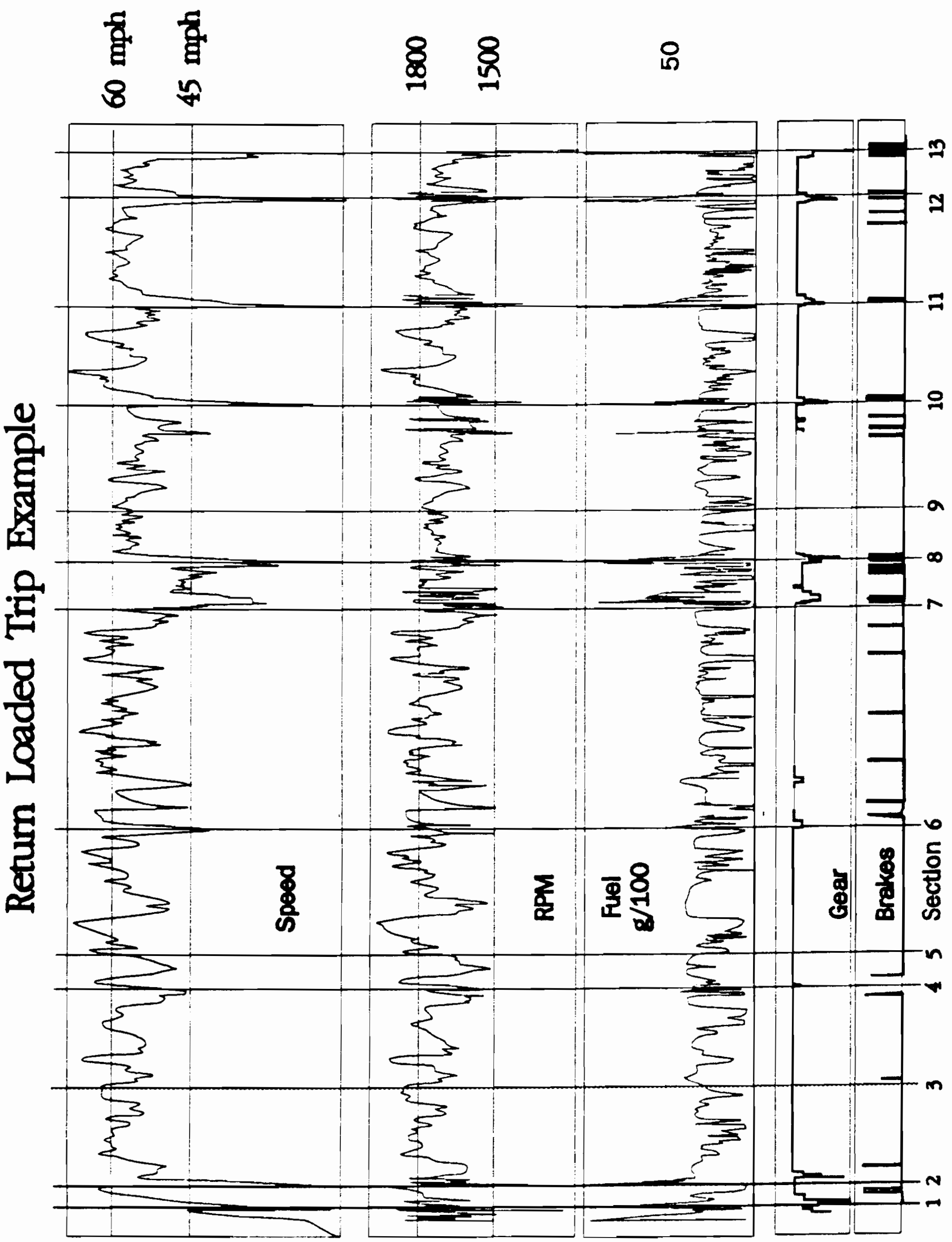


Figure 7.1 Trip Data Trace showing Sections

The substantial speed penalty of a standing start in a short section is clearly shown in the first two sections. The sequence of hills and valleys in the rural sections 3-7 and 10 -11 are evident in the speed trace, as is the more consistent speeds on flatter sections 9, 12 and 13. Drivers were able to make most of the trip in 8 th gear and the fuel trace shows that accelerator pedal usage was generally either *down or up*. The constant 30-35 g/100 miles consumption level for full throttle / top gear operation is also evident. Brake usage was limited.

The differences between road sections were explored by averaging the data from all 15 trips to minimize the influences of differences in driving style. Truck speed, fuel consumption and braking data were developed for each of the 13 road sections and differences related to section characteristics where possible.

Speed Differences on Road Sections

The effect of differences in road characteristics are demonstrated in Figure 7.2. The bar for each section spans the region from the lowest to the highest observed fuel consumption for that section. The horizontal bar bisecting the box marks the average for the 15 trips. Data for two selected individual trips, one loaded trip from the fastest driver and one from the slowest driver are also plotted on Figure 7.2 to provide an indication of individual driver consistency. The two demonstration trips are shown by the lines connecting the data points for each section.

The high average speeds of Sections 3 to 7 and 9 to 12 reflect the open rural road conditions. The low speed of the short section *starting* data is evident in Sections 1 and 2.

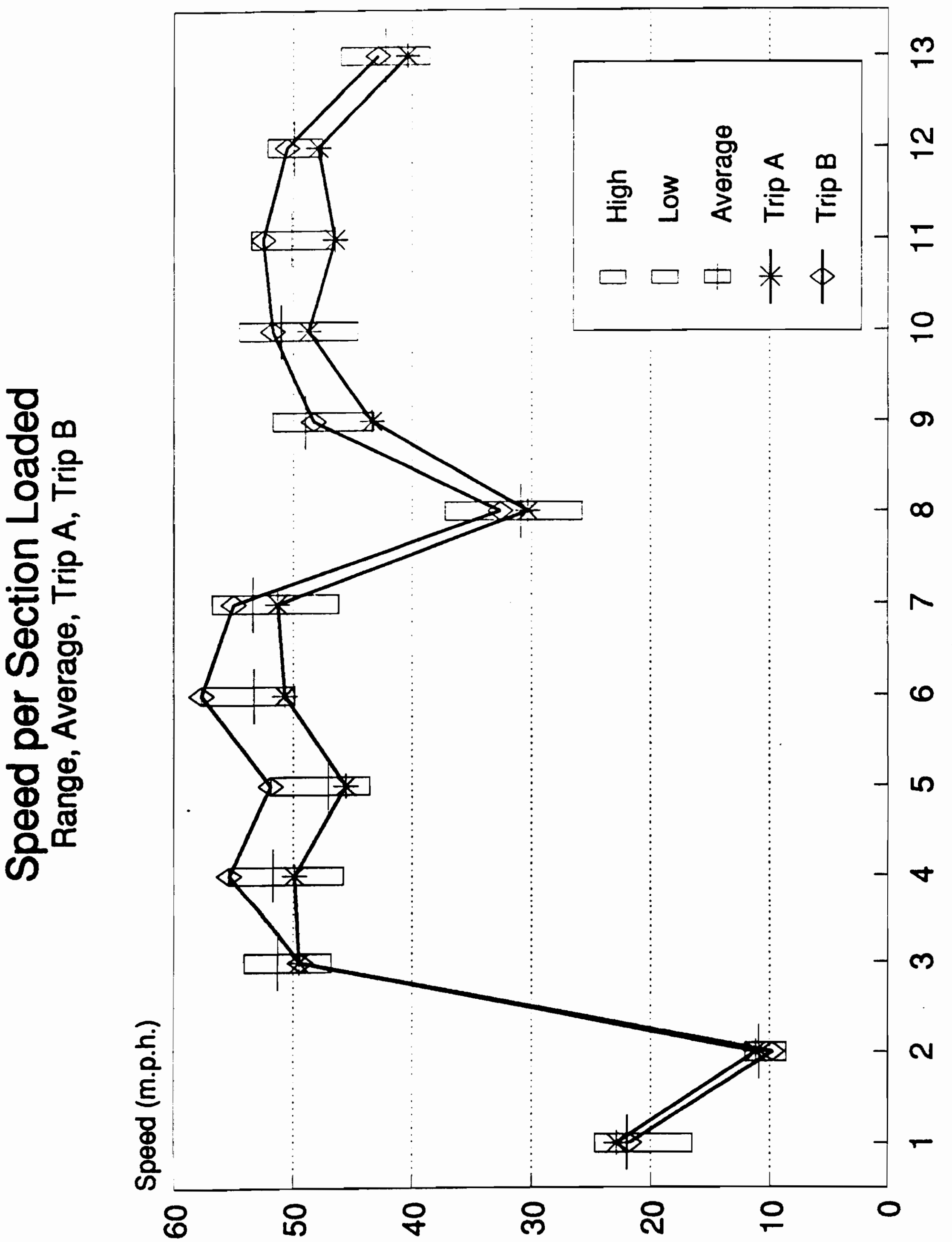


Figure 7.2 Loaded Speed per Road Section

The restrictions of both speed limit and traffic control (stop signs and traffic lights) is evident in the speed for Section 8. The effect of narrow roadway and sharper corners is seen in Section 13.

Detailed analysis of the difference between sections considered both loaded and unloaded performance since changes in either leg of the journey affect round trip time. The two legs were considered separately because of the differing truck response to the gross vehicle weight. Surprisingly, data for loaded, unloaded and averaged round trip speed per section, presented in Table 7.2, shows that loaded and unloaded speeds are nearly the same. This indicates that the 350 HP engine provided more than adequate reserve power (228 lbs / Gross HP loaded) to maintain speed on the moderate grades found in this terrain. This was also manifest in the observed high proportion of the trip using top (8th) gear. (Figure 7.1).

Also of interest is the uniformly high speeds on the rural sections which included hilly sections, areas of poorer sight distance and lower alignment standard. Likely explanations include the drivers high degree of familiarity with the route and confidence in the truck's braking ability.

Fuel Consumption Differences on Road Sections

Figure 7.3 presents an overview of fuel consumption differences between sections for the loaded journey, with range, average and the two representative trips used in Figure 7.2 (Trip A Slow and Trip B Fast). The underlying data for this table including both loaded and unloaded averages is presented in Table 7.3.

Table 7.2 Average Speed per Section for 15 Trips

Section	Unloaded	Loaded	Round Trip
1	32.26	21.96	25.95
2	15.47	10.86	12.73
3	54.34	51.34	52.75
4	54.10	51.74	52.85
5	48.75	47.16	47.70
6	56.28	53.33	54.76
7	55.57	53.41	54.50
8	36.54	30.92	33.31
9	48.45	49.05	48.73
10	51.57	51.03	51.21
11	54.86	50.18	52.38
12	54.42	49.86	52.04
13	46.12	42.37	44.10
Distance Weighted Average	**52.85**	**50.06**	**51.37**

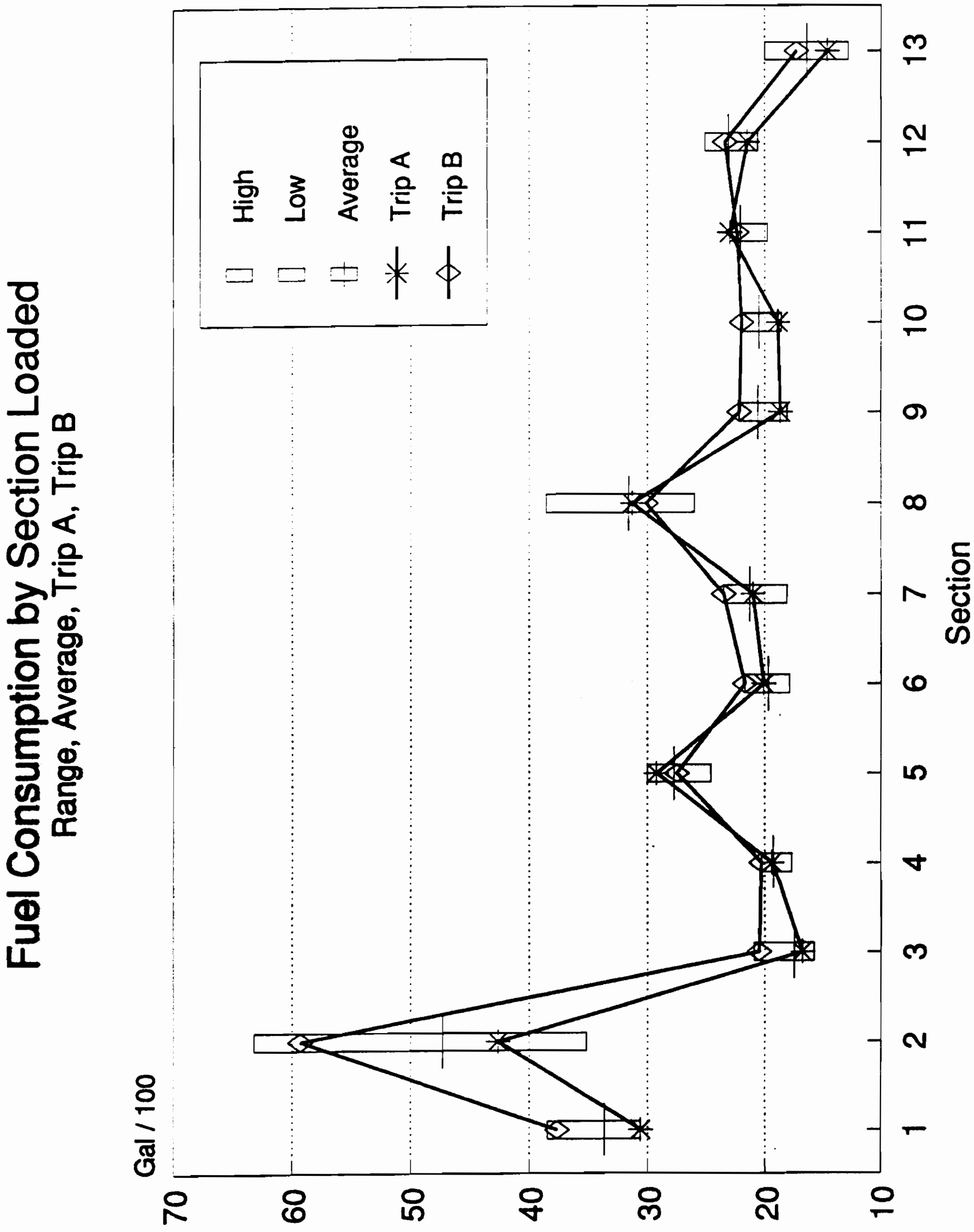


Figure 7.3 Fuel Consumption per Road Section

Considerable variation in fuel usage was noted between sections. Urban sections 1,2 5 and 8 were all above the levels for the rural sections. This is further confirmation of the high fuel cost of stop/start operations in urban areas. Trips A and B demonstrate relatively consistent driver behavior with regard to fuel consumption. Trip B uses more fuel on the rural sections with the exception of Section 11 and 5 and 8 of the urban sections where chance traffic effects had the largest influence.

Road gradient variation provides another source of difference between sections and affects fuel consumption directly. Adverse grade in one direction is cancelled somewhat by the corresponding favorable grade on the other leg of the round trip. However, adverse grade loaded has a greater influence on fuel consumption that adverse grade unloaded. Again, as discussed in Chapter 6, the loaded/unloaded fuel consumption ratio provides an indicator of these effects.

Table 7.3 presents these ratios for each section of the study route. After combining section data on a distance weighted basis the average ratio for this study was 1.6. The most extreme result was in Section 5 with a ratio of loaded to unloaded fuel consumption of 3.5. This is caused by a sustained adverse grade in the loaded direction for most of its 1.5 mile length. High loaded consumption was compensated for by the very low fuel usage in the unloaded direction (7.84 G/100 or over 12 mpg). The unloaded trips for this section had the lowest per section fuel consumption recorded in this trial. As a result the final average round trip consumption for Section 5 was surprisingly only 3% above the average for the study as a whole (the average of all 15 full trips).

Section 3 provides an example of favorable grade in the loaded direction. Loaded fuel consumption was about 18% below average, and unloaded consumption about 5% above average. Final round trip consumption (Loaded + Unloaded) was almost 9% lower than average. The Loaded/Unloaded consumption ratio was a low 1.2 (almost as much fuel used unloaded as loaded).

Table 7.3 Average Fuel Consumption per Section for 15 Trips.

Section	Unloaded	Loaded	Round Trip	Ratio
1	13.07	33.65	23.64	2.6
2	18.59	47.36	34.17	2.5
3	14.12	17.49	15.82	1.2
4	12.86	19.33	16.07	1.5
5	7.84	27.67	17.73	3.5
6	13.75	19.74	16.72	1.4
7	13.37	21.25	17.31	1.6
8	12.77	31.55	22.17	2.5
9	12.88	20.64	16.79	1.6
10	12.90	20.55	16.78	1.6
11	13.58	22.06	17.86	1.6
12	13.09	23.04	18.04	1.8
13	18.06	16.08	17.10	0.9
Distance Weighted Average	**13.41**	**21.15**	**17.28**	**1.6**

In Section 13 unloaded consumption is greater than loaded consumption (ratio < 1.0). Explanations for this apparent anomaly include the a moderate favorable grade (loaded), a somewhat lower travel speed and a coast down with engine at idle fuel flow to the mill entrance.

Braking Difference on Road Sections

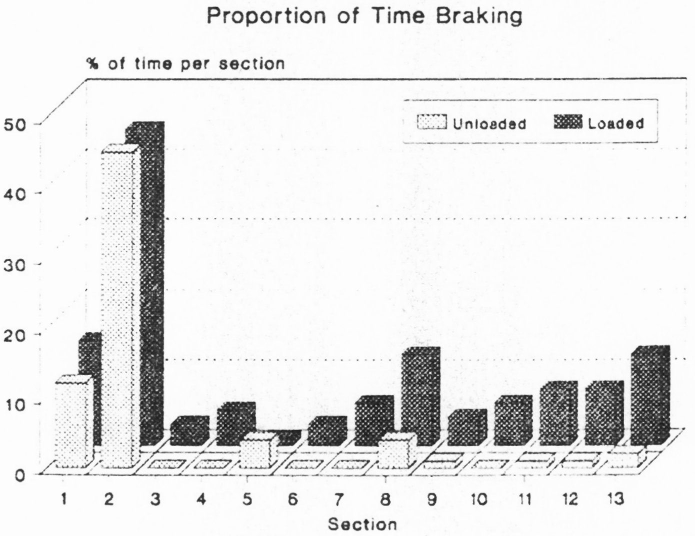
Table 7.4 presents total braking time and the proportions of braking time to total transit time for each section. Data are the average of all 15 observations per section (three trips by five drivers) and are presented for both unloaded and loaded directions. Figure 7.4 provides a graphical display of the percentage of time spent braking. Because the sections were different length, total braking time is presented to provide an indication of the magnitude of total brake usage. It is noted again that these data are for braking time and not total braking effort, which could not be readily measured in these experiments.

Brake usage on the study route in the unloaded direction is very sparing, about 1% of the time. The high usage in Section 8 obviously relates to the five stop lights. The traffic and residential requirements of Sections 1 and 2. would explain their higher levels. Section 5 with sustained favorable grade (unloaded) provides an example of greater braking time unloaded that loaded. Brake usage in Section 13 can be attributed to poor road alignment (corners).

Brake usage on the loaded journey is much higher (6% of trip time) due to the need to restrain speed on the rolling terrain. The urban sections (1,2,8) again show high braking requirements (13- 45%). Rural sections 4,7,10,11,12,13 all show braking proportions of 5% or higher. In sections 11 and 13 this can be attributed to rolling hills, narrow road and poorer alignment. Section 12, a state 4 lane highway of good alignment and gentle grade, includes a long gentle favorable grade immediately before a stop sign at the bottom of the highway exit ramp.

Table 7.4 Braking Time Unloaded and Loaded

	Unloaded			Loaded		
Section	Time (mins)	Br %	Br Time (mins)	Time (mins)	Br %	Br Time (mins)
1	1.31	0.12	0.16	2.03	0.15	0.31
2	0.39	0.45	0.17	0.62	0.45	0.28
3	8.44	0.00	0.04	9.04	0.03	0.31
4	8.17	0.00	0.01	8.45	0.05	0.39
5	2.00	0.04	0.08	2.03	0.01	0.01
6	9.78	0.00	0.01	10.21	0.03	0.31
7	17.41	0.00	0.01	18.26	0.06	1.02
8	5.08	0.04	0.18	5.94	0.13	0.80
9	4.30	0.01	0.06	4.28	0.04	0.18
10	9.03	0.00	0.04	9.08	0.06	0.53
11	7.29	0.01	0.04	7.97	0.08	0.60
12	8.14	0.01	0.05	8.78	0.08	0.69
13	3.73	0.02	0.09	4.08	0.13	0.53
Average	85.06	0.01	0.94	90.77	0.07	5.97



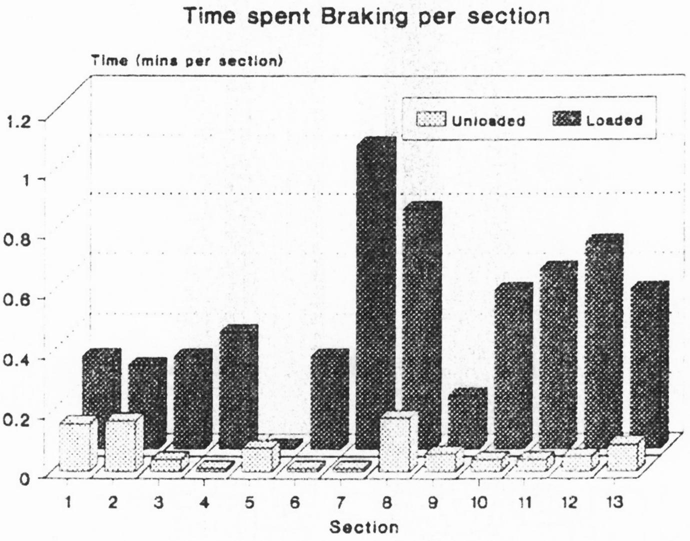


Figure 7.4 Time spent Braking (Unloaded and Loaded)

Summary of the Section Evaluation

Analysis of the performance on 13 individual road sections, after minimizing the driver effect by averaging the data, indicated a consistent speed on rural sections despite gradient and alignment restriction.

Fuel consumption on these same rural sections appears more sensitive to grade confirming the indications of different operating costs for different sections presented in the earlier trials. Urban operations were shown to require significantly more fuel as well as the obvious decrease in achieved speed and increased brake usage. A ratio of loaded to unloaded fuel consumption of about 1.6 was observed for the study. Differences between sections were from a low of 0.9 to a high of 2.5.

Differences between Drivers

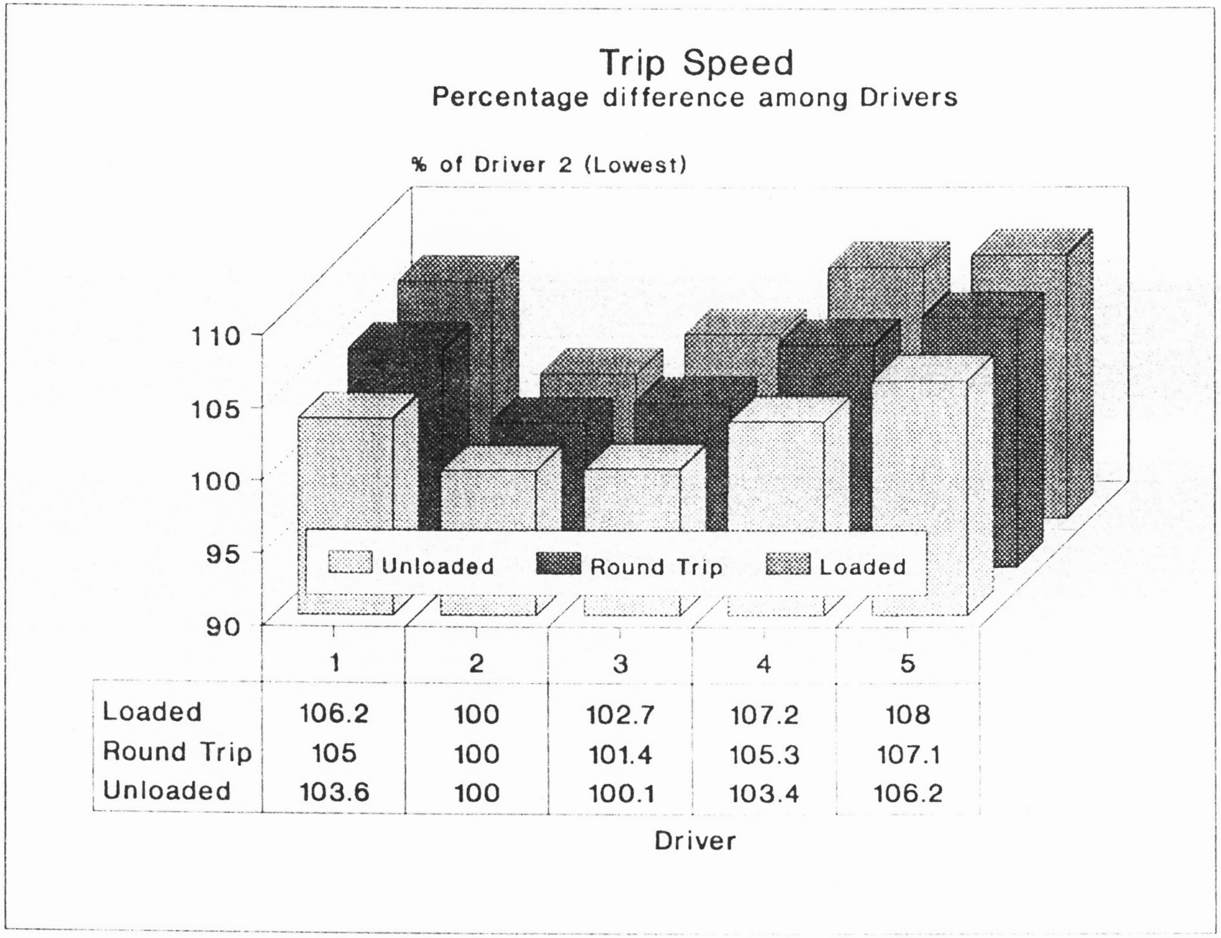
The primary purpose for this trial was a comparison of the performance of the five drivers. With the exception of driver 1, all made three trips in one day. Data were analyzed by averaging speed and fuel usage over the three trips.

Differences between Drivers in Speed

Average speeds for the five drivers are presented in Table 7.5. The relative differences between these drivers is more clearly evident in Figure 7.5 where they are expressed as percentage differences using the slowest driver as 100%. The difference in round trip speed between the fastest and slowest driver was about 7%. There appeared little difference between the slowest two drivers (2 and 3). In all cases the differences in loaded speed were greater than the differences in unloaded speed. This indicates that the

Table 7.5 Speeds for each Driver Averaged over Three Trips

Driver	Unloaded	Loaded	Round Trip
1	53.3	50.7	52.0
2	51.5	47.8	49.5
3	51.5	49.1	50.2
4	53.2	51.2	52.1
5	54.7	51.6	53.1



	1	2	3	4	5
Loaded	106.2	100	102.7	107.2	108
Round Trip	105	100	101.4	105.3	107.1
Unloaded	103.6	100	100.1	103.4	106.2

Figure 7.5 Percentage Difference between Drivers in Trip Speed

drivers were prepared to drive at a common speed while unloaded, but some of the drivers (2 and 3) were more cautious while loaded.

The statistical significance of these differences was tested using Friedmans analysis of variance by ranks. The comparison procedure is based on ranks and compares the ranked mean speeds of each of the five drivers in each of the 13 sections comprising the whole trip. Three sets of test results for the unloaded, loaded and round trip speeds, produced using the MINITAB statistical package, are presented in Table 7.6. Note that results are presented slowest driver first, fastest driver last. This test indicates that there is a highly significant difference between at least some of the drivers for all three speed categories.

Accepting the significance of this test allows testing for difference between individual drivers. The Wilcoxon Paired Rank Sum test (Minitab package) was used to test pairs among drivers until a significant difference was established at a 90% confidence level .

These results are presented in Table 7.6 as underbars to the table of means. Pairs of means connected by a continuous underbar are not significantly different at the 90% confidence level. In the case of unloaded speeds, the slower pair (2 and 3) were significantly different from the fastest pair (1 and 5). In both the loaded and round trip cases drivers 1 and 4 were not significantly different, but the other three (2,3,5) were different from this pair and each other. Overall, the drivers displayed considerable consistency with driver 2 the slowest both loaded and unloaded and driver 5 the fastest. With the exception of unloaded speed for drivers 1 and 4 (where the difference was not statistically significant) each of the other drivers maintained their ranks.

Table 7.6 Friedman Test for Differences in Speed (*m.p.h.*) between Drivers for Three Trips over 13 Road Sections

	Driver [1]				
	2	3	4	1	5
Unloaded Speed	49.90	50.36	51.22	51.65	52.64 [2]
	———	———			
		———	———		
			———	———	
				———	———
	Friedman's S = 20.18 d.f = 4 p < 0.001				

	Driver				
	2	3	1	4	5
Loaded Speed	47.85	49.13	49.81	50.40	51.52
			———	———	
	Friedman's S = 29.60 d.f = 4 p < 0.001				

	Driver				
	2	3	1	4	5
Average Speed	49.27	50.32	51.32	51.36	52.66
			———	———	
	Friedman's S = 34.58 d.f = 4 p < 0.001				

[1] Drivers arranged in ascending order of Trip Speed

[2] Underbars indicate pairs not significantly different at 90% confidence level by Wilcoxon Paired Sample Rank Sum test.

Differences between Drivers in Fuel Consumption

Mean fuel consumption levels for each driver's three trips are presented in Table 7.7. Values are presented in Figure 7.6 as percentage differences, slowest driver at 100%. The higher consumption levels recorded for drivers 4 and 5 is evident. Also noticeable is the low fuel usage recorded by driver 1 who was one of the higher speed group in the previous results. The Friedman test was used to test for the significance of any difference between drivers and again the result was highly significant (Table 7.8). Results for a comparison between pairs of drivers using the Wilcoxon procedure is reported as underbars in Table 7.8.

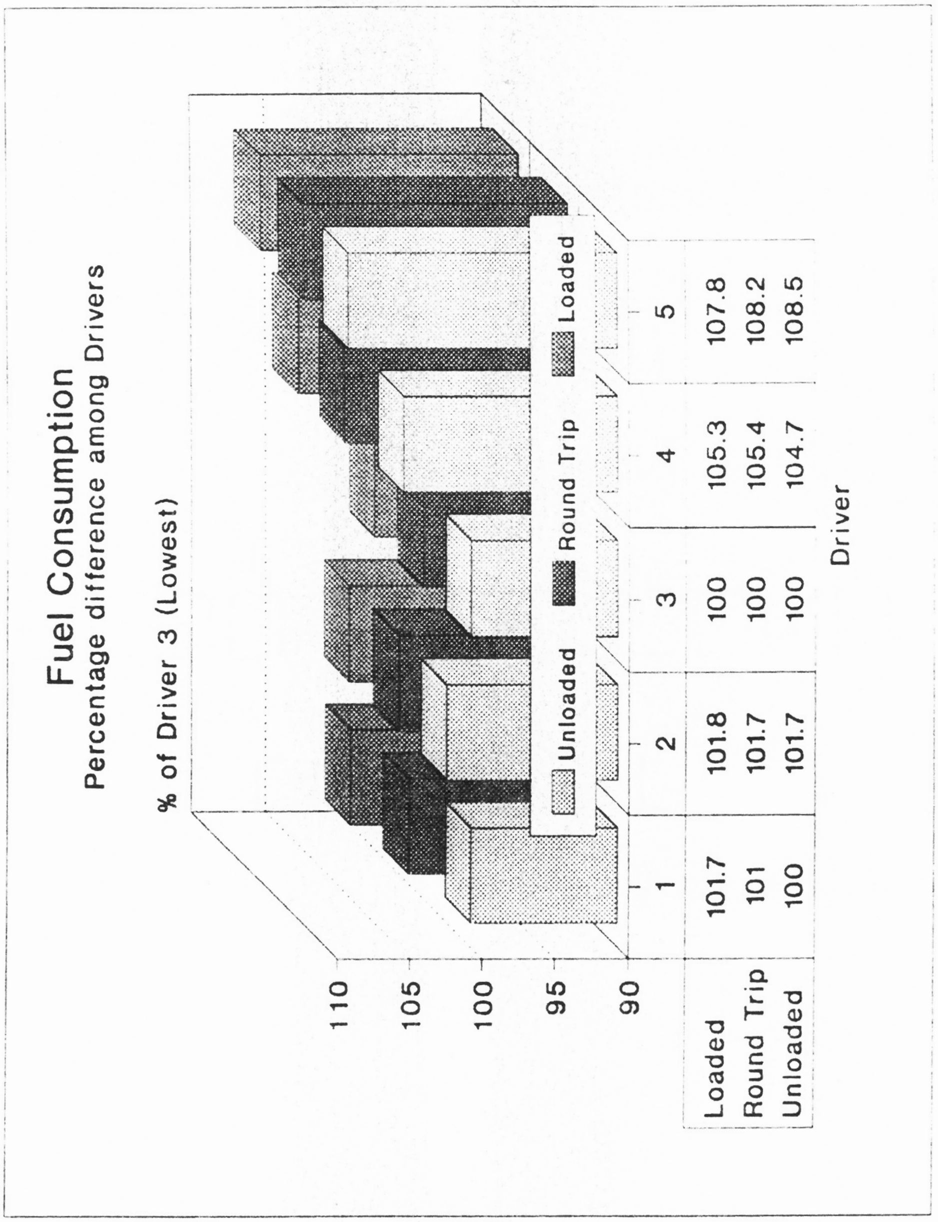
In this case Drivers 1, 2 and 3 appear to form a group with low fuel usage with drivers 4 and 5 producing significantly higher consumption (at the 90% confidence level). Driver rankings were again consistent with the exception of a reversal between driver 1 and 3 in the unloaded direction.

Relationship between Fuel Consumption and Speed

Table 7.9 presents the collated speed and fuel consumption data for each driver. The fuel - speed data are plotted in Figure 7.7. Two significant observations can be made from these data. Firstly, the expected trend of fuel consumption increasing with truck speed is evident. Second, some important divergence is noted. Driver 1 was among the faster group of drivers, but associated with the lower fuel usage group. Driver 3 was consistently faster than Driver 2 (the slowest driver) but returned fuel results which were not significantly different from the slower man. These differences may indicate aspects of fuel efficient driving style.

Table 7.7 Mean Fuel Consumption over Three Trips for each Driver

Driver	Unloaded	Loaded	Round Trip
1	13.0	20.8	16.9
2	13.3	20.8	17.0
3	13.0	20.5	16.7
4	13.6	21.6	17.6
5	14.1	22.1	18.1
Average	13.4	21.3	17.3



	1	2	3	4	5
Loaded	101.7	101.8	100	105.3	107.8
Round Trip	101	101.7	100	105.4	108.2
Unloaded	100	101.7	100	104.7	108.5

Figure 7.6 Percentage Difference in Fuel Consumption between Drivers

Table 7.8 Friedman Test for Differences in Fuel Consumption (G/100 mile) between Drivers for Three Trips over 13 Road Sections

	Driver[1]				
	1	2	3	4	5
Unloaded Trips	12.61	12.94	12.79	13.24	13.89[2]

Friedman's S = 20.49 d.f = 4 $p < 0.001$

	Driver				
	3	2	1	4	5
Loaded Trips	20.71	21.1	21.22	21.57	22.12

Friedman's S = 24.68 d.f = 4 $p < 0.001$

	Driver				
	3	2	1	4	5
Round Trips	16.59	16.83	16.92	17.5	18.15

Friedman's S = 34.58 d.f = 4 $p < 0.001$

[1] Drivers arranged in ascending order of Fuel Consumption

[2] Underbars indicate pairs not significantly different at 90% confidence level by Wilcoxon Paired Sample Rank Sum test.

Table 7.9 Speed and Fuel Consumption for Individual Drivers

Unloaded

Driver[1]	Speed	Fuel	Fuel Rank
2	49.9	12.9	3
3	50.4	12.8	2
1	51.6	12.6	1
4	51.7	13.2	4
5	52.6	13.9	5
Correlation r = 0.76			

[1] Arranged in order of increasing Speed

Loaded

Driver	Speed	Fuel	Fuel Rank
2	47.9	20.7	1
3	49.1	21.1	2
1	49.8	21.2	3
4	50.4	21.6	4
5	51.2	22.1	5
Correlation r = 0.81			

Round Trip

Driver	Speed	Fuel	Fuel Rank
2	49.3	16.8	2
3	50.3	16.6	1
1	51.3	16.9	3
4	51.4	17.5	4
5	52.6	18.1	5
Correlation r = 0.83			

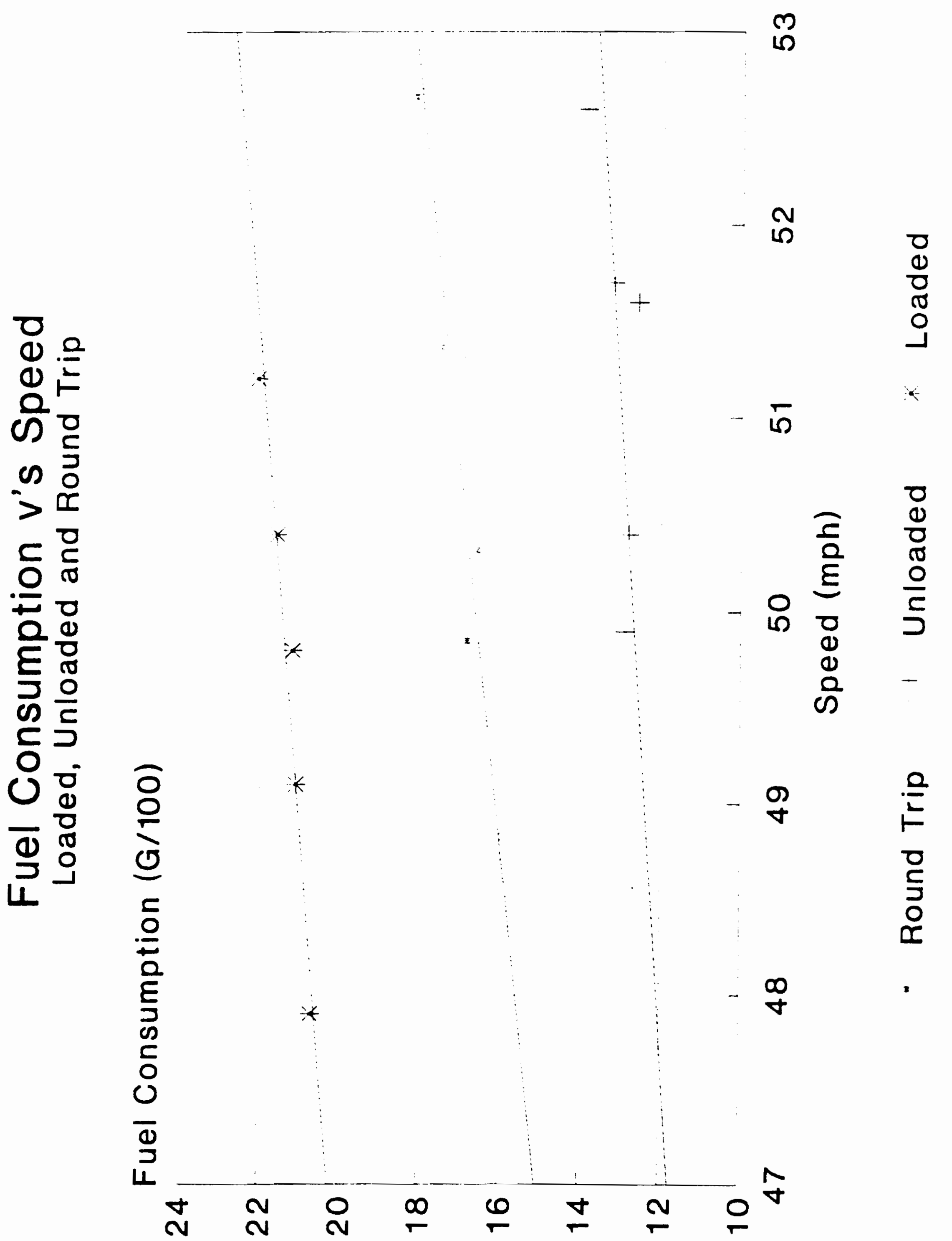


Figure 7.7 Fuel - Speed Relationships for Unloaded, Loaded and Round Trips

High correlation of increased fuel consumption with increasing speed (Table 7.9) was expected because only one route was used. The effects of gradient and road alignment differences which show up between routes are therefore eliminated. The level of association in the inter driver comparison was much higher than that obtained in the trial comparing routes (Table 6.2 and subsequent discussion).

Summary

Data from a detailed study of operations on one route by five drivers was analyzed to investigate the influence of driving style on performance. These data were also used to further examine the differences in truck performance on road sections with different characteristics.

A considerable difference in speed and fuel consumption was recorded between urban / urban fringe and rural road sections. A difference of lesser magnitude was seen between different rural sections. This latter difference may still be of considerable importance because of the greater distances of rural hauling encountered on most logging routes. Similar or greater differences were also evident in fuel consumption and the extent of braking required, both of which contribute directly to truck operating cost.

A surprisingly high speed was maintained on the rural two lane roads. This was attributed to the relatively powerful truck and driver familiarity with the route.

Differences between drivers (averaged over three trips) were consistent and statistically significant. Speed was strongly related to fuel consumption. The fastest driver was 7% faster than the slowest. He also used about 8% more fuel. Perhaps more important was the identification of at least one driver whose driving style appeared to yield above average speed with low fuel consumption.

Each of the issues evaluated in this trial , differences in speed, fuel usage and braking between road sections and differences between drivers in speed and fuel usage, lead to a better understanding and basis for management of trucking. Investigation of these issues was built on the evaluations of the earlier trials which studied truck utilization and work assignment, the effect of road surfaces and performance differences between routes. Taken together, the data from these four trials support the preliminary investigation of several fundamental aspects of truck performance. These include the effect of increased speed on fuel consumption, the effect of increased weight on speed and fuel consumption and an evaluation of the effects of increased speed on engine operations.

CHAPTER 8 ANALYSIS

Consideration of the effects of speed, load, road and driver are fundamental to understanding trucking performance. Trials undertaken in this project contribute information to an understanding of these factors, as they effect the southern US forest products industry. Time and resources limited the scope of the investigation to an exploratory *first look* in most areas, however some of the data collected supports additional analysis of:

1) the effects of speed on fuel consumption,

2) the effects of load on speed and fuel consumption, and

3) the effects of speed on engine operation.

Evaluation of the Increase in Fuel Consumption with Speed

The power (and therefore fuel) required to overcome air resistance rises with increasing truck speed. Important factors which determine the power required to move air out of the path of the truck are the total frontal area of the truck and load, it's smoothness (or roughness) and shape (eg. load taper). These latter factors are measured as the coefficient of drag (C_D). Unfortunately, this power requirement increases as the cube of speed. It is typically insignificant below 30 mph but about 60 mph air resistance often becomes the largest factor resisting the forward motion of the truck. Smith (1973) suggests an air resistance power requirement computation of the form :

$$Power\ required = (0.001\ C_D * Frontal\ Area)*Speed^3 / 375 \qquad (1)$$

Average Speed - Fuel Consumption Relationship

Section 7 of the route followed in Study 4, where speeds were regularly in excess of 60 miles per hour, was used to test the hypothesis that air resistance was a major contributor to the fuel consumption of this truck. This section of 16 miles was the longest rural section of the route (Table 7.1) and had the second highest average loaded speed at 54.5 mph (Table 7.2). It contained no traffic lights or stop signs. Table 8.1 presents the total fuel usage and average speeds for the 15 loaded trips over this section.

Linear regression was used to evaluate the relative contribution of speed and non speed related resistances to fuel consumption. At the high speeds encountered during the study, air resistance is assumed to be the major component of the speed related resistance. An equation form of Total Fuel = a + b*(Average Section Speed)^3 following that used by Smith (Eqn 1) above, was estimated (Table 8.2). Although the data were drawn from a narrow range of speeds, the regression was highly significant. The estimated value for the slope term provides an indication of the quantity of fuel required to overcome air resistance and the rate at which it increases with speed. The speed-independent level of fuel consumption is estimated by the intercept term.

This evaluation was based on average speeds. However one of the most important differences in driving style was that of the pattern of speed variation within each section. Some drivers followed a more constant speed while the driving of the fastest driver exhibited numerous high speed peaks. Since the fuel usage increase for higher speed is non linear (increasing at an increasing rate), a fuel consumption analysis which accounted for the effects of speed differences within the section was warranted.

Table 8.1 Average Section Speeds and Fuel Consumption for Section 7

Trip	Fuel	Speed
1	2.93	53.1
2	3.40	56.0
3	3.67	56.8
4	3.15	46.3
5	3.33	52.8
6	3.40	51.2
7	3.43	53.8
8	3.25	50.6
9	3.39	52.6
10	3.60	55.3
11	3.49	56.3
12	3.57	55.2
13	3.65	53.6
14	3.80	55.0
15	3.56	52.6

Table 8.2 Regression Results between Total Fuel Consumption and Speed

*(1) TOTAL FUEL = 2.54 + 0.0000058 SPEED **3* *R-sq = 0.33*

Predictor	Coefficient	t-ratio	Probability
Const	2.54	7.08	< 0.001
SPEED	0.0000058	2.53	0.025

Analysis of Variance

SOURCE	DF	MS	F	Probability
Regression	1	0.23	6.41	0.025
Error	13	0.036		
Total	14			

Direct Estimation of Fuel Used to Overcome Air Resistance using Speed Profiles

Data drawn at two second intervals from the speed profiles for each of the 15 loaded trips were used to estimate the fuel needed to overcome air resistance. An estimate of the power needed for each interval was made using Equation 1. A coefficient of drag (C_D) of 1.0 arising from wind tunnel tests for different log truck configurations (Garner, 1978) was used in the computation. This C_D of 1.0 fits well with Garner's 1978 parallel loaded butt first test case. A frontal area of 100 square feet was used. Both values are reasonable approximations. Cross sectional area would vary with load height and the C_D would vary with load taper and surface roughness.

Equation 1 estimated the power required at the wheels. A considerable amount of energy is lost in friction in bearings and gears between the engine flywheel and the tire/road interface. McNally (1975) suggests transmission losses of between 11 and 15% with the lower figure applying to direct drive top gear. The particular transmission employed in this test had an overdrive top gear and therefore the higher loss level of 15% was assumed. Thus gross power requirements were:

$$\text{Gross HP needed} = \text{Power needed at the wheel} / 0.85 \qquad (2)$$

Engine fuel efficiency varies with RPM, and is usually maximum (lowest fuel consumption per unit of power produced) at mid range. Fuel efficiency declines at higher RPM. Manufacturers typically publish engine charts describing power, torque and fuel efficiencies derived from testing under standard conditions. The full throttle brake specific fuel curve (BSFC) derived under SAE J816B conditions for the truck engine model used in the test truck is presented in Figure 8.1 Fuel efficiency levels from this curve, and a fuel weight of 7.065 lbs / Gal were used to estimate fuel usage from power requirements. The fuel efficiency of these engines also declines at part load but this relationship was not available for this engine and the full load conversion factor was assumed.

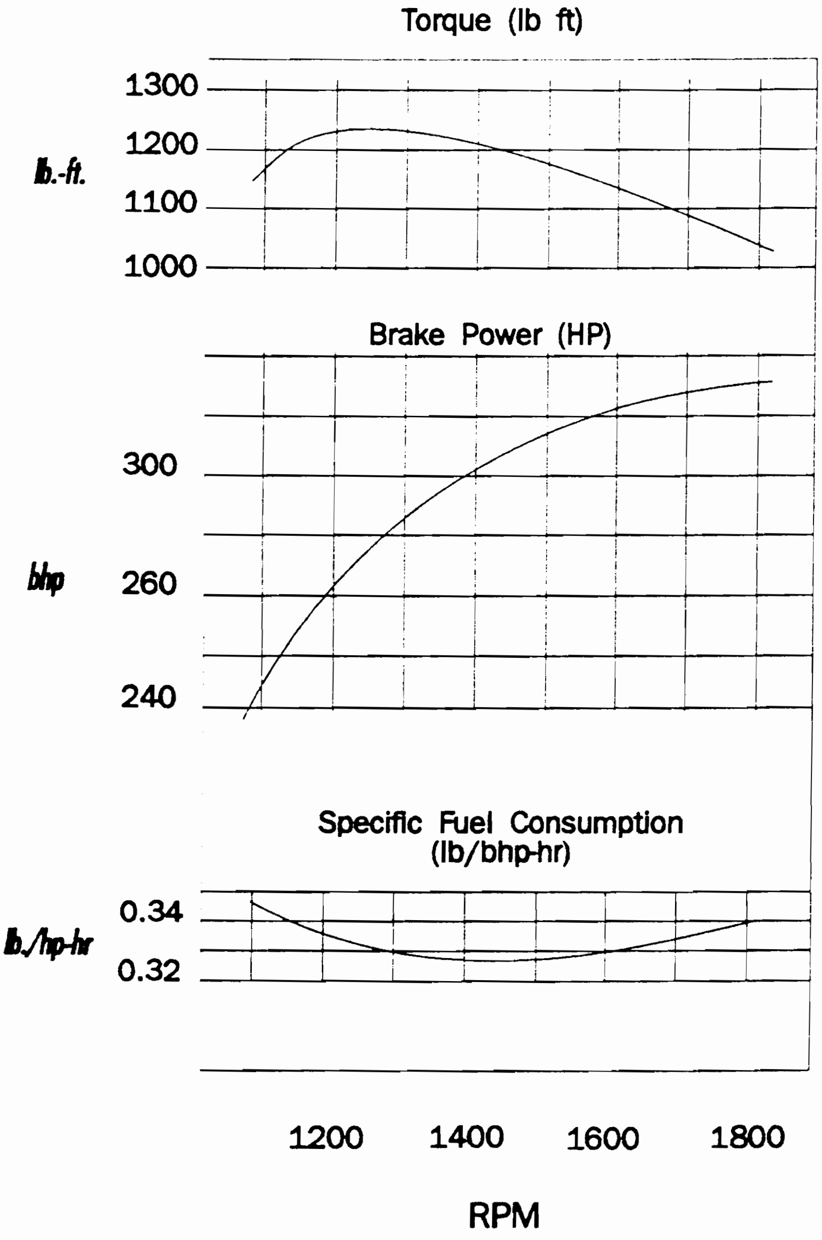


Figure 8.1 Full Throttle Fuel Flow

A computer program was written to estimate the fuel requirement for each speed profile. Some additional logical rules were required to interpret the specific engine power requirement to overcome air resistance. On sufficiently steep downhill sections, power input from the engine to overcome air and road rolling resistance is not required. These portions of the trip are marked by idle fuel flow only. It was assumed that no fuel was used to overcome air resistance on these sections. Other portions of the trip involved some grade assistance but not enough to fully overcome the combination of air and rolling resistance. Some power input from the engine was necessary. In these cases it was assumed that the marginal power input (and thus observed fuel usage) was used to overcome air resistance. Estimated fuel requirement was the cumulative total of the lower of the observed flow or estimated requirement for each two second interval.

The total quantities of fuel required to overcome air resistance, estimated by the computer program, were subtracted from total fuel used for each of the 15 trips (Table 8.3). Overcoming road surface rolling resistance, adverse gradient and driving engine accessories were assumed to have used the remaining fuel. Consumption attributed to these causes would be expected to be constant among drivers. Traffic influences and differences in load weight and shape could have caused the remaining variation.

Regression analysis was used to test for any remaining relationship between the residual non-speed-related fuel usage and average section speed. The overall regression was not significant (Table 8.4) indicating that the use of the theoretical air resistance equation and the two second speed profile had effectively removed all speed related effects from this data set. A fuel quantity of about 2 gallons was indicated as required to overcome the non-speed-related resistances encountered in traversing the section (eg. gradient, road surface resistance and engine accessories).

Table 8.3 Fuel used to Overcome Air Resistance

Trip	Total Fuel	Air Estimate	Remainder	Speed
1	2.93	1.35	1.58	53.1
2	3.40	1.71	1.68	56.0
3	3.67	1.80	2.13	56.8
4	3.15	.99	1.94	46.3
5	3.33	1.36	2.04	52.8
6	3.40	1.36	1.98	51.2
7	3.43	1.46	1.92	53.8
8	3.25	1.34	1.88	50.6
9	3.39	1.50	1.97	52.6
10	3.60	1.63	1.82	55.3
11	3.49	1.67	1.87	56.3
12	3.57	1.69	1.90	55.2
13	3.65	1.74	2.17	53.6
14	3.80	1.63	1.88	55.0
15	3.56	1.67	1.86	52.6

Table 8.4 Regression Results for Residual Fuel Consumption and Speed

(2) RESIDUAL FUEL = 2.07 - 0.003 SPEED *R-sqr = 0.003*

Predictor	**Coefficient**	**t-ratio**	**Probability**
Const	2.07	2.51	0.026
SPEED	0.00046	-0.20	0.847

Analysis of Variance

SOURCE	**DF**	**MS**	**F**	**Probability**
Regression	1	0.00095	0.04	0.847
Error	13	0.015		
Total	14			

Consequences for Operations

Figure 8.2 presents the fuel consumption, derived non-speed related fuel usage and the estimated regression lines for this analysis. The fuel penalty associated with higher road speed is evident in the Regression 1 plot. Residual variation between trips is attributed to differences in traffic and environmental conditions (temperature, wind) as well as to non speed related aspects of driving style.

The data indicate that the total fuel required to traverse the section loaded at an average speed of 60 mph would be about 3.8 gallons (23.7 g/100). As a comparison, the equation predicts that at an average speed of 45 mph the requirement would be about 3 gallons (18.75 g/100), about a 20% improvement in fuel consumption. It is also noted that at 60 mph, fuel used in overcoming air resistance is about 1/2 of the total requirement for the flat to rolling section. Log transport operations in the southern forest products industry now routinely include periods of high speed running and these incur a direct cost in increased fuel consumption.

Engine Operations - Comparison of Two Trips

Differences in speed and fuel consumption noted between drivers is directly related to differences in engine operating regime (RPM and power levels). Truck operators should be concerned with the operating regime to which their truck engines are subjected because higher wear and premature failure are associated with excessively high RPM and power levels.

The two trips used in Chapter 7 selected to display driver behavior and consistency were selected again for a detailed comparison of engine operations (Figure 7.2, Trip A and Trip B). Trip A was relatively slow with low fuel consumption and Trip B faster with high fuel consumption. Summary data for the two trips is presented in Table 8.5.

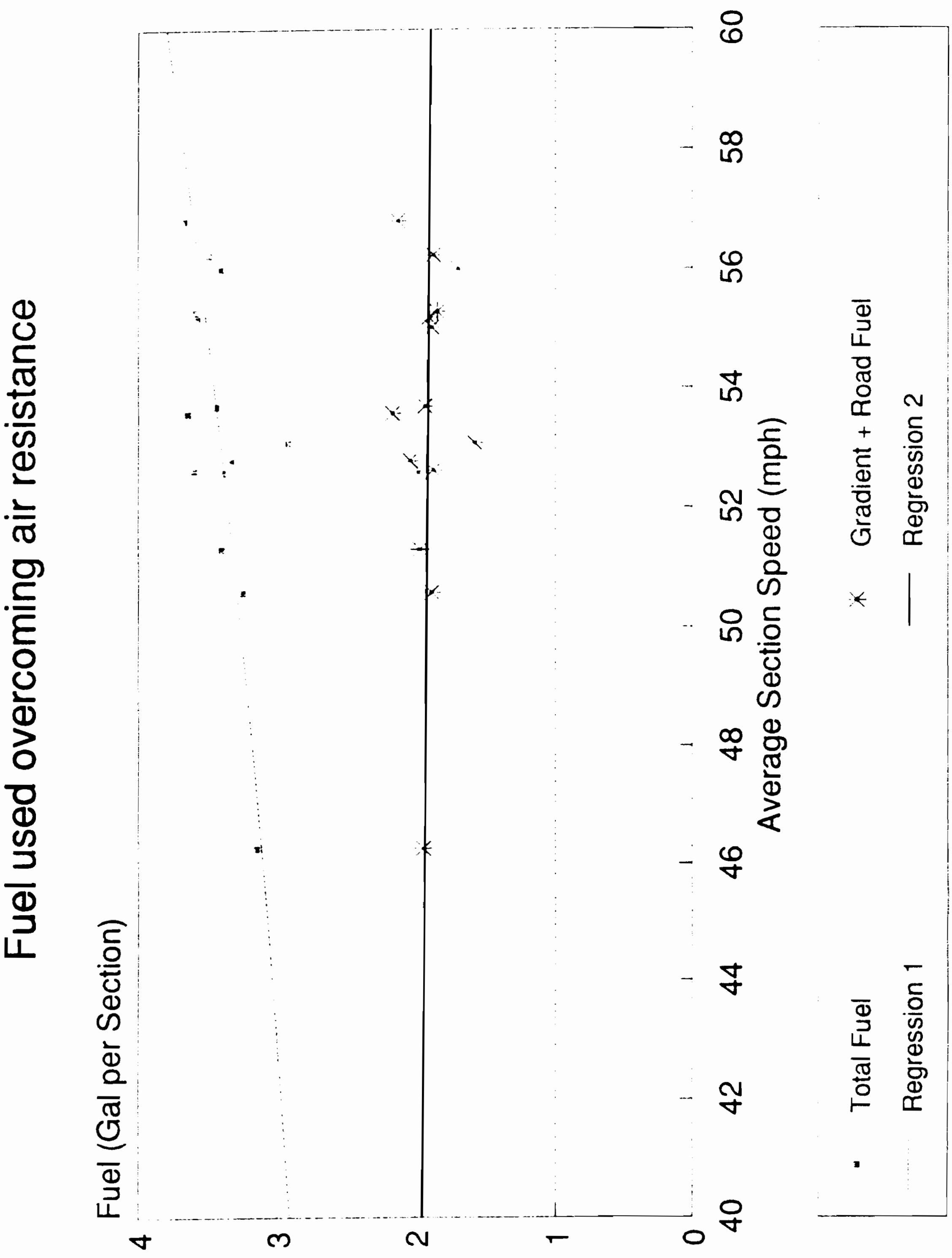


Figure 8.2 Regression Results for Total and Residual Fuel Consumption versus Speed.

Table 8.5 Summary Data for the Two Selected Trips.

	Trip A Driver 3 Trip 3	Trip B Driver 5 Trip 2
Trip Time(mins)	96.5	91.6
Speed (mph)	46.3	48.7
Fuel Used (Gal)	15.3	16.7
Fuel Consumption(G/100)	20.68	22.64
Average RPM	1680	1795
Average Brake	7.5%	6.7%
Load (,000lb)	80.00	80.60

Average engine RPM was almost directly related to road speed on this route because most of the trip was spent in top gear. The higher average speed for trip B was therefore associated with higher RPM (Table 8.5). A higher average power levels was required to produce the higher speed in Trip B, evidenced by a higher overall fuel consumption.

The engine operating domain (power level versus engine RPM) for these two trips is presented in Figure 8.3 as a direct plot of fuel flow v's engine speed. Fuel flow provides a good approximation to power produced by the engine. Each engine has it's own characteristic efficiency relationship between power output and fuel consumption across the range of loads and speeds and is usually described by manufacturer's in an engine map. Figure 8.4 presented a representative engine map for a similar turbo charged intercooled engine (350 HP). The decreasing efficiency of the engine (increasing fuel consumption per unit of power produced) with increased engine RPM past mid range is evident. High RPM operations are less fuel efficient.

The heavy outline of points comprising the upper boundary of the scatter of points in the two plots in Figure 8.3 trace the full throttle response curve for this engine. The injector pump / governor combination maintains efficient fuel / air ratios by restricting full throttle fuel flow at lower RPM. The governor also serves to restrict maximum engine RPM. At RPM higher than the preset limit, fuel flow is sharply restricted, falling to a zero at about 200 RPM above governed limit. The steadily rising fuel flow up to 1800 RPM and the rapid falloff after this point are readily seen in the Figure 8.3 Trip B data.

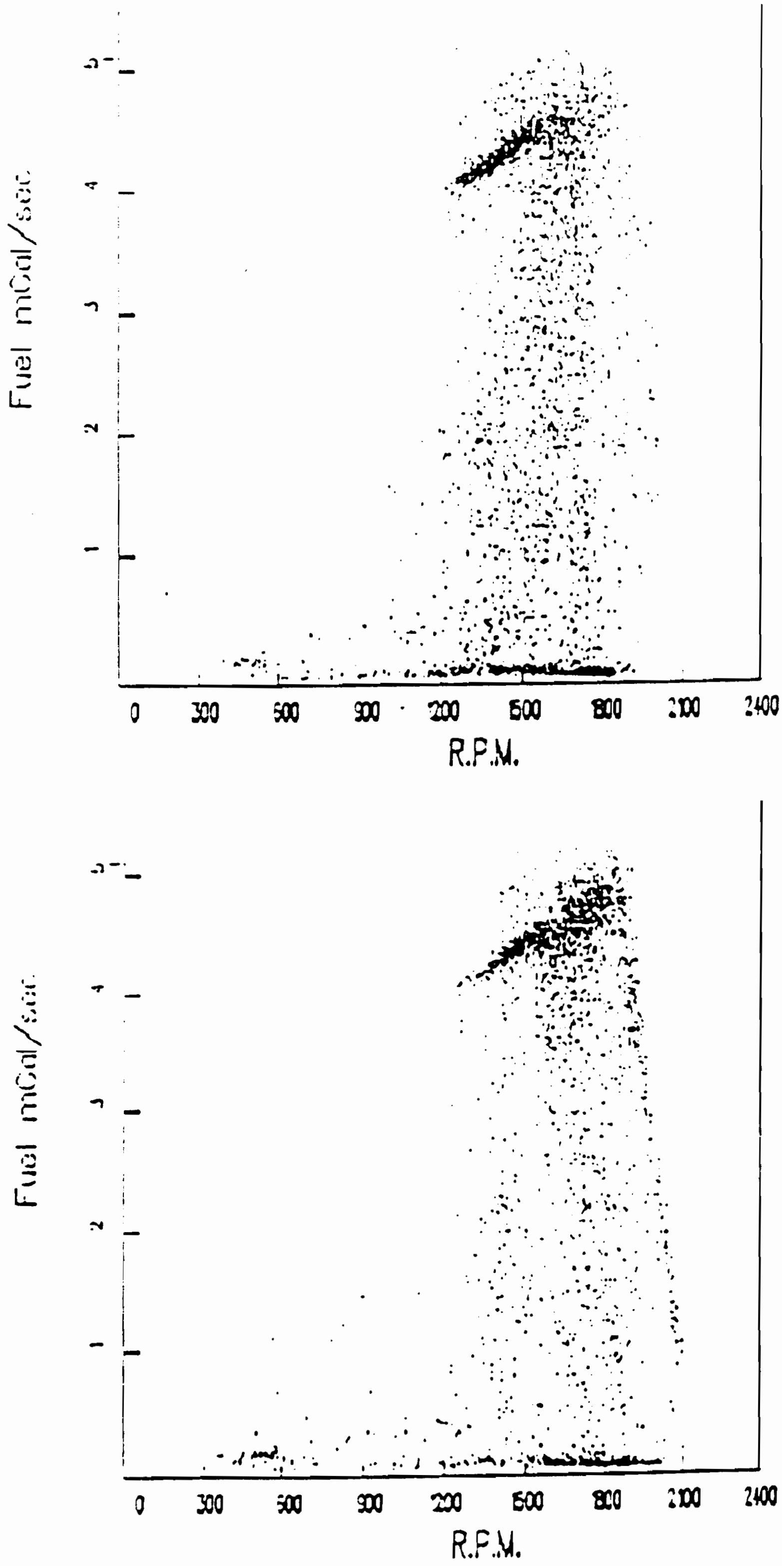


Figure 8.3 Fuel versus Engine RPM plots for Trips A and B.

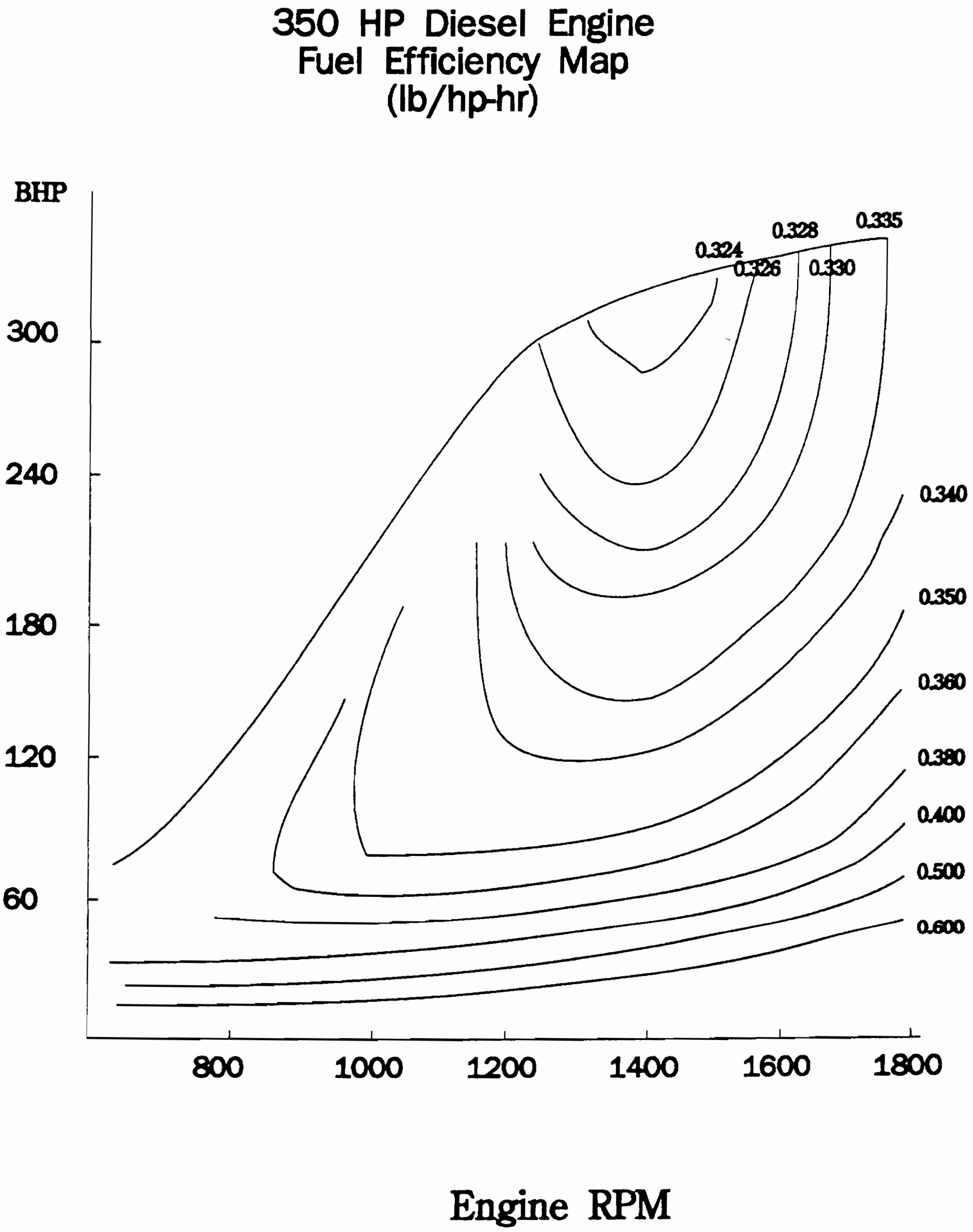


Figure 8.4 Engine Map for a Turbocharged, Intercooled 350 HP Diesel.

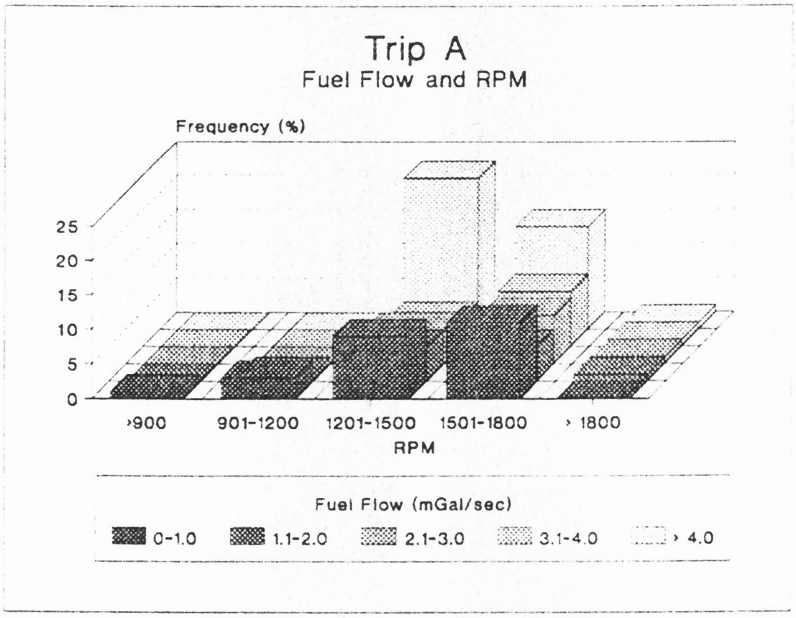
Another cluster of points is observed along the lower boundary (minimum fuel flow). These points arise from down hill or engine braking operation when the inertial mass of the truck is 'motoring' the engine. Differences in driving style can be judged from different densities of observations across the speed/power ranges. A fuel conscious driving style would be typified by more points in the interior of the plot where less than full power is being used, and fewer along the top, maximum power line. A heavy band of points along the upper and lower bounds indicates full on and full off throttle usage respectively.

The concentration of points in excess of 1800 RPM (road speed in excess of about 60 mph) for Trip B is readily evident. These data are summarized in Table 8.6 as frequencies with cells of 300 RPM and 1 milli gallon per second (mG/sec) fuel flow. Figure 8.5 is a graphical representation of this data.

Trip B involved about 15% of operating time over 1800 RPM while Trip A had only 3%. More than 50% of engine operating time during Trip B was spent at fuel flow levels over 4 mGal/sec (Full power) as compared to only 38% for Trip A. Trip A involved about 25% of time in no power *engine motoring* conditions. Trip B had only 18% of time at this level. Overall Trip B only saved 4.9 minutes in trip time, not enough to be useful, but required an additional 1.4 gallons of fuel and engine operation at high RPM and high power levels. Both these latter factors increase costs. Optimal trip speed for this route would appear to be closer to the slower speed of Trip A than the faster Trip B.

Effect of Payload Increase on Fuel Consumption

Data for a sequence of five loads where Gross Weights weights varied from 80,000 to 100,000 lbs was reported in Chapter 4. These data indicated that increasing load had little incremental effect on travel speed on the flat lower coastal plain haul route (Table 8.7). Fuel consumption rose from 23.1 g/100 to 25.8 g/100, up 12%,.



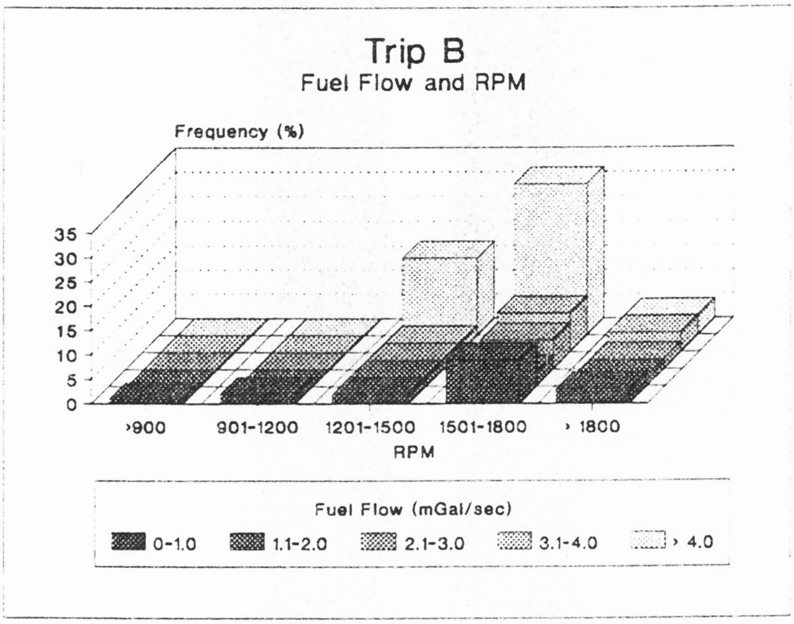


Figure 8.5 Frequency Observations for Fuel / Engine RPM Domain

Table 8.6 Proportions of Time at Engine RPM and Fuel Flow

Trip A

Fuel Consumption mG/sec	Engine RPM					
	>900	901-1200	1201-1500	1501-1800	>1800	
>4.01	0%	0%	22%	15%	1%	38%
3.01-4.0	0%	0%	4%	8%	1%	13%
2.01-3.0	0%	0%	5%	7%	1%	13%
1.01-2.0	0%	1%	5%	5%	1%	11%
0.0-1.0	1%	3%	9%	11%	0%	25%
Total	1%	4%	45%	48%	3%	100%

Trip B

Fuel Consumption mG/sec	Engine RPM					
	>900	901-1200	1201-1500	1501-1800	>1800	
>4.01	0%	0%	16%	31%	4%	50%
3.01-4.0	0%	0%	2%	8%	4%	13%
2.01-3.0	0%	0%	2%	6%	2%	10%
1.01-2.0	0%	0%	2%	3%	2%	8%
0.0-1.0	1%	2%	2%	9%	3%	18%
Total	1%	2%	24%	57%	15%	100%

Table 8.7 Comparison of different loads on one haul route for Contractor Operation

Trip	GVW (,000lb)	FuelSpeed (g/100)	(mph)
1	83.0	23.1	42.4
2	89.0	24.6	46.2
3	91.7	23.7	45.5
4	96.9	25.3	41.1
5	102.0	25.8	45.3

* Trips arranged in order of increasing load.

Analysis in the first section of this chapter indicated that, for a specific truck and haul route, at 60 mph about half the total fuel appeared to be used to overcome air resistance leaving half for the other factors (road surface resistance and gradient). A high number of stop signs and road crossings meant that the average speed of 45 mph was only attained by considerable periods of travel in excess of 60 mph between stops. Since the additional weight was attained by carrying longer, rather than more stems, air resistance could be expected to increase by only a small amount.

In the case of the selected load set (Table 8.6) GVW rose 22% from lightest to heaviest load (83,000 lb to 102,000 lb). Thus the fuel consumption attributable to load rose by 22%. If only half the fuel were used to overcome load related resistance, total consumption would rise 11%, very close to the observed 12%. While not a rigorous analysis, the calculation provides a cross check that the results recorded were reasonable.

It should also be noted that while these data indicate the considerable direct productivity benefits associated with hauling heavy loads, they do not capture any of the associated additional costs in wear and tear and risks associated with hauling these weights

Summary

Exploratory analysis based on data collected during the four trials was made for several fundamental truck performance relationships, effect of speed on fuel consumption, effect of speed on engine operation and effect of load on fuel consumption.

A comparison of two trips from the study data indicated that high travel speed involved a large increase in the proportion of high RPM / high power factor engine operation time. This could lead to increased engine wear.

Evaluation of the speed influence on fuel usage indicated that for the particular truck studied, the fuel consumption associated with overcoming air resistance was shown to be about 1/2 of total fuel consumption at road speeds of 55-60 mph. Higher speeds incur increasingly higher fuel consumption. Therefore where higher travel speeds do not result in higher truck utilization (eg. a fixed number of trips per day), there appear to be significant economic losses associated with travelling too fast.

In a comparison of hauls made on one route with varying load weight on flat terrain, both truck efficiency (t-m/h) and fuel efficiency (t-m/g) rose with increasing load. Additional costs associated with hauling heavier loads were not measured.

CHAPTER 9 DISCUSSION

Two major objectives were set for this project, (1) the development of a robust data logger capable of measuring the performance of forest harvesting equipment and (2) the use of the equipment to collect information on aspects of log truck operation.

Data Logger

A general purpose, harsh environment data logger was developed successfully and applied to the measurement of truck performance. The equipment was based on widely used industrial control technologies designed to operate in demanding environments. The system functioned as an IBM PC compatible computer under the widely used MSDOS operating system. A development environment using two similar systems was implemented, a laboratory / office master system with a hard disk, screen and keyboard and a smaller field version with floppy disk, ramdisk and a 12 volt power supply. Both systems used the same components which provided for redundancy and spare parts availability while working in the field. Control programs for this project were written in QuickBasic on an IBM PC and the Master system. Basing the data logger on IBMPC compatible components significantly reduced the specialist technical knowledge required for it's operation.

The two major transducers, the fuel monitors and the wheel encoder worked successfully in field applications after an initial problem with electrical spikes caused by transmissions from the truck's CB radio was identified. The encoder and associated voltage translation system was also sensitive to radio frequency interference, in part because of the longer data transmission lines needed to relay the signal to the computer. Improved protection and transmission circuitry would be required if CB radio use was necessary. The fuel transducers were both operated successfully, with the minor exception of an incident of sludge or dirt buildup in one sensor. This was quickly detected by comparison with other fuel records and corrected. Considerable care is required in the installation of fuel monitoring systems and it is recommended that a fuel filter be inserted directly ahead of the fuel sensor.

The data logger was used intensively for 6 weeks of data collection. Conditions encountered included extreme heat, high humidity and severe vibration. Only one failure occurred and that was traced to a loose connection to the power supply.

Data reduction, using the suite of graphical and numeric editing and display packages generated a considerable number of data files. Approximately 20 megabytes of initial data were expanded, processed and then summarized into a similarly sized set of trip section data. Processing was conducted on an IBM PS/2 Model 80 with an 110 Mbyte disk and high resolution screen. This large disk storage capacity was required to successfully store original, intermediate and final data sets.

Assessment Measures

Two major aspects of performance were monitored during this study - truck speed and fuel consumption. These were reported in miles per hour and gallons per 100 miles. Several additional ratios were developed to better describe overall truck performance. Both were based on ton - mile production using delivered payload and round trip distance. Overall truck productivity was described by the ratio ton - mile / hour, a measure reflecting both net payload and achieved speed. Road surface condition exerted a major influence through it's effect on truck speed. Figure 9.1 presents the ranges of truck productivity (in ton - mile / hour) from the road surface comparison trial (Study 2).

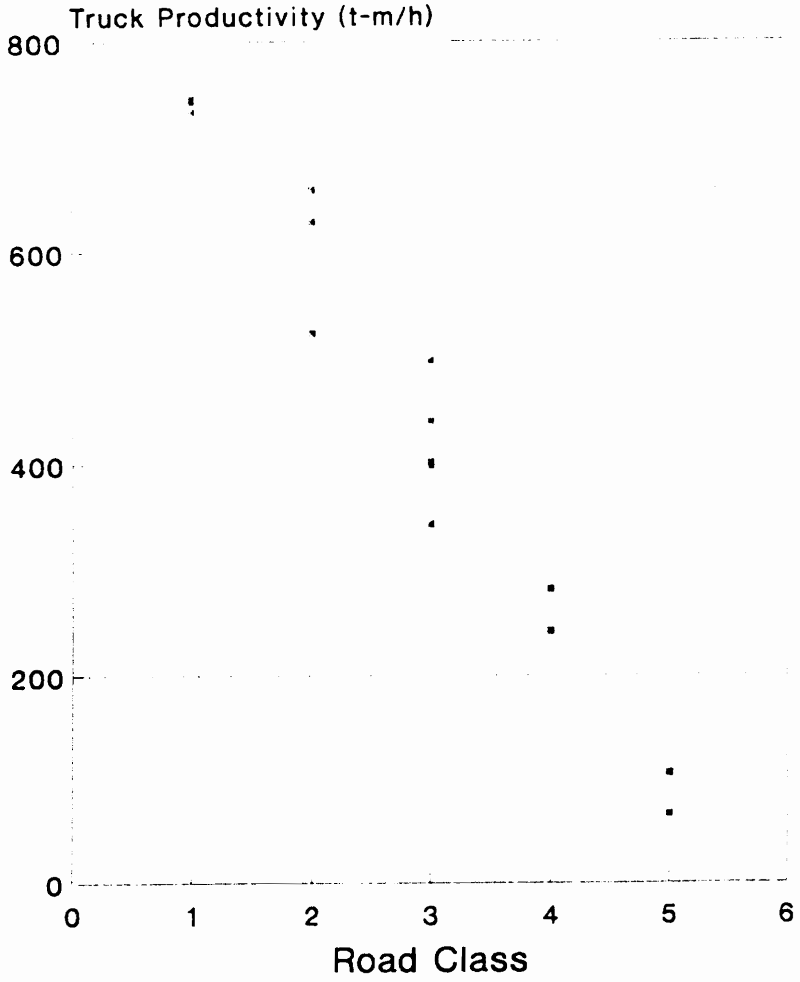


Figure 9.1 Truck Productivity Measured in t-m/h on Different Road Classes

Values ranged from about 750 t-m/h for highway operations (Class 1) to less than 100 for forest trails (Class 5). As a contrast, line haul transport operations commonly achieve values in excess of 1200 t-m/h where loaded backhaul is available. These data are almost in direct proportion to truck speed since nearly the same load was carried on each trip. This ratio provides an important efficiency indication where it is used to compare truck / trailer combinations with different tare weights.

Fuel productivity was described in units of ton - miles per gallon of fuel used. This measure is sensitive to delivered payload and fuel consumption. Figure 9.2 presents corresponding fuel productivity data for the road surfaces trial. Fuel productivities did not decline linearly with road class and speed as the overall truck productivity did. Interpretation of these results provides an additional demonstration of the usefulness of the ratios. Levels of about 70 t-m/g were achieved on both class of paved roads (Class 1 and 2). Line haul operators with loaded backhaul readily achieve levels of fuel productivity in excess of 100 t-m/g because their trucks are productive in both directions. Increased fuel efficiency was not observed on Class 1, most likely due to increased air resistance losses at higher speed offsetting the reduction on rolling losses when compared to Class 2. At the other end of the road surface spectrum, the formed sand road (Class 4) showed only a minor improvement over the sand trails (Class 5) (28 t-m/g compared to 22 t-m/g) despite a three fold increase in speed. In this case it appeared that road rolling resistance was probably near the same level on both classes.

The relative consumption levels between loaded and unloaded performance were also studied. These were described in the Loaded / Unloaded Fuel Consumption Ratio. Typical values for flat terrain ranged from 1.5 - 1.7. Adverse grade in the loaded direction increased the ratio to as much as 3.5. Excessive unloaded speed or favorable grade in the loaded direction reduced the ratio (approaching 1.0).

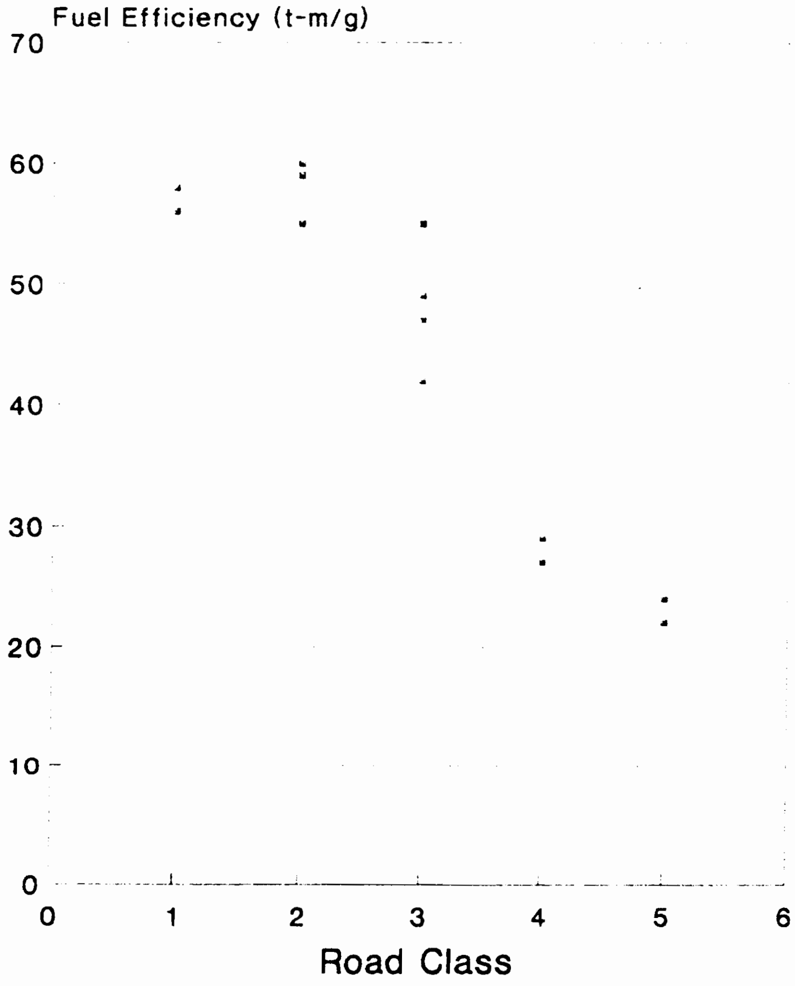


Figure 9.2 Fuel Efficiency Measured in t-m/g on Different Road Classes

Figure 9.3 presents the Loaded/Unloaded ratio data for the road surfaces comparison. A general increase in the ratio with declining road standard is noted. This is a response to the counterbalancing role of air and road rolling resistance with changing speed noted in the discussion of the t-m/g ratio. On the higher standard (higher speed) Class 1 roads, air resistance plays a significant part in fuel consumption. The difference in air resistance between the loaded and unloaded truck is relatively small (determined most importantly by frontal area). On the poorest (Class 4 and 5) roads, air resistance plays a small or negligible role. Fuel consumption is determined mostly by road surface rolling resistance. Since the magnitude of the resistance experienced by the truck is directly related to it's total weight, the Loaded / Unloaded ratio more nearly approximated the ratio of loaded to unloaded weight (80,000 lbs / 32,000 lbs). A considerable level of variation is evident in these data. Contributors to this variation could include net gradient differences between directions, changes in driving style for loaded and unloaded conditions, and changes in overall truck efficiency as a response to changed power to weight ratio.

Assessment of the Contractor Normal Operations Study

A week long study of one truck in a contractors fleet found that the truck was heavily utilized, and that a considerable time and cost overhead in dead running miles (12%) was incurred. This non-productive operation was a function the distance of the logging operations from the contractor's base and from each other. Fuel usage level during unloaded running was high. The ratio between loaded and unloaded fuel consumption was between 1.3 and 1.5, that is unloaded fuel usage levels used as much as 70 to 80% of the loaded level. A slightly higher fuel usage level was recorded for equipment relocation.

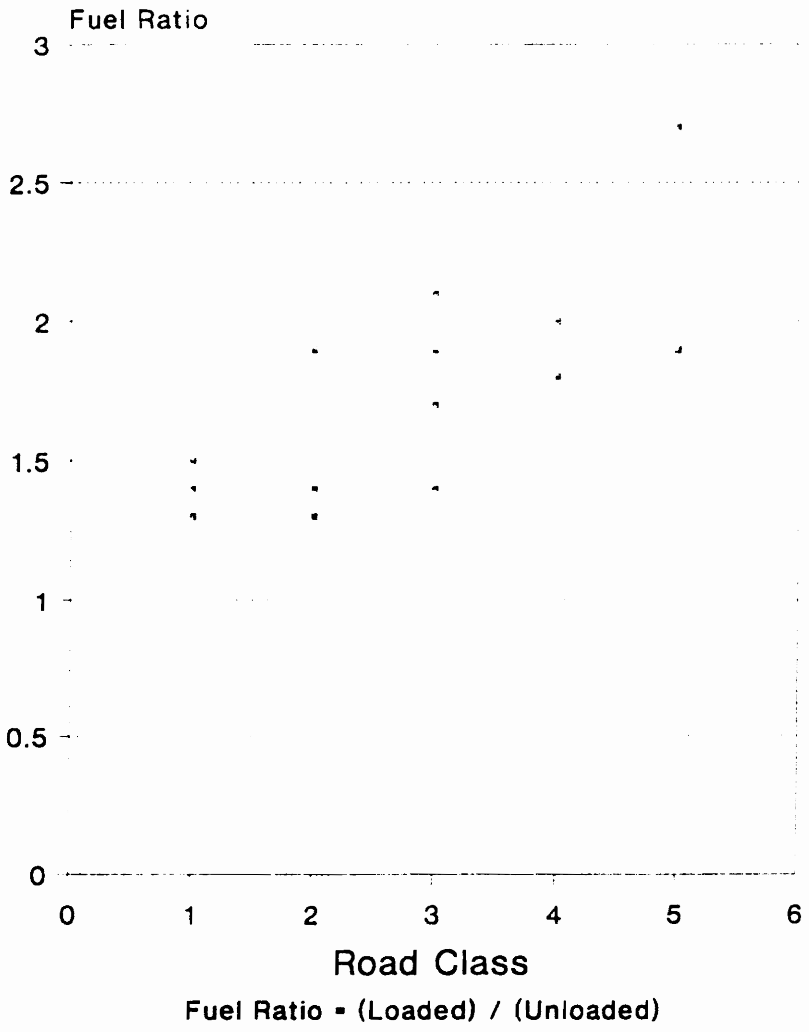


Figure 9.3 Loaded / Unloaded Fuel Ratio Results for Different Road Classes

Assessment of the Effect of Different Road Surfaces

A study in northern Florida identified five road classes ranging from unimproved sand to divided four lane highway and the effect of road surface on truck speed and fuel consumption was studied. Operations on sand tracks and sand roads consumed between twice and three times as much fuel as four lane highway operations. Comparisons throughout this section are with the levels recorded for four lane highway (Class1). Travel speeds were low, between 1/7 th and 1/3 of the highway speeds, but the total distances of these sections were relatively short.

Operations on longer sections of better formed and maintained gravel roads (Class 3) were a more important part of the haul. Speed on these sections appeared restricted by power requirements and road roughness to about 60% of four lane highway levels. Fuel requirements were 25% above highway levels. The larger component of these sections in the haul gives these results economic importance.

Softer road surfaces were seen to reduce road speed and increase fuel consumption, both factors which can contribute to higher trucking costs. Haul routes with a high component of these sections would have a high average cost. Driver skill was also noted as a very important factor in successful operations on these road surfaces.

Assessment of Differences Between Routes

A study of seven haul routes delivering to one point demonstrated considerable variation in performance even when the two important factors of driver variation and road surface variation were eliminated or minimized. Truck efficiency (t-m/h) varied about 17% between least productive (slowest) and most productive route. Fuel efficiency varied by about 15%. Possible explanations are relative differences in grades and traffic control (stop signs, traffic lights) between routes.

Truck operators and transport buyers currently believe that bad luck with an unduly expensive route will be offset with good luck and a relatively low cost route at some time in the future. Also the perceived differences between routes are small, or not measured. Therefore there is no apparent demand for change by truckers toward systems which more accurately reflect the costs of hauling on different routes. This study indicates that the differences might be larger than is appreciated. Unfortunately, there is not, at present, any simple, accurate way to obtain data on these differences at an operational level.

Future changes in the level and intensity of management, within the forest companies, and an increasingly sophisticated logging transport industry may offer opportunities for more accurate pricing of the transport task. Such an analysis could be based on setting per section prices based on five to 10 mile route sections and the types of classification used in this study. Thus, for example, where a haul involves a high proportion of interstate, job price would be relatively low, where it involves considerable distances of poor surface, the price would be high.

Assessment of the Influence of Driver on Truck Performance

In a detailed comparison of five drivers operating over one route it was determined that there was a significant and consistent difference between drivers in both travel speed and fuel consumption. While there was a high correlation between increased speed and increased fuel consumption, several drivers appeared to go against the trend. This indicates that, even for this relatively undemanding route, there were differences in driving style which achieved higher speed without corresponding increases in fuel consumption. Use of down grade to build momentum to *"roll over"* the upcoming adverse grade appeared to be an important component of this style associated with a somewhat lower cruising speed when grade was not assisting. Further explanation of these requires a more detailed evaluation.

Economic Aspects of Increased Truck Speed

The economic consequences of higher travel speed and thus higher truck productivity depend on the nature and extent of the haulage operation and the specification of the truck. Where trucks are operating on a short haul, this increase in productivity might allow an increase in the number of loads per day. This might allow a reduced fleet size, higher utilization, and reduced costs for the remaining trucks. In most log hauling operations this is not the case. On longer hauls, the time saved is not sufficient to allow another trip. The consequence of increased truck speed in these cases is increased costs of fuel and maintenance, without increased revenue.

Examination of the data used in Table 8.4 (Trip A from the slow driver and Trip B from the faster driver) indicated a 5 % reduction in driving time. This represents a saving of about 15 minutes, and is not sufficient to allow another load (3 1/2 hours). The analysis of these trips in Chapter 8 demonstrated excessive high RPM operation. In this case the faster trip could be judged as too fast, because it achieved no additional truck utilization (no extra wood was hauled) while incurring additional fuel and wear costs. The data points to an economically optimum speed for each truck, route and utilization situation.

Comparison of Studies

Each of the four studies focussed on a different aspect of truck operation, but all collected at least some round trip data. Table 9.1 presents a collated summary of average round trip results for all routes studied

Table 9.1 Average Trip Fuel and Speed Performance from All Studies

		Unloaded		Loaded					
Operation*	Trips	Fuel	Speed	Fuel	Speed	Load	Ratio	t-m/h	t-m/g
Study 1 Contractor Normal Operation									
Chip (UC)	2	17.2	41.6	22.4	39.0	85.2	1.3	530	66
Log 1 (LC)	2	15.3	49.7	23.9	46.3	86.0	1.5	604	73
Log 2 (UC)	3	16.9	52.4	22.4	48.0	79.8	1.3	632	64
Study 2 Road Surfaces									
Route 1 (LC)	1	19.2	36.0	28.9	33.6	79.0	1.5	403	50
Route 2 (LC)	1	18.6	44.9	28.6	40.8	78.7	1.5	487	51
Route 3 (LC)	2	17.4	53.8	26.1	48.9	79.2	1.5	589	55
Study 3 Comparison of Routes									
Lattimore (PD)	3	14.3	47.6	22.8	41.1	78.1	1.6**	515	68
Lilesville (UC)	1	13.7	47.3	21.9	45.5	46.4	1.6	551	68
Mt Croghan (UC)	4	12.9	46.7	22.7	43.7	45.2	1.8	564	72
Hickory Gr (PD)	4	14.0	44.9	22.0	39.2	42.1	1.6	524	74
Mooresville (PD)	2	13.8	55.1	19.5	53.4	54.2	1.4	664	75
Clinton (PD)	3	12.8	51.1	20.9	47.5	81.3	1.6	633	79
Study 4 Comparison of Drivers									
Newberry (PD)	3	13.1	51.0	21.2	48.9	79.5	1.6	630	75

* Identifiers in Brackets designate physiographic region, PD - Piedmont, UC - Upper Coastal Plain, LC - Lower Coastal Plain.

** Ratio is Loaded / Unloaded Fuel Consumption Ratio over the four field phases of the project. Direct comparison of these data to establish a merit order for these results is not realistic because they involved different locations, trucks, drivers and routes. The data do provide an indication of the comparative magnitude of the effects under study. Study locations contained representative routes from each of the three major physiographic regions (piedmont, upper and lower coastal plains).

Studies 1, 3 and 4 used similar road classes (mostly Class 2 paved two lane roads) and ton-mile / hour productivities were similar (550 - 650 t-m/h). However, fuel productivity appeared somewhat better for Studies 3 and 4 than Study 1, despite the rolling piedmont terrain. The lower Loaded/Unloaded fuel ratio for Study 1 points out the high underlying unloaded fuel consumption. Explanations could include the relatively high consumption associated with hauling the empty chip van, fundamental differences in engine efficiency and differences in driving style and route (particularly stop signs).

The impact of both the sand and gravel surfaces and the higher tare weight of Study 2 is evident in both lower truck and fuel productivity. This is despite the almost complete absence of road gradient in the lower coastal plain site.

Analysis of Speed Related Effects

Two speed related performance effects were evaluated in detail, the relationship between speed and fuel consumption and the influence of speed on engine operation.

The speed profiles for one section of the loaded data from Study 4 was analyzed in detail and an estimate made of the fuel required to overcome air resistance at two second intervals for all 15 profiles. These estimates indicated that at 60 mph about half of the fuel requirement for this section was attributable to air resistance. Slower speed trips had considerably lower fuel consumption.

An analysis of two selected trips from the Study 4 data set demonstrated that excessive high RPM engine operation was required to produce the faster trip speed.

CHAPTER 10 CONCLUSIONS

Two objectives were set for this research. The first was to develop a robust data logging system including both field and laboratory support hardware, and control and analysis software. The second was to apply the resulting system to the collection and analysis of indicative performance data for log truck operations in a series of controlled studies. Development and application of the data logging system proceeded without major difficulty.

1) Conclusion: *Data logging based on standard industrial control hardware (ie. STDBUS) and IBMPC compatible software provides a good basis for instrumentation in forest harvesting research.*

The first of the application studies focussed on documenting the work assignment of a truck in a contractor's fleet for one week. This study indicated a very high level of utilization but a significant overhead in dead running (12% above round trip distance) for operations located at a considerable distance from base. Fuel usage in unloaded running was high (70 to 80 % of loaded usage). THe use of restricted delivery hours to ration wood delivery generated additional transport cost.

*2) **Conclusion:** Excessive dead running increases trucking costs. Provision of secure overnight truck and/or trailer parking at mills could assist, particularly for mills with restricted woodyard hours.*

Levels of truck performance on different road surfaces ranging from unprepared sand trails and sand compartment access tracks to four lane divided highway were evaluated in a second study. Results established a significant gradient of both decreasing speed and increasing fuel performance for decline in road surface standard.

3) Conclusion: *Operations on poor road surfaces, particularly landing to roadside, have a major impact on truck performance. Improved knowledge of means to reduce this impact such as better temporary road preparation and layout or the further development of temporary surfaces such as mats could reduce transport cost.*

A third study evaluated performance variation due to other road related factors (grade and traffic control) by using one truck and driver to haul over seven similarly surfaced routes. A 17% difference in truck productivity and a 15% difference in fuel economy were recorded between the best and worst of these routes. Traffic control and road grade were established as important factors even in a region of moderate grades and urbanization.

3) Conclusion: *Variation in truck performance can be associated with characteristics of individual road sections (surface, grade, traffic control). Inter-sectional variations are sufficient to generate significant differences in average truck performance over whole haul routes. Rewards for managing road transport productivity, costs and prices on a more accurate sectional rather than whole trip basis might be considerable.*

A fourth study of truck performance with different drivers indicated a trend of increasing fuel consumption with increased speed. However one driver recorded a high speed with low fuel consumption. Study data suggests the existence of an economic optimum speed for a particular truck, route and work availability situation.

*4) **Conclusion:** Some driving styles are more effective than others (ie. high speed with low fuel consumption). Considerable gains in fleet performance might be achieved at low cost by identifying superior driving styles and persuading drivers to adopt them.*

Suggestions for further research

1 - Some aspects of driving style which minimize fuel consumption were evident from the trials. However the data, and common truckers' experience indicate there are times when a speed buildup is desirable (ie rolling a downgrade to make a better start on an upcoming adverse grade). Extension of a detailed driver comparison (such as Study 4) to evaluate the specific influence of grade and road alignment would yield useful insight into better driving styles, efficient road speeds and efficient forest road design. It may dispel some *myths* about how much speed helps or doesn't help in climbing grades. Such research would need to be supported by a comprehensive economic model of transport operations, from the operator's viewpoint to best evaluate the real impact of any proposed changes.

2 - A considerable body of detailed knowledge on the general effects of factors such as tire type, alignment and inflation, engine tune, temperature and load on truck performance and fuel consumption already exists. A controlled experiment using the data logger and the high resolution fuel flow meter would provide a useful demonstration to the southern forest products industry of practical methods to increase truck efficiency and minimize fuel cost.

3 - Air resistance was observed to be a major contributor to fuel consumption during these studies, due to the high proportion of higher speed running observed in southern forest products trucking. A wide variety of wind deflection devices have been developed which might reduce this cost. Field testing is required to determine their effectiveness in log and chip transport.

4 - It is clear from the data that truckers' per mile costs differ between haul routes. More accurate pricing resulting from management on a road section rather than whole trip basis could promote better decision making by transport sellers and buyers. Equitable pricing for individual hauls could permit specialization

in truck specification. It could also support new and as yet largely untested commercial arrangements such as split phase hauling by different contractors (stump to paved road / paved road to mill). This would involve a high degree of cooperation between loggers, specialist transport contractors and mills. Further investigation and development would be required to :

1) find practical methods to collect section performance data on an operational scale as a basis for negotiating prices, and

2) incorporate them into practical operational decision making systems.

This challenge requires cooperation of the transport buyer, logger and the transport seller, and could bring considerable economic benefit.

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