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AN ENERGY APPROACH TO ECOLOGICAL IMPACT ASSESSMENT

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ABSTRACT

This paper was prepared to educate the transportation planner/engineer in some of the rudiments of ecology and with the hope of systematizing current approaches to ecological assessment. Considerations of *energy*, or *bio-energetics*, have been found to be singularly applicable to transportation impact assessment. This method of evaluating the effects of environmental impacting factors on environmental elements is outlined herein. The method can be applied to the analysis of the ecological impact of all types of activities, and with particular pertinence to transportation.

The energy theory is based on analysis of the amount of energy which is required by plants or animals or ecosystems or subsystems, to permit their growth or stability to continue. The numerical calculations involved permit quantification of impact effects of transportation facilities.

Planners and engineers find themselves, to an increasing degree, in a position of broadening their expertise, widening their technical horizons, and absorbing technical knowledge from other fields. One

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such field is that of *ecology*, incorporating knowledge of biology, botany, geography, and geology, broadly speaking, but including within itself many subspecialties related to all natural (living and non-living) things. The scope of this one new aspect of environmental impact (the other is the realm of social, psychological, and economic impacts) is so broad that no proposed methodology or approach for assessment will ever replace the services of trained ecologists.

With a view, however to providing planning and engineering professionals with some of the rudiments of ecology, and with the hope of systematizing current approaches to ecological assessment, considerations of *energy*, or *bio-energetics*, have been found to be singularly applicable to transportation impact assessment. This concept stems from work done by Odum, Woodwell, Whittaker, and Lakens, among others [1-3].

The fact that living organisms can be categorized into *ecosystems*[1] permits a two-pronged approach to the development of a systematic ecological impact assessment methodology: first, a straightforward analysis of the effect of a transportation facility on an ecosystem, which at some point requires the services of a specialist in ecology or biology; and second, use of the knowledge of *energy transfer* between *trophic levels* (bio-energetics) for calculating *natural energy lost* in modifying or destroying various ecosystems.

Nutrients, when combined with carbon dioxide in the presence of radiant energy, produce organic material, with the concomitant evolution of gaseous oxygen. Energy is thus made available for the maintenance of other components of the ecosystem, which functions through the *transfer of energy* from one component to the other. A simplified illustration of such a "trophic pyramid" is given as Figure 1.

ECOLOGY

Living organisms operate in *ecosystems*. There are five major ecosystem types:

- terrestrial (earth)
- aquatic (fresh water)
- marine (salt water)
- aquatic marsh (freshwater)
- marine marsh (saltwater)

In each *ecosystem*, there are four basic units:

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[1] Balanced relationships between living and non-living things, such as a lake or a forest.

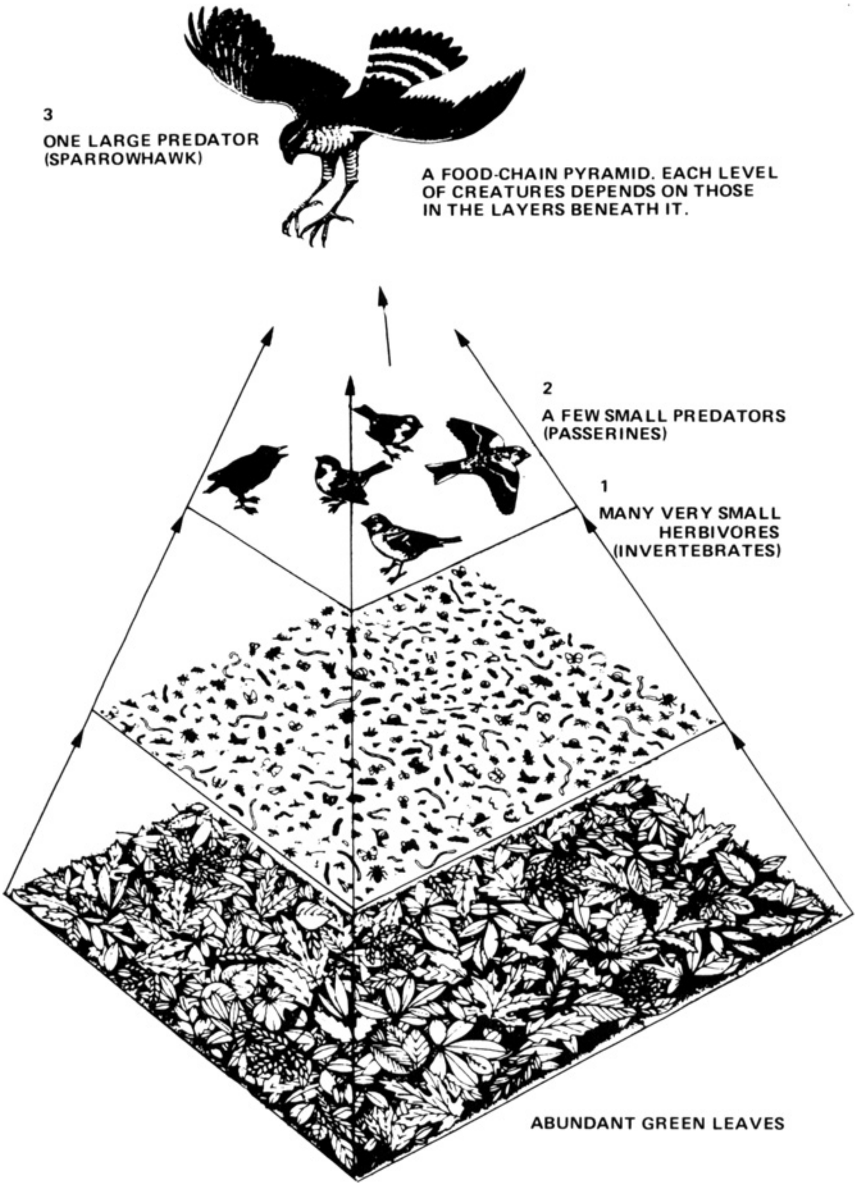

Figure 1. Trophic levels. Source: G. Clay, *Close-Up, How to Read the American City,* Praeger Publishers, New York, 1973.

- abiotic (non-living)
- autotrophs (producers, mostly plants)
- heterotrophs (consumers, mostly animals)
- decomposers (bacteria and fungi)

The *abiotic* includes

- rain
- nutrients
- soil or sediment

The *autotrophic* organisms produce organic materials from inorganic materials and sunlight.

The *heterotrophs* get their energy from the autotrophs (a rabbit eats plants, a fox eats the rabbit).

The *decomposers* break down the tissue of dead autotrophs and heterotrophs.

An ecosystem, then, works through *transfer of energy.* Changing the energy transfer at any one point will affect the rest of the cycle.

Energy levels are called *trophic* levels. All organisms which get their energy from the same source are at the *same trophic level* (grasshoppers, rabbits, and field mice eat plants, and are at the same *trophic level*; a hawk, and a fox, which eat the mice and rabbits, are at another *trophic level*). The number of trophic levels is different for each ecosystem, usually between one and five.

The average efficiency of transferring energy from one trophic level to another is about 10 per cent.[2] Figure 2 shows the energy flow.

Table 1 gives figures for energy production for various ecosystems. The difference between *gross* production and *net* production is the loss in respiration, or "maintenance." The *net* production is what is left over for transfer to other organisms. These are the values used in calculations.

Evaluation Approaches

Knowledge of the energy production of natural systems permits an approach to assessing impacts on a basis which deals with a single unit: energy units, whether in BTU[3] or kilo-calories. But while all energy in its ultimate form can be said to be the same, the forms within which it exists or passes through are quite different, and in many cases not currently comparable.

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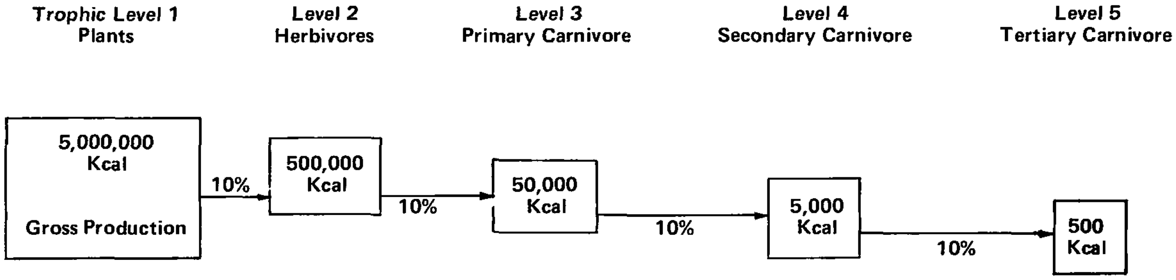
[2] This figure varies from zero to 30 per cent.

[3] British Thermal Units (BTU).



Note: Illustration of relationship of Gross Production and energy transfer. Because of respiratory, decomposition, and other biological maintenance activities, only an average of 10 per cent of energy is available to each successive level. If the tertiary carnivore requires 500 Kcal/day, at least 5 million Kcal would have to be produced for it to survive.

Figure 2. Energy flow.

Table 1. Energy Production by Ecosystem

	Gross Production		*Net Production*	
Ecosystem	*g/m²/yr.*	*Kcal/m²/yr.*	*g/m²/yr.*	*Kcal/m²/yr.*
Tropical forest	6700	28,140	2000	8400
Temperate forest	4300	19,780	1300	5980
Boreal forest	2700	12,690	800	3760
Tropical savannah	1200	4,800	700	2800
Grassland	500	2,000	300	1200
Desert	120	480	70	280
Cultivated land (non-subsidized)	1100	4,730	650	2795
Tundra	300	1,410	200	940
Snow and ice	0	0	0	0
Open ocean	200	1,000	125	625
Continental shelf	600	3,000	350	1750
Estuaries	3300	16,500	2000	10000
Saltmarsh (Odum)	4280	20,000	3300	15414
Mangrove swamp (Kreb)	1210	5,650	930	4344
Swamp and marsh (mean) (Whittaker)	2570	12,000	2000	9342
Lakes and streams (mean) (Whittaker)	642	3,000	500	2335
Clear deep lakes (Odum)	255	1,200	153	720
Shallow eutrophic lakes (Odum)	767	3,600	460	2160

Note: 4.671 Kcal/gm.dry wt. Conversion factor for gross and net primary productivity in g/m²/yr. and Kcal/m²/yr. for various ecosystem types.

Source: Values from Colley F. B. (1961, 1972) (Energy flux in Ecosystem. In *Ecosystem Structure and Function,* Oregon State University Press, pp. 69-90), Odum (1959), Whittaker (1970), Kreb (1972).

For instance, in terms of "energy" we may see three basic evaluation approaches to facility impact: national, regional, and local:

1. Effects on *national* energy sources and availability.
2. Effects on *regional* energy consumption, ecosystem energy production, and impacts on primary and secondary elements of the environment.
3. Effects on local ecosystem energy production, and impacts on primary and secondary elements of the environment.

This allows the assessment at each level of *energy impacts.* In assessing *national impact,* we may consider:

1. natural resources energy consumed in construction;
2. hidden energy costs of construction (of an averaged alternative);
3. fuel consumption energy costs (of an averaged alternative);
4. road maintenance costs in energy (of an averaged alternative).

For *regional impact*, consider:

1. regional land use and ecosystem inventory;
2. direct energy losses, per ecosystem type by alternative;
3. regional impacts on Primary and Secondary Elements;[4]
4. natural resources energy consumed in construction (related to regional demands and priorities);
5. hidden energy costs of construction by facility alternative (related to regional demands and priorities);
6. product consumption energy costs by facility alternative;
7. road maintenance costs in energy by facility alternative.

And for *local impact*, consider:

1. local land use and ecosystem inventory;
2. direct energy losses, per ecosystem type, by facility alternative;
3. localized impacts on Primary and Secondary Elements.

Methods of calculating these energy quantities follow.

Natural Resources Energy Consumed in Construction

This may be calculated by using engineering methods of estimating the construction materials involved, or by calculating losses based on the dollar cost of the facility. Due to changing economics, the first method is more reliable.

In practice, if the second method is used, the current dollar cost of the facility is converted to the amount of material used. This value is used to multiply the number of natural resources units to obtain the total amount of natural resources required for each alternate.

Table 2 lists material and labor demands per million dollars of highway cost. These values may not be applicable to other transportation facilities.

HIDDEN (INDIRECT) ENERGY

Unfortunately, indirect energy costs have been omitted in previous estimates of environmental impact. *Indirect energy cost* is defined as energy required to *produce*, *mine*, and/or *fabricate* the

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[4] Nomenclature defined in Reference [4].

Table 2. Materials and Labor Required for Highway Construction

Material	*Unit*	*No. units/million dollars construction cost*
Cement	Barrels	13,600 (1 bbl = 0.18 tons)
Bituminous Material	Tons	856
Aggregates	Tons	36,000[a]
Steel	Tons	413
Lumber	Board Feet	49,000
Petroleum Products	Gallons	125,000
Labor	Man-Hours	68,000

[a] Assumes 50 per cent purchased and 50 per cent produced on site by contractor.

Source: (Adapted from *Highway Statistics,* 1969. Does not include costs of rights of way).

raw materials used in construction. Also included here is energy expenditure in terms of human resources. Table 3 lists energy consumption in basic materials processing in Kilowatt-hours-thermal (Kwht) and Kilocalories (Kcal) per unit of resource.

For example, estimates of the indirect energy costs of steel are as follows:

- Assume a 31.36-million-dollar facility.
- Number of millions of dollars X number of units/million dollars = total number of units.
- Total number of units X Kwht/unit or Kcal/unit equals total energy required.

The same reasoning is used in calculation of each basic resource. The mathematics reduces to the following series of equations:

$$\begin{aligned}
\text{Steel} &= 31.36 \text{ millions} \times 413 \text{ tons/million} \times 12600 \text{ Kwht/} \\
&\quad \text{ton} \times 860.01 \text{ Kcal/Kwht} = 1.4 \times 10^{11} \text{ Kcal} = \\
&\quad \text{millions of dollars} \times 4.495 \times 10^{9} \text{ Kcal required.} \\
\text{Cement} &= \text{millions of dollars} \times 4.842 \times 10^{9} \\
\text{Aggregate} &= \text{millions of dollars} \times 0.650 \times 10^{9} \\
\text{Lumber} &= \text{millions of dollars} \times 0.063 \times 10^{9} \\
\text{Coal} &= \text{millions of dollars} \times 0.031 \times 10^{9} \\
\text{Petroleum} &= \text{millions of dollars} \times 4.300 \times 10^{9}
\end{aligned}$$

FUEL CONSUMPTION

Once operational, a transportation facility has a continuous impact on the environment by the generation of emissions, by fuel consumption and by maintenance procedures (e.g., salting).

Table 3. Energy Consumption in Basic Materials Processing

Material	*Kwht/unit*	*Kcal/unit*
Steel	12,600/ton	10.84×10^6/ton
Cement	2,300/ton	1.98×10^6/ton
Aggregates	21/ton	$.018 \times 10^6$/ton
Lumber	1.51/board foot	12.99×10^2/board foot
Coal (Bituminous Products)	42 ton	$.036 \times 10^6$/ton
Petroleum Products	40/gal	$.034 \times 10^6$/gal.
Labor[a]		452/man-hour

[a] Assumes a 70-kg man expending 6.45 Kcal/kg/hr. A 70-kg man at hard labor expends 452 Kcal/man-hour of labor.

Source: (Makhijani and Lichtenberg. *Environment* 14(5):14).

Transportation facility design must consider future environmental costs. It is necessary to determine ambient conditions for these factors and to project the future impact of each alternative.

The following factors must be related to facility evaluation: fuel consumption; present and future energy drain; emissions generated; and the impact of facility maintenance (salt application, etc.).

1. Fuel Consumption generated:

Traditionally, estimates of newly generated traffic have been made to measure the adequacy of the proposed facility to handle present and future traffic. However, no attention has been paid to the *energy drain* resulting from additional fuel consumption. The factors required for such calculations are:

- Length of facility
- Number of vehicular trips/day or year-present or newly generated
- Per cent gasoline vs. diesel vehicles
- Fuel consumption: average automobile and truck consumption in miles/gallon; must be continuously updated. Factors listed here are for 1972 (*1973 Automobile Facts and Figures*, Motor Vehicle Manufacturing Association, p. 52): Automobiles 11.2 miles/gallon; Diesel Vehicles, 8.39 miles/gallon.

2. Calculations:

- (Length of facility) (No. vehicle trips/day) = vehicle-miles/day

- $\frac{\text{(Vehicle-miles/day) (\% automobiles)}}{\text{12.4 miles/gallon}}$ = number of gallons of gasoline consumption
- $\frac{\text{(Vehicle-miles/day) (\% diesel)}}{\text{8.39 miles/gallon}}$ = number of gallons of diesel fuel consumption
- Energy consumption for automobiles = (number gallons gasoline consumed) (3.2×10^4 Kcal/gal)
- Energy consumption for diesels = (Number of gallons diesel fuel consumed) (3.5×10^4 Kcal/gal)
- Energy Cost for fuel production: Gasoline = (Number of gallons gasoline consumed) (1.2) (3.2×10^4 Kcal/gal)
- Energy Cost for fuel production: Diesel = (# gals diesel fuel consumed) (approx. 2) (3.2×10^4 Kcal/gal)
- Total Cost of Fuel Consumption
  (Energy consumption automobiles + energy consumption diesels + energy production gasoline + energy production diesel fuel). (4 + 5 + 6 + 7).

ROAD MAINTENANCE

In addition to the energy used in construction and utilization of the facility, estimates should be made of the energy costs of maintenance due to lighting, roadbed maintenance, landscaping and weed control. These factors will vary depending upon the facility.

Effects of *deicing salts* should be considered in those areas requiring their use. The following equations pertain:

1. Estimate Total Salt Used:
   (No. Applications/yr) (lane-miles) (# tons/lane-mile)
2. Approximate Economic Cost due to automobile body corrosion from deicing salts:
   (Number vehicles/year) (approx. $50/vehicle)

Land Use and Ecosystem Inventory

For the item on *ecosystem energy*, the concept being introduced in this paper, ecosystems affected by the facility, whether directly by physical intrusion or indirectly by vehicular emissions into the air or water, drainage/erosion effects, etc., must be identified, classified, and measured. Methods for this activity are described elsewhere [4]. However, a general *land use and ecosystem inventory* must be made. For small projects, actual on-site surveys are best. For larger projects covering many miles, especially in undeveloped areas, aerial photos, land-use overlays, and topographic maps decrease the number of man-hours required for field surveys. However, where these aids are employed, selected ground-collected data must be obtained to verify accuracy and interpretations, and to catalogue local effects due to the *construction* and/or the *physical presence* of the proposed facility.

In practice, proposed routes are transferred to an aerial photograph or to a topographic map. The ecosystem inventory may be made directly by aerial photo interpretation or in conjunction with selected ground data.

Direct Energy Losses, Per Ecosystem Type

Direct energy loss is defined as that energy which would have been fixed by photosynthetic plants had the natural ecosystem not been altered or removed by the construction or presence of the facility. The losses are cumulative with time, in that the system would have continuously fixed this energy had it not been removed. These losses will have indirect effects on the stability of the system. The losses must be evaluated in light of *total energy presently fixed by the system.*

> Tabulate the total area of each ecosystem type for each alternate. Multiply these values by appropriate Gross Productivity Factor (Kcal/m^2/yr) found in Table 1 (Primary Production). The total direct energy loss is the sum of losses by each system component for each alternate. At this point some preliminary tradeoffs may be made if it is determined that a significant amount of a particular ecosystem type will be removed by one alternate as compared to another. Alternate routes may be compared on the basis of *total direct energy losses* for each proposed route, regardless of ecosystem type.

Summary

Depending on the level of energy impact analysis to be made, then, some combination of the following calculations will be listed:

1. The total land area removed (per facility alternate or average)
2. The area removed by ecosystem type (by facility alternate)
3. The total direct energy loss in Kcal/year (for each alternate, or average)

4. The total direct energy loss by each ecosystem type in Kcal/ year for each alternate
5. The amounts of natural resources consumed for each alternate
6. The indirect energy cost of construction material processing
7. The energy cost of newly generated traffic, per unit time, by alternate
8. The energy cost generated by facility maintenance
9. Calculation of other factors peculiar to the facility (e.g., deicing salts, pesticides).

In addition, quantities of emissions produced, in pounds per unit time for each alternate, would be calculated. Direct relationships between quantities of emissions and energy losses in ecosystems have not yet, however, been developed for inclusion in this numerical analysis.

EVALUATION AND COMPARISON OF ENVIRONMENTAL IMPACT OF ALTERNATES

Having summarized the individual parameters for each alternate, a first-cut evaluation of the environmental impact of each alternate may be made.

1. An evaluation of the impact of the total land and individual ecosystem types removed cannot be made based solely on absolute values. These figures must be evaluated in relation to the total area available, but more important in relation to each *ecosystem type* present. For example:
    - An alternate route may remove a significant amount of a unique ecosystem type.
    - Another may remove a smaller total area, but cause the loss of an entire ecosystem type.
    - Two or more alternates may remove exactly the same amount.
2. The direct energy losses by ecosystem type allows a more detailed evaluation of the impact of the facility on the dynamics of the system. A possible indication of the degree of impact can be found by:
    - Comparing *absolute energy losses* by ecosystem type for each alternate.
    - Determining whether a change in the *ecological trophic structure* of the system will occur due to loss of this energy. Will the loss of energy decrease the probability of survival for the organisms in the various trophic levels? The

ecosystem type, the number of trophic levels, and the energy transfer between trophic levels will vary for each facility.

3. The amount of natural resources consumed in the construction of each alternate can be compared in absolute terms in relation to known reserves and national priorities.
4. Indirect energy costs to produce materials used in construction should be evaluated in light of natural energy priorities. Until now the energy drain due to facility construction has been totally overlooked. This is especially significant when viewed on the national level, although it may be used on the local and regional levels.
5. Energy costs due to newly generated traffic and that which would normally use the facility is one of the easiest parameters to calculate since all transportation planning includes estimates of vehicle trips and newly generated traffic. This energy cost should be considered in relation to existing facilities and the proposed project. This factor forms a significant portion of the energy budget of the system.
6. The environmental cost of gaseous emissions can be looked at both from an ecological and economic point of view. Ecologically, they decrease the rate of energy fixation by inhibiting the photosynthetic mechanism. In addition, they may also have direct deleterious effects on the higher organisms present. Emission levels should be considered in conjunction with local meteorological conditions and the threshold levels exhibited by organisms in the area.
7. The cost of maintaining a facility should be reviewed from an energy standpoint. Such factors as electrical energy for lighting, fuel for maintenance vehicles, and repair of the facility should be taken into consideration early in the planning procedure. These are recurring energy costs which must be taken in relation to local, regional and national priorities.

Conclusion

A method for evaluating the effects of environmental impacting factors on environmental elements has been outlined. This method will permit a more scientific approach to the analysis of environmental impacts. Its application, at present, is related only to *ecological* issues. The method can be applied to the analysis of the ecological impact of all types of activities and, therefore, is pertinent to transportation facilities.

The "energy theory" or "bio-energetics" is based on analysis of the *amount* of energy which is required by plants or animals or ecosystems or subsystems, to permit their growth, or stability, or even decline, to continue. By measuring the amount of energy required by each species in the ecosystem, an assessment of the impact of a potential energy loss due to a transportation facility may be objectively made with respect to the effect on the life cycle being affected. In this manner, threshold criteria may be identified for each project's impact as a function of its location and type of environmental system.

In addition to these life-cycle criteria, it is expected that this energy theory may be of utility in the more fundamental issue of energy conservation at the State or National level. This approach will permit an assessment of the *total* energy requirements for the implementation of transportation projects. This will include the energy resources used in the form of *materials* as well as the fuels necessary for the operation of the transportation facilities themselves. Alternate transportation investments, when analyzed in this energy context, may then be evaluated with respect to the needs of energy conservation policies.

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