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PERFORMANCE-OBJECTIVE DESIGN FOR ENERGY CONSTRAINED TRANSPORTATION SYSTEM

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Abstract: Recent evidence indicates that the peak in world oil supply may arrive within the design life of present transport systems. The current transportation planning paradigm has no means for managing, building and operating under energy constraints. We present a new paradigm based on control systems theory to incorporate energy constraints into transportation planning. The systems paradigm focuses on integrating transportation, and activity systems dynamically constrained by the total amount of energy available. Our research has shown that this approach is new to the field, and we propose a formal method to design an Energy Constrained Activity-Transportation System (ECATS). A case study in Christchurch, New Zealand resulted in a transportation service using only renewable resources, and designed for maximum activity with reasonable economics. The analysis shows that an energy constrained activity transportation system would be designed and operated very differently compared with the current fossil fuelled system.

Key Words: transportation planning, energy, sustainability, control systems

1. INTRODUCTION

The finite availability of oil has realistically never been in question, but the risk to the economy and even modern society as a result of oil reserve depletion is a hotly contested subject (Goodstein 2004). Land use, transport vehicles and infrastructure have been planned, designed, organized and managed with minor consideration of robust functionality within energy or environmental constraints (Heinberg, 2004). Record high oil prices have highlighted the urgent realities for future transportation planning (Deffeyes, 2003). According to Boyle (1996) since the 1970's there have been serious fears over the collapse in fuel supplies, which after the 1973 fuel crisis prompted Organizations of Petroleum Exporting Countries (OPEC) to attempt for the first time to coordinate their policies, which raised the price of oil dramatically. History has revealed the dramatic and far-reaching economic impacts of fuel shortages and high fuel prices in the mid 1970's and 1980's (Campbell 2004). Even if the United State Geographic Survey (USGS) most optimistic estimates of world oil reserves are true (Masters *et. al*. 1994), then roads, railways, and other transport infrastructure existing now will still have years of service life when the peak in world oil production occurs.

The most probable oil supply reduction scenario in the future will have impacts on society (Tainter, 1990). The current activity structure of developed countries consumes almost exclusively fossil fuels from oil. Ordinary activities are very likely to be negatively impacted by un-planned and un-managed fuel shortages. High oil prices increase costs in all sectors which rely on transportation for dynamic activities such as food distribution, waste collection, commercial and leisure activities (Burnett 1991). At extreme high prices, economic crisis will emerge in the form of economic contraction, recession and possibly depression (Mitchell 2000). Various analysts indicate that extremely high oil prices might cause disruptions, which range from collapse of monetary systems, unemployment, starvation and even war (Klare 2002).

During past oil crises high prices resulted in reduced activity, particularly elective travel (Sagner 1974). Krumdieck's (2004) analysis of the oil market from an engineering perspective shows that fuel demand, which historically has been synonymous with consumption, cannot actually exceed supply. The infrastructure, land use patterns, vehicle fleet and activity distribution combine to define a consumptive capacity for normal activity. During the next few years, the supply of transportation fuel will be below the consumptive capacity of the transportation systems in most industrialized countries (Kunstler 1998).

Alternative fuels are well known, but may not be available at the time that oil supply falls short, and they will not equal the quantity of oil. Biofuels are not currently available as a substitute, and even optimistic analysis of future supplies are a fraction of current fuel consumption (Horne 1996). Hydrogen has long been proposed as the "next generation" transportation fuel, but there is no source of hydrogen, no infrastructure for delivering the fuel to a transportation system, and no energy source available to produce hydrogen at a price and scale for feasible use in transportation (McAlister 2003). Electric vehicles, while technically feasible, have never been cost competitive and energy requirements are still unfeasible and cannot match the performance standard of the petroleum personal automobile, and fuel cell vehicles are decades away (Larminie and Dicks 2003).

Although it is acknowledged that the oil depletion scenario will occur in the future, a survey of transportation engineering texts (Wright *et al*, 1998, Khisty, 1990, Dickey, 1983, Bruton 1975, Meyer and Miller, 1984) illustrates that current modeling and planning techniques do not include any method to consider constraints in natural resources, emissions, or, most importantly, energy. Moreover, a review of the state-of-the-art in advanced modeling techniques for transportation planning indicates that no references to a method, or even a treatment of the subject are observed (Ortuzar and Willumsen, 1994, Spear, 1996, Daganzo, 1997, Harris, 1996, Oppenheim, 1995). This is mainly a consequence of the current paradigm used in transportation engineering and planning. It is assumed that demand will be met by increasing or changing the supply. Few attempts have been made to control fuel consumption, rather they have concentrated on the land use distribution and density without taking into consideration energy constraints (Carrier, 1974, Sagner, 1974, Lim, 1997, Meyer, 1999)

In this work, we apply control systems theory to the planning of energy constrained transportation systems. We present a new paradigm that focuses on integrating transportation, and activity systems dynamically constrained by the total amount of energy available. We propose a formal approach to design an Energy Constrained Activity-Transportation System (ECATS) in which human needs/activities are fulfilled/performed taking into consideration energy resource limitations. The engineering objectives are to achieve a system that is robust and reliable, economically reasonable, environmentally responsible and runs on renewable energy. In the ECATS conception, finite resources are invested in materials and infrastructure, but not consumed for fuel. Using the ECATS approach, transportation and activity systems would be designed and organized based on real-time assessments of energy availability, and long-term evaluation of environmental health. Infrastructure, including the transportation system, would not be provided on the basis that future growth in demand is expected. Instead, given a predicted amount of energy, planning actions would focus on determining the optimal use of available resources (vehicles, transport network, personnel, etc). Simultaneously, land use, which determines the spatial arrangement of activities would be planned to cope with the dynamic energy availability and limitations that would constrain mobility and accessibility.

Based upon the ECATS conceptual framework, we proposed a planning structure that incorporates a new method to assess the technical feasibility, the environmental desirability and the economic possibility of using various renewable energy sources. The new method is based on performance-objective designs for each particular transportation service. A case study is presented for a public transportation service in Christchurch, New Zealand.

This paper is divided into six sections. After this introduction, section two summarizes the fundamentals of control systems theory, which is the key to understand and conceive ECATS. The general concept of ECATS is presented in section three. The description of the method for performance-objective design is presented in section four. The case study in section five illustrates the application of the method. Finally, section six presents the conclusions and addresses future research directions.

2. BACKGROUND IN CONTROL SYSTEMS THEORY

The field of Aerospace Engineering has led to the spin-off capabilities of Control Systems Analysis and Design, or more commonly “Controls” (D’Azzo, 1981), and Systems Engineering (Khisty, 2001). These two disciplines are growing rapidly and finding broad application in advanced societies. Controls is based on a theoretical description of the behavior of closed-loop feedback-controlled systems. Controls uses a standard methodology and mathematical and modeling approach for analysis and design for stability. Fourier transform of governing equations describing the system dynamics in the frequency domain is the powerful approach used in Controls. Systems Engineering is a complimentary broad-based art encompassing problem solving, economic evaluation, reliability and variability analysis, decision analysis, optimization, simulation and interpretation. The Systems Engineering approach starts with defining, in advance, the range of outcomes, constraints and performance indicators. The prominent mathematical tools employed are statistical methods, which facilitate decision analysis.

The basic idea used in analysis of feedback control systems is shown in Figure 1. Examples of automatic feedback control systems range from the simple operation of a toilet fill unit to a sophisticated aircraft autopilot system as outlined in Table 1. The output represents the system performance or "what is happening". The performance is measured by some means and converted to a feedback signal by the feedback elements. The feedback signal is compared to the reference input, which is supplied to the system from the reference selector. The desired performance of the system is called the command input. If the reference input is different from the feedback signal, then an actuating signal is produced which generates a response in the control elements according to the control set points. The control elements then affect some change in the forward elements according to the system dynamics, which then change the output. It can be seen that this is not a beginning and end process, but rather a continuous, cyclic process reflected by the frequency domain analysis usually employed in Controls Analysis.

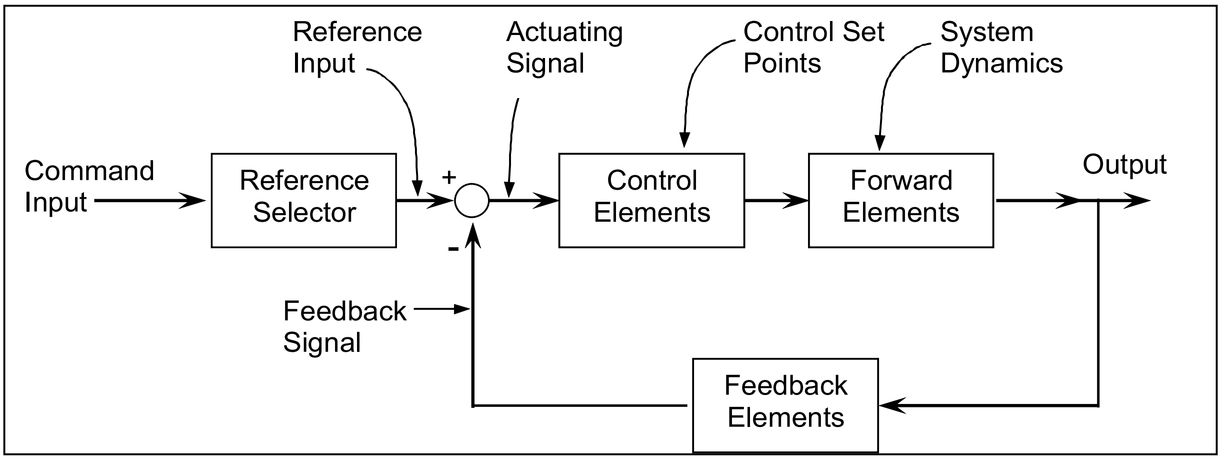

Figure 1. Functional block diagram of a closed-loop feedback control system

Table 1. Examples of the functional elements of automatic feedback control systems

Control System Component	Toilet Tank Example	Aircraft Autopilot Example
Output	toilet tank is half full	plane is flying 10°W of South
Feedback Elements Feedback Signal	buoyancy force of water raises a plastic ball so that a lever arm is in a new position	signal from a locator is processed by the navigation system
Command Input	Fill with enough water to flush, but don't overflow.	Fly a course due south to Dallas
Reference Selector Reference Input	A screw to adjust lever arm position at the correct water level for a full tank	Electronics for setting flight path, and the electronic signal
Actuating Signal	Angle of the lever	5 volts
Control Elements Control Set Points	Valve opening cross section area	Electronic signal from microprocessor
Forward Elements System Dynamics	Water pressure across the valve opening, water flow through pipe into tank, water level rises.	Signal opens valve to increase pressure in hydraulic line which pushes a lever arm which moves a flap slightly, generating more lift on one wing, and causing a slight turn of the aircraft.
Output	Toilet tank is 55% full	Plane is flying 8° W of South

2.1. Control systems applied to Energy-Activity Systems

Krumdieck and Wood (1989) applied control systems analysis to regional energy-environment-socioeconomic systems. The system control elements are represented by individual people and businesses. The behavior of the systems at all levels is a result of the cumulative day-to-day decisions of people. Decisions can be generalized to maximize utility within the context of what is available, allowable, and affordable.

In other words, people do what they want to do, using what they know will work. People typically follow social and government rules, and access technology, goods, services and energy through the economy. People can only utilize the existing built environment, and they will use it as it has been designed and built to be used. All of this behavior and the very nature of the economy and the built environment are shaped by the cultural, technological and environmental context of the civilization.

A functional diagram of the regional system is shown in Figure 2. While this model is a conceptual description only, study of various human subsystems in this context has led to development of a methodology for working on difficult regional issues including air pollution, land use, energy security and transportation. We have described this approach as the Strategic Analysis of Complex Systems (Krumdieck *et al* 2004). The method is focused on identifying the existing system behavior, and then proposing (or inventing) the new technology, information, and regulatory elements, which would complete the feedback and reference, input functions required for stable system performance in the long-term.

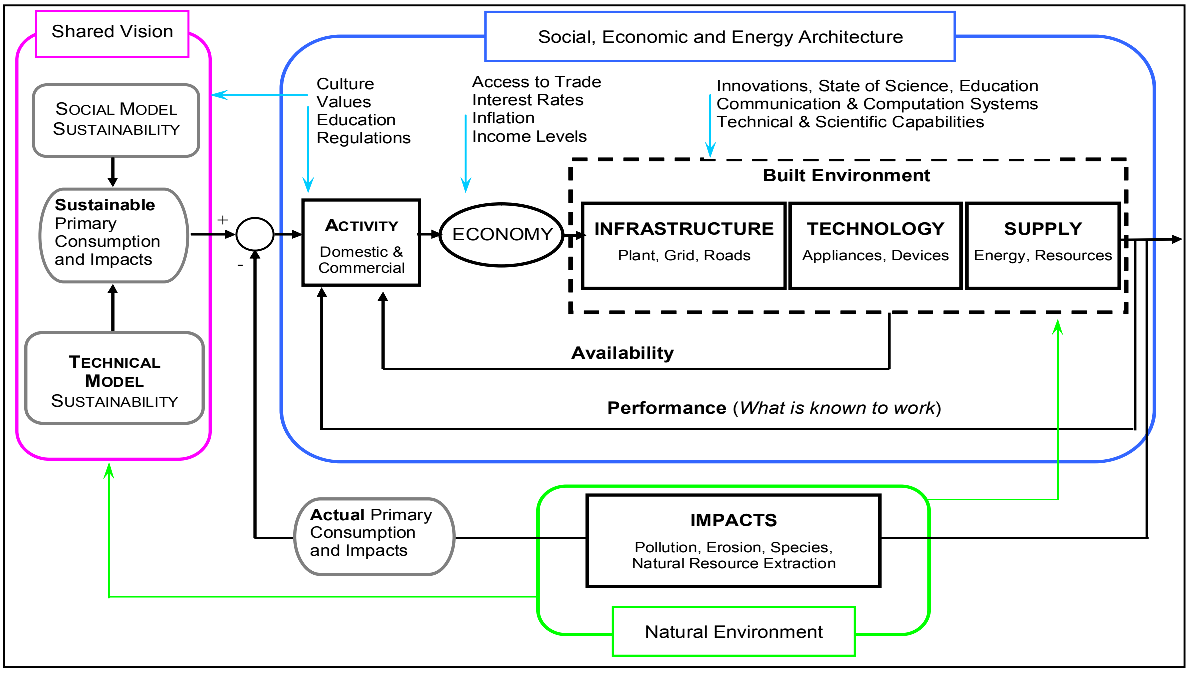

Figure 2: Regional-Energy-Environment-Socioeconomic Control System Diagram

3. ECATS APPROACH

Transportation activity systems in developed countries can be modeled using the feedback system model. Individuals undertaking domestic and commercial activities use primary feedback about the transport system. They know what roads, mass transport, and vehicles are available to them, and they choose to use the options, which will work best for them. A person driving to work actuates this use of the built environment of roads, traffic lights, car and petrol through an economic linkage. In general, the environmental impacts of the drive to work such as air pollution are not processed in a way that acts as a feedback signal to the individual. Another "missing element" for robust performance of the system with changes in energy supply is the command input and reference input. The means to actuate change in individual behaviors and functional elements to maintain activity within energy and environmental constrains are the core aspects of any new reference and feedback components for a robust and reliable transportation system.

3.1. ECATS concept

The main concept associated with ECATS analysis and design is that a sustainable activity-transport system is achieved through infrastructure and service design of system dynamics to maintain function within energy constraints and at the same time reach "affordable" levels of service and user satisfaction. This concept is represented in Figure 3. In order to achieve desired activity levels within renewable energy availability constraints, the built environment of the activity-transportation system must be designed for functional stability. The development policy and regulatory policies will ensure that the system continues to develop within the environmental and resource constraints. Information about long-term and dynamic availability is essentially feedback into the decision process at all activity levels. The services that are available, the infrastructure that is available, and the cost of alternatives all factor into the activity decision of individuals on a day-to-day basis. The performance of the transport system, compared to the desired performance, and the sustainable performance represent the system control signals and influence activity decisions as well.

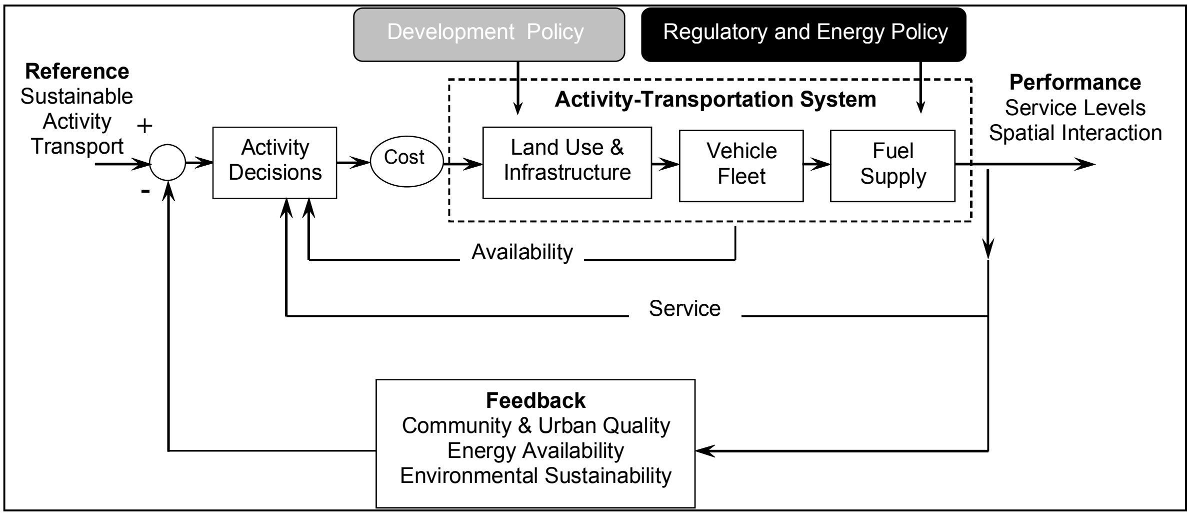

Figure 3. ECATS Concept based on feedback control theory

As in the case of the airplane dynamic control system, the pilot's decisions are made about a built system that has been designed to fly. In the ECATS concept, a critical conclusion from the controls analogy is that sustainable transportation can only be achieved through design according to performance metrics and sustainability objectives.

3.2. ECATS Planning Process

Present and future energy availability dictates the course of ECATS planning actions. Both at strategic and operational planning levels, ECATS planners are expected to predict future levels of natural resources taking into consideration a life-cycle costs approach (e.g. high consumption of fossil fuels is punished through increased costs). As shown in Figure 4, strategic and operational planning phases are linked to each other in order to guarantee a dynamic assessment of resource availability and system performance. Another critical part of ECATS is the information system that gathers all instant variations of the control system elements and delivers useful information of energy availability and costs to the users.

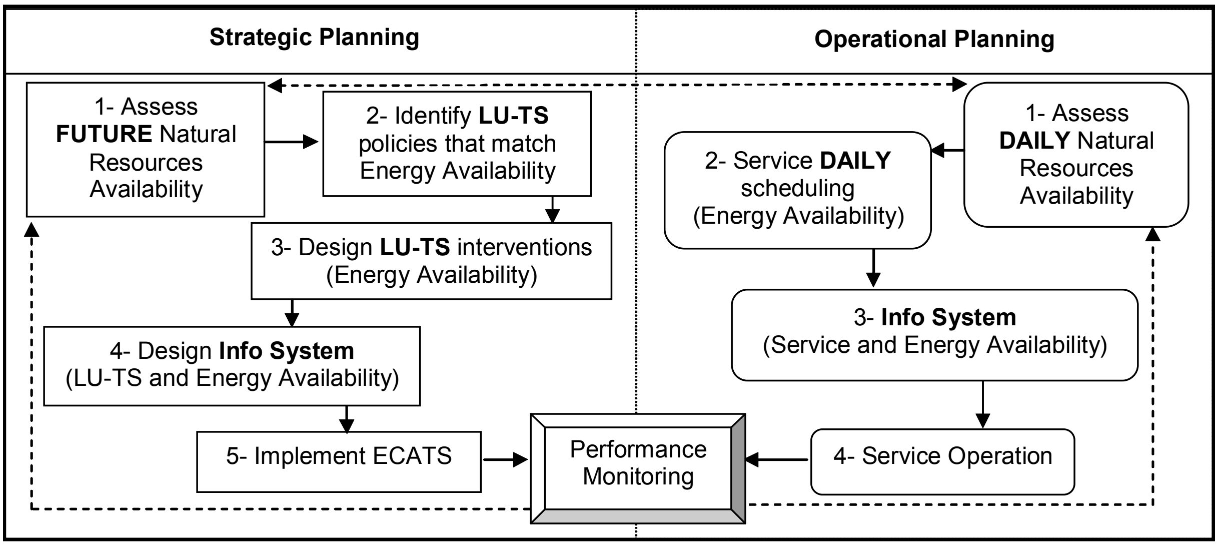

Figure 4. ECATS planning phases

3.3. Performance-Objective Design of ECATS Elements

As part of the strategic and operational planning actions, ECATS planners face the challenge of designing and selecting the best combination of transportation technology that matches energy availability and constraints. Once performance constraints and objectives are set out, the engineering design process enters into a creative and logical progression, optimizing utility, safety, cost and reliability, to achieve a technically feasible and desirable solution.

In order to conduct this task, a method for performance-objective design of ECATS is introduced. It comprises five steps as shown in Figure 5. Initially, the system is defined by determining the system activity requirements, energy resource constraints, and the existing transport technologies. The combination of these elements is used in the design of alternative concepts. Processing and simulation of real-time data is employed to estimate energy usage for each alternative concept of the transportation system. Results are compared in order to evaluate the performance of each alternative against the existing system. Finally, the environmental feasibility, the service level performance and the economic performance are assessed as part of the Decision making phase.

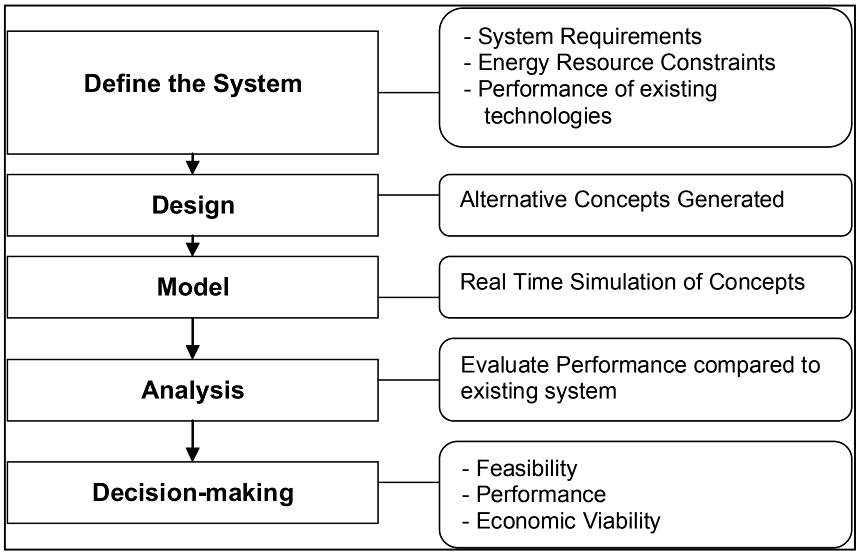

Figure 5. Performance-objective design steps of ECATS

4. CASE STUDY

The ECATS method proposed in section 4 is applied to a city in New Zealand. Christchurch is the third largest city in New Zealand with a population of 350,000. The city covers a land area of 450 km^2 and is bounded by the Waimakariri River to the north, the Pacific Ocean to the east, the Canterbury Plain to the west, and the Port Hills to the south. The Port Hills extend for 16 km along the south, and rise to approximately 500 meters.

In a remote and isolated island nation without major oil resources and an agriculture and tourism-based economy, Christchurch has an established program to explore sustainability, and the city leaders have interest in renewable energy for transportation in urban areas. Even though the public perception is that renewable energy will power the transport systems of the future, little analysis has been done which provides some understanding of the level of investment required, the nature of the performance, or the type of service provided by such a system.

The systems paradigm requires that a fully sustainable transportation service must use only available renewable energy. The scope of the project is to investigate an affordable public transport service with energy supply constrained by using only renewable resources (Krumdieck *et. al* 2004). The following sections investigate the performance-objective design using the ECATS approach.

5.1. System definition

Christchurch has a reasonable bus system, which comprises mainly radial bus routes. An exception is the service called ***The Orbiter.*** It is successful in terms of ridership (600,000 passengers per year or 11% of all bus trips) which is thought to be due to high quality vehicles, route plan, and most importantly, frequent service availability. Evening and weekend buses typically run below 5% occupancy, with only one or two passengers. Figure 6 presents the Orbirter's circular-type bus route service (18 diesel-propulsion buses; 1.5 hour circuit; 10 minute headway), which covers a considerable part of the urban area. The service is currently most vital to high school and university students, and those without the ability or means to use personal automobiles. The schedule reflects high ridership around school and shopping hours. The service costs $2NZ ($1.30US) for adults and $1NZ for students.

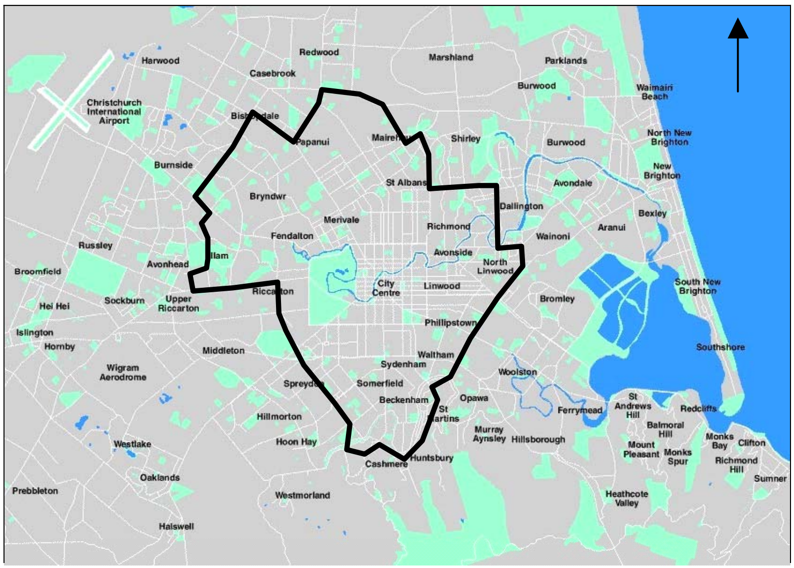

Figure 6. The Orbiter's bus route*Source: ECAN (2004)
*image not to scale for display purposes

The solar radiation is total horizontal radiation (beam and diffuse). The wind resource has not been well studied, but is in the range of class 4-5 on the hills. The solar resource in Christchurch is not ideal, with the coastal weather patterns producing a climate somewhat similar to Portland, Oregon. South Island solar resource in mid winter has an average daily total solar energy of 1.25kWh/m^2. The national electric grid system is supplied primarily by hydroelectricity and geothermal generation with less than 20% coal, oil and gas fired thermal plants.

5.2. System design

To gain an understanding of the nature of a transport system which consumes only wind or solar generated energy, several combinations of renewable energy and storage technologies were modeled that provide the transportation energy required to meet the same service load as the present bus system. In this sense, an electric light rail passenger system has been designed to replace the existing *Orbiter* route.

The renewable energy is converted to electricity and supplied through a dedicated network (not grid connected) from the modeled renewable generating plants, through a power conditioning and control center, then to the rail line as shown in Figure 7. The grid network was built several decades ago, and the power supply to Christchurch cannot be increased for the purposes of providing transportation without major network upgrades. In addition, the national generating capability has been near capacity in three of the last four years, requiring national campaigns to reduce electricity consumption during the winter months. Thus, the constraining factors for the model system are that wind and solar energy can be developed, but the transport system must be served by an independent electrical network.

The wind turbines are modeled by commercial three-blade variable speed machines, with specifications matching the *DE-Wind D6* version. The solar PV system is modeled on the *UniSolar* specifications, with nominal conversion and conditioning efficiency of 8%. In the final stage of the architecture development, a pump-storage water system was designed using a Francis turbine with maximum pump energy efficiency of 80% and generation efficiency of 85% with decreasing performance for part load operation.

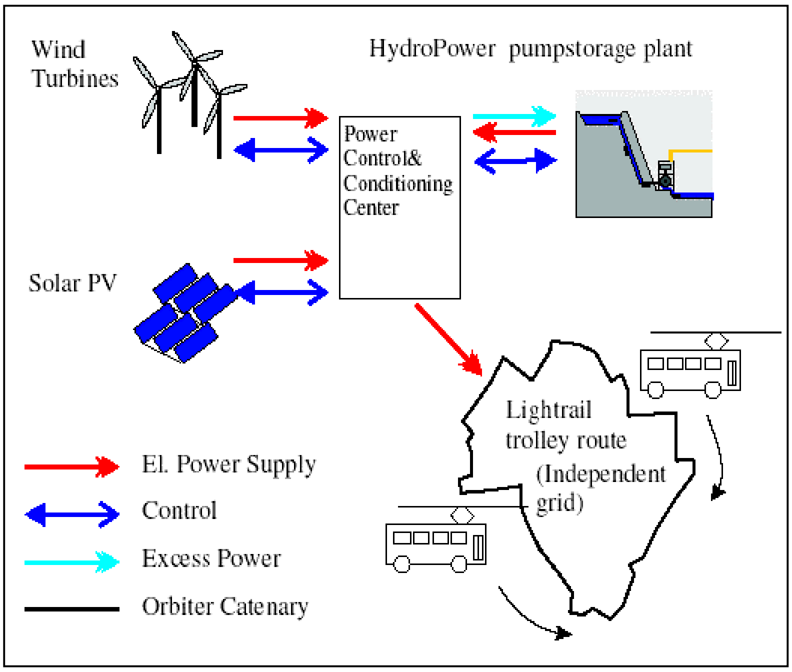

Figure 7. Renewable energy conversion process into dedicated-trolley system

The trolleys are modelled as light-weight passenger conveyance with average an speed of 35km/hr using a 25kW motor, equipped with a water-cooled gel battery backup power for urban driving conditions. The trolley line uses overhead power cables and traction rails, and the system maximum power consumption is 430kW (18 buses) during peak load. Trolleys travel in both directions continuously, with pickup frequencies of 10-min during business hours, 15-min in off-peak, and 30-min late night and weekends.

5.3. Energy system modeling

A real-time reservation and schedule system has been proposed to facilitate optimal operational efficiency of the model system to maximize service and minimize investment. The 15-minute wind and solar data used for the study was resourced from the weather station in the Department of Geography, University of Canterbury. Five scenarios were defined by combining the energy sources and their characteristics to the real-time reservation system:

- ***Scenario 1 (One Wind Turbine)***: the lowest investment concept, to install a single wind turbine with no energy storage. A wind turbine with 1MW rated power, placed in a wind power site on the Port Hills;

- ***Scenario 2 (Multiple Wind Turbines)***: investigates the relationship between wind generation capacity and a scheduled service load;

- ***Scenario 3 (Solar PV)***:.Solar PV is known to be a very expensive option, and so was not expected to be a viable option. The main point of investigation was the relationship between solar PV collector area and service provided.

- ***Scenario 4 (One Wind Turbine plus Solar PV)***: investigates the idea that the wind and the sun might compliment each other over the course of the year. The 1MW wind turbine output power was combined with the power from 20,000m^2 solar PV panels; and

- ***Scenario 5 (Wind Turbine plus Pumped-Hydro Storage)***: The wind energy available often exceeds the transport load by as much as a factor of two. The pumped-hydro storage plan involves a 500kW electric generation plant using a Francis turbine. A water storage facility is placed on a nearby hill with a storage capacity of 1Mio.m^3 and a head of 100m. The model uses the turbine to pump water from a small reservoir on the river up to the storage facility whenever the wind power exceeds the load by the minimum pump power of 150kW.

5.4. Energy system analysis

In order to compare performance between scenarios we use a service factor, calculated as the total number of trolleys that were run over the year compared to the number scheduled. The results for each scenario are:

- Scenario 1: One Wind Turbine

Considering a utilization factor of 0.4, it is expected that the annual average power generation of 435kW would be a good match for the current transport load of 430kW. However, while the total energy generated exceeds the requirements for the trolley system, the power is only available on the same schedule as the winds. For this case the annual service factor of only 61% was calculated. Figure 8 shows a random week in mid winter and the wind power generation minus the electric trolley load. Of course, in the 11:00pm to 5:00am timeframe, there is no trolley load, so the load is met regardless of the wind generation.

- Scenario 2: Multiple Wind Turbines

Increasing the number of 1MW wind turbines did increase the service factor. Two turbines improved the service factor from 61% to 69%. Three turbines increased the service factor to 73%, and four turbines gave a service factor of 75%. However, greatly increasing the number of 1MW wind turbines from four to ten only increases the service factor by 5% to 80%.

- Scenario 3: Solar PV

With 8% efficiency, a total of 35,000m^2 of solar PV is utilised. Using the actual solar incidence data, hour by hour assessment gave a service factor of 56% for this scenario. The collector area was increased with the effect of increasing the service factor only 4% to 60% for an addition 30,000m^2 collector area to 65,000m^2.

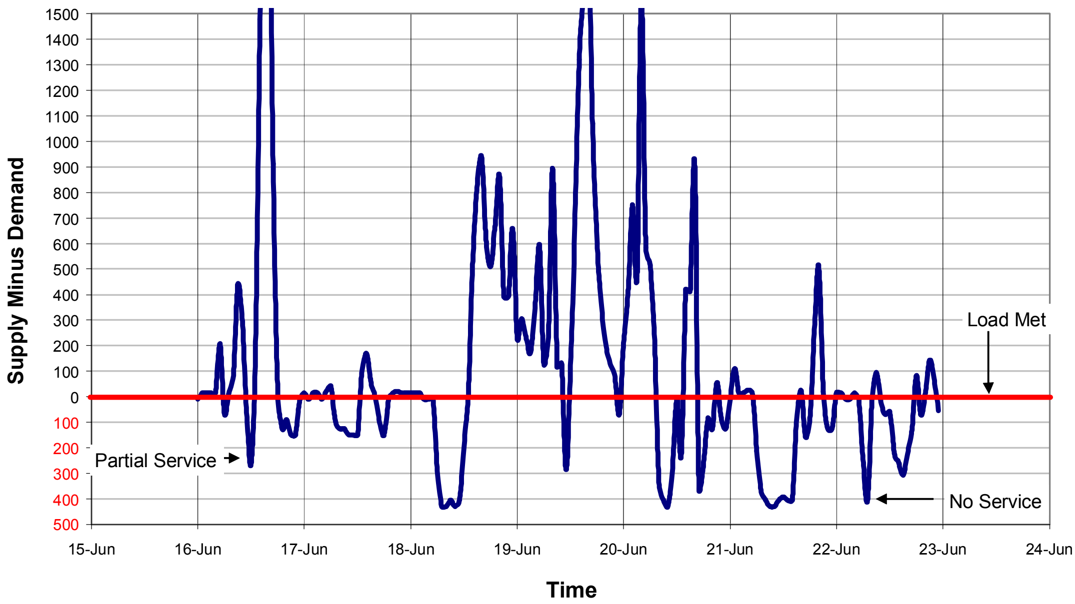

Figure 8. Set schedule load supplied by a wind turbine.

- Scenario 4: One Wind Turbine plus Solar PV

This scenario produced a fewer number of hours where there was no service provided. However, the service factor was still only 80% over the year. Figure 9 shows the wind energy, solar energy, and trolley service provided compared to the service schedule for a winter day in 2002. In the time period from 11:00 a.m. until 4:00 p.m., all 18 trolleys were running according to schedule. However, there were approximately 7 hours where trolley service was severely reduced or curtailed.

- Scenario 5: Wind Turbine plus Pumped-Hydro Storage

As seen in Figure 8 for June 19, 2003, the nature of the variable wind resource means that there are a significant number of periods with no or strictly reduced service. Unlike battery storage, the pump cannot come on-line until sufficient power is available to operate it at the minimum part load operation specification. Therefore the utilization factor may be enhanced by increasing the number of (pump-) turbines. The functionality and the total service factor are increased when adding complexity to the system by using three smaller 200kW Francis turbines on separate penstocks. The smaller penstocks, however, have higher friction head loss and lower pumping efficiency. We can operate the first pump to store water when the wind power exceeds trolley demand by only 20%. We can also run just one turbine at higher flow volume, and thus higher generation efficiency when the wind power is 20% below the demand. The service factor for the 500kW pumped-hydro storage design is 97%, while it increases to 99.1% for the system with three 200kW pump/generators on three separate penstocks.

5.5. Decision-making

Under the ECATS approach and concept, the final decision does not focus in satisfying demand with the maximum generation of energy. Rather, it comprises a carefully examination of what can be achieved in terms of economic, environmental and technical feasibility. Figure 10 shows the results of the study, summarizing how the increasing service factor exponentially drives up the cost of the system. From a conventional engineering perspective, we would conclude that the best design for the renewable energy transport system is the combined wind, solar PV battery and pump-hydro storage because it can provide 100% of the trolley service.

However, this option could be undesirable because of damage that might be created to the environment in order to produce hydro and solar energy.

On the other hand, the one-turbine transport system would have a rather random availability at any given time. Furthermore, this option would have to be associated with an information system to manage the trolley network. Weather forecasting and real-time GPS data on trolley location could be used in an information system to let potential travelers and freight service customers know the service schedule. This type of flexibility could be managed through information at a much lesser cost than managing a fixed schedule though increased energy supply.

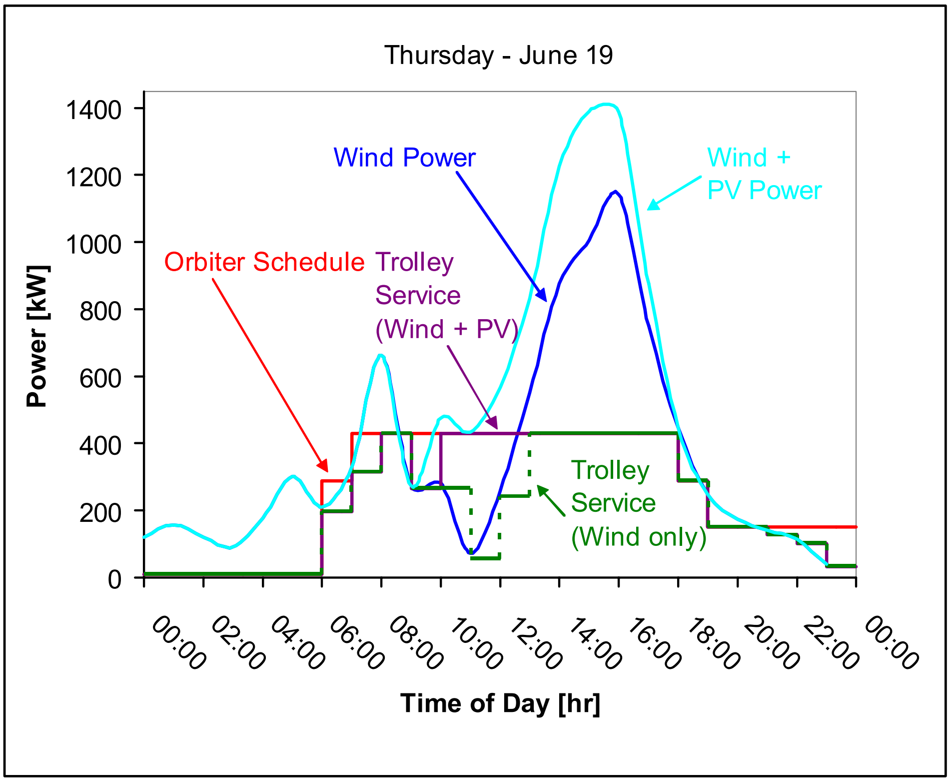

Figure 9. Scenario 3 Wind and solar energy resource compared to transport load for one winter day.

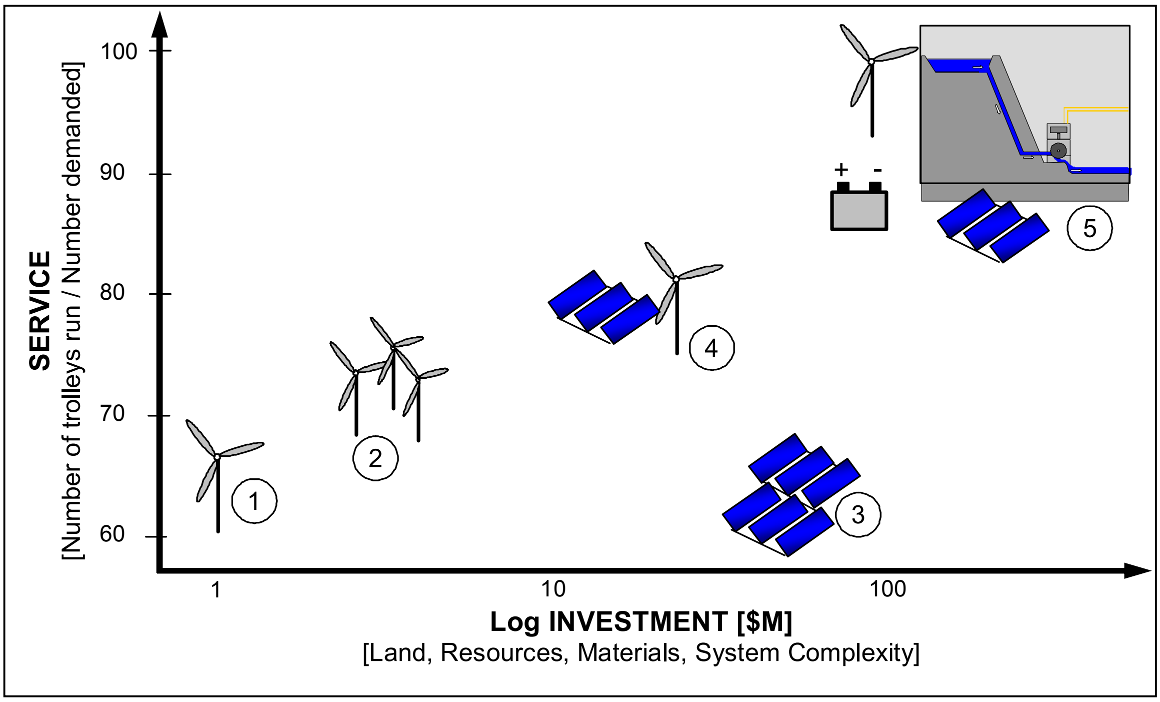

Figure 10. Scenario Comparative analysis (Service *versus* Investment)

6. CONCLUSIONS

Recent evidence indicates that world oil production rate will peak in the near future. With a shortage of energy from oil, there is substantial risk that human activities would collapse as one of the fundamental components of activity is the movement of goods and people.

We presented a hypothesis that future energy-dependent systems must be designed for robust and reliable operation including energy and environmental constraints. In this paper, we presented a new paradigm and an alterative engineering approach that may lead to a genuine sustainable energy scenario in the future. In opposition to traditional planning approaches that aim to match supply with predicted demand, a systems engineering based methodology focuses on conceiving a system that integrates transportation and activity systems constrained by the total amount of energy available. The process includes defining sustainability performance parameters in engineering terms, defining service objectives in socio-economic terms, and then generating concept designs using standard engineering modeling.

In a case study in Christchurch, New Zealand, the ECATS approach was used to develop the performance-objective design for a wind and solar powered public transportation service that provides a 35km circuit of schools, shopping malls, and industrial parks. The system requirements for the design were set by an existing bus service. A number of concepts were explored for the renewable energy supply of an electric light rail trolley circuit on a dedicated (not grid connected) electric supply network. Each concept represents a different degree of capital investment and system complexity, and achieves a certain level of the desired transportation service on any given day. Real-time simulated performance modeled with historical local weather data was used to compare the performance of each of the possible designs to the objective. A service factor was calculated to evaluate the level of transport service performance achieved compared with the objective.

The results demonstrate that no amount of investment in wind and solar energy capacity can provide the same service as the fossil fuel system. When pumped-hydro storage of wind and solar energy was added to the system, the service factor could be increased to 100%, but economic (willingness to pay) and environmental (area for hydro and solar energy generation schemes) feasibility would not reach desirable levels. The modeling exercise points out that a relatively modest investment in wind generation can produce a useful service when new information technology elements are included in the system.

This work has introduced the Energy Constrained Activity-Transportation Systems (ECATS) approach as a method for performance-objective design of future energy constrained systems. In addition, the ECATS approach adds a new dimension to current transportation decision-making. New modeling techniques must be developed for each step of the planning and operation process. No current method or models exist for incorporating energy constraints into land-use planning. Our goal is to develop direct real-time simulation modeling tools with the capability to include operational service factor requirements and investigate system behavior with the application of innovative new information technologies. The simulations would be flexible for use in specific regions and transport services and would communicate functionality and costs to planners, stakeholders, and citizens.

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