Title
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Publication Date
2004-10-01

CONCEPTUAL AND METHODOLOGICAL ISSUES IN LIFECYCLE ANALYSES OF TRANSPORTATION FUELS

UCD-ITS-RR-04-45

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prepared for:
The U. S. Environmental Protection Agency Office of Transportation and Air Quality

October 2004

INTRODUCTION

Human activities associated with the production and use of energy and materials can pollute the air and water. Since the late 1960s concern about regional and local air pollution has led to the adoption of environmental laws and regulations regarding major polluting human activities, such as fuel use for transportation or electricity production. More recently, concern about the impact of human activities on global climate has led to discussions about ways to reduce emissions of the so-called "greenhouse gases" that affect global climate.

In the United States and worldwide, the transportation sector is one of the largest sources of urban air pollutants and greenhouse-gases (GHGs). As a result, policy makers and analysts often evaluate the impact of transportation policies on urban air quality and on global climate. The tools available for evaluating impacts on urban air quality (emission-factor models, travel models, and air-quality models) are reasonably well developed, but some of the tools for evaluating impacts on global climate (namely, lifecycle emissions models) are rudimentary and incomplete. This paper discusses some of the methodological and data issues pertinent to using lifecycle analysis (LCA) to evaluate the impacts of transportation on global climate.

Current practice in LCA

An LCA model represents the energy use and environmental impacts of a set of production and consumption activities linked to the use of a particular commodity. Thus, in the case of transportation fuels and technologies, an LCA captures more than just emissions associated with the burning of fuel by vehicles: it accounts for emissions associated with making the fuel and vehicles, distributing fuels and vehicles, and so on. In an analysis of the impacts of transportation on global climate it is important to account for all emission sources in a lifecycle because -- unlike in the analysis of the impacts on urban air quality[1]-- the effect of a pollutant on global climate generally is independent of the location and the timing of the emission[2]. For this reason, analysts

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[1] In an analysis of urban air quality, only the emissions that occur within a specified period of time within the air basin of interest matter.

[2] This is true at least for CO2, N2O, and CH4, which have long lifetimes and are mixed over large scales. It may not be true for PM and ozone, which have shorter lifetimes and are mixed over regional scales.

have used LCA rather than just estimates of end-use emissions to evaluate the effect on energy use and global climate of alternative transportation fuels and technologies.

Brief historical background. Current LCAs of transportation and climate change can be traced back to "net energy" analyses done in the late 1970s and early 1980s in response to the energy crises of the 1970s, which had motivated a search for alternatives to petroleum. These were relatively straightforward, generic, partial "engineering" analyses of the amount of energy required to produce and distribute energy feedstocks and finished fuels. Their objective was to compare alternatives to conventional gasoline and diesel fuel according to total fuelcycle use of energy, fossil fuels, or petroleum.

In the late 1980s, analysts, policy makers, and the public began to worry that burning coal, oil, and gas would affect global climate. Interest in alternative transportation fuels, which had subsided on account of low oil prices in the mid 1980s, was renewed. Motivated now by global (and local) environmental concerns, engineers again analyzed alternative transportation fuelcycles. Unsurprisingly, they adopted the methods of their "net-energy" engineering predecessors, except that they took the additional step of estimating net CO_2 emissions, based on the carbon content of fuels. By the early 1990s analysts had added other GHGs (methane and nitrous oxide) weighted by their "Global Warming Potential" (GWP) to come up with fuelcycle CO_2-equivalent emissions for alternative transportation fuels. Today, most LCAs of transportation and global climate are not appreciably different in method from the analyses done in the early 1990s. And although different analysts have made different assumptions and used slightly different methods, and as a result have come up with different answers, few have questioned the validity of the general method that has been handed down to them.

The problem with the pedigree. LCAs of transportation and climate are *much* broader than the net-energy analyses from which they were derived, and hence have all of the shortcomings of net-energy analyses *plus* many more. If the original net-energy analyses of the 1970s and 80s could be criticized for failing to include economic variables, on the grounds that any alternative-energy policy would affect prices and hence uses of all major sources of energy, then the lifecycle GHG analyses they spawned can be criticized on the same grounds, but even more severely, because in the

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case of lifecycle GHG analyses we care about any economic effect anywhere in the world, whereas in the case of net-energy analysis we cared about economic effects only in the country of interest. Beyond this, lifecycle GHG analysis encompasses additional areas of data (such as emission factors) and additional systems (such as the global climate) which introduce considerable additional uncertainty.

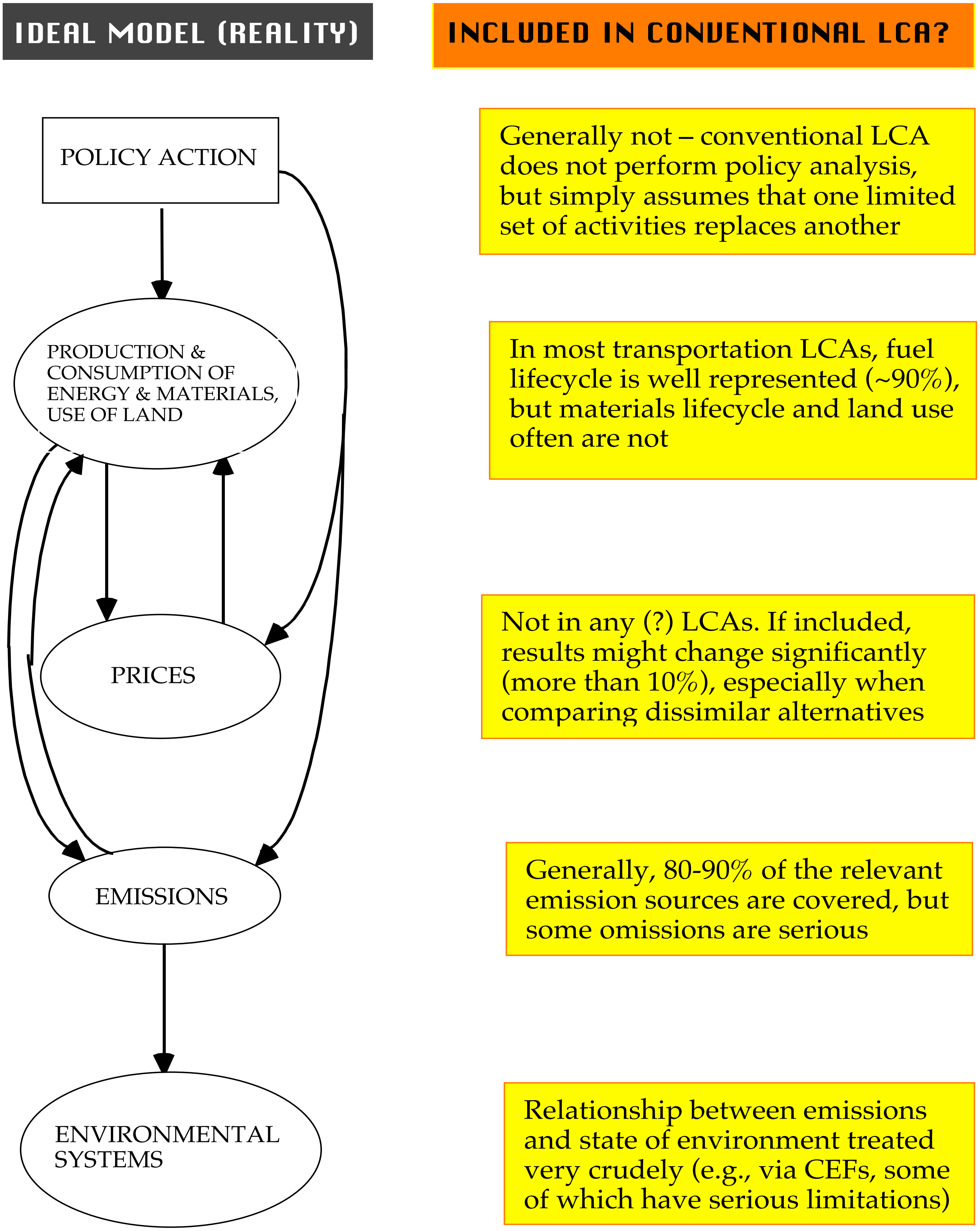
The upshot is that LCAs of transportation and climate are *not* built on a carefully derived, broad, theoretically solid foundation, but rather are an ad-hoc extension of a method -- net-energy analysis -- that was itself too incomplete and theoretically ungrounded to be valid on its own terms and which could not reasonably be extended to the considerably broader and more complex problem of global climate change.

COMPARISON OF CURRENT PRACTICE WITH THE IDEAL

Indeed, when we begin to examine the development and application of lifecycle models for transportation we find right away that it is not even clear what precise questions the models are supposed to answer. This turns out to be a serious flaw, because if we don't know what question a model is meant to answer, we cannot comprehend the answers (outputs) the model provides. In the case of LCAs of transportation and global climate, we are forced often to infer a question from the nature of the outputs and the methods used. What we find, generally, is an unrealistic and irrelevant research question and a limited modeling method.

The strengths of weaknesses of current LCAs applied in transportation can be seen best by comparing current practice with an ideal model. An ideal model, of course, would replicate reality. In this major section, I first outline an ideal LCA model of reality, and then compare actual conventional LCA with this ideal.

Figure 1 shows a conceptual flow chart of an ideal model, one which replicates reality. The ideal, shown on the left side of Figure 1, comprises several components, in boxes, with arrows showing relationships between components. Across from each component, on the right side, is a yellow box that discusses whether and how the component is treated in conventional LCA. I begin by discussing the ideal model.



INCLUDED IN CONVENTIONAL LCA?

Generally not – conventional LCA does not perform policy analysis, but simply assumes that one limited set of activities replaces another

In most transportation LCAs, fuel lifecycle is well represented (~90%), but materials lifecycle and land use often are not

Not in any (?) LCAs. If included, results might change significantly (more than 10%), especially when comparing dissimilar alternatives

Generally, 80-90% of the relevant emission sources are covered, but some omissions are serious

Relationship between emissions and state of environment treated very crudely (e.g., via CEFs, some of which have serious limitations)

Figure 1. Ideal versus conventional LCA

An ideal model of LCA of transportation and climate change

In principle, LCAs of transportation and climate change are meant to help us understand the impact on global climate of some proposed transportation action. Let us call the proposed action to be evaluated a "policy," and refer generally to the impacts of the policy on "environmental systems." Hence, in Figure 1, the model starts with the specification of a policy, and ends with the impacts on environmental systems. In between are a series of steps that constitute the conceptual components of our model of reality.

In reviewing these components, it is easiest to work backwards from the output of interest, the impact on environmental systems. The state of an environmental system – the ultimate output of interest -- is determined by the magnitude and quantity of emissions and by other environmental variables. Hence, in Figure 1, an "emissions" component is shown affecting the "environmental systems" output component. Emissions, in turn, are related to the production and consumption of energy and materials and the use of land (PCEM); hence, Figure 1 shows an arrow from the PCEM box to the emissions box. But emissions also may be affected directly by policy measures; this is indicated by the arrow directly from the policy box to the emissions box.

Thus far the main aspects of our model of reality is that changes in PCEM result in changes in emissions which result in changes in environmental systems. This much generally appears in conventional LCA. But the next and critical question is: what affects changes in PCEM? Here the ideal model has an important component that as we shall see is missing from conventional LCAs of transportation. Changes in PCEM can be related directly to policy, which is what most conventional LCAs assume, *implicitly* and which is shown by the arrow from the policy box to the PCEM box. But changes in PCEM also are related to changes in prices of major goods and services throughout the global economy. Prices, in turn, are affected directly by policies, but also by – and here is the nub – indirectly by changes in PCEM. There is thus a circular feedback between changes in PCEM, changes in prices, and further changes in PCEM.

Our conclusion, then, is that economic systems, whose states are determined partly by prices, are an inextricable part of the real world. As a result, prices are a necessary part of an ideal model of the impact of policy on climate change.

Unfortunately, conventional LCAs of transportation and climate change do not consider prices or other aspects of economic systems. This omission introduces an error of unknown but potentially large magnitude, and thereby may render the results of conventional LCAs meaningless.

Comparing conventional LCAs of transportation and climate change with the ideal model: policy

Conventional LCAs of transportation and climate change typically do not analyze a specific policy. Indeed, conventional LCAs typically do not even posit a specific question for analysis. The implicit questions of conventional LCA must be inferred from the conclusory statements and the methods of analysis. In transportation, the *conclusory statements* of lifecycle analysis typically are of the sort: "the use of fuel F in light-duty vehicles has X% more [or less] emissions of CO_2-equivalent GHG emissions per mile than does the use of gasoline in light-duty vehicles". The *method of analysis* usually is a limited input-output representation of energy use and emissions for a relatively small number of activities linked together to make a lifecycle, with no parameters for policies or the function of markets. Recalling that CO_2-equivalent emissions (which typically are part of the conclusory statements, as mentioned above) are equal to emissions of CO_2 plus equivalency-weighted emissions of non-CO2 gases, where the equivalency weighting usually is done with respect to temperature change over a 100-year time period, we then can *infer* that the question being addressed by most LCAs of GHG emissions in transportation is something like:

> "What would happen to climate forcing over the next 100 years if we simply replaced the set of activities that we have defined to be the 'gasoline lifecycle' with the set of activities that we have defined to be the 'fuel *F* lifecycle,' with no other changes occurring in the world"?

The problem here is that this question is irrelevant, *because no action that anyone can take in the real world will have the net effect of just replacing the narrowly defined set of 'gasoline activities with the narrowly defined set of 'fuel-F activities'*. Any action that involves fuel *F* – *any* action – will have complex effects on production and consumption activities throughout the world, via global political and economic linkages. These effects *will* occur, and a priori cannot be dismissed as insignificant. To omit them, therefore, is to introduce into the analysis an error of unknown sign and magnitude.

To recap, in the real world one evaluates specific policies, but conventional LCAs do not evaluate specific policies, they evaluate implicit, unrealistic questions. As a consequence, it is difficult if not impossible to relate the results of conventional LCAs to any actual policy actions we might be considering.

Now, one cannot conceive of any *potential* use of the results of an LCA apart from the evaluation of policy. And the details of the specification of the policy are important because different policies will have different effects on climate. For example, considering the case of ethanol from corn, a policy to increase (or eliminate) the ethanol subsidy will have a different impact on climate than will a policy to mandate ethanol vehicles, mainly because different policies affect people, prices, and choices differently. One thus cannot make heads or tails of an analysis that not only is unrelated to any particular policy, but, what's worse, does not even have any important policy relevant variables, such as price, supply, or other market parameters. In order to analyze the impacts of a particular policy, or indeed of any conceivable policy, one must, include all of the variables affected directly by policy. Many of these are economic variables, which are conspicuously absent from conventional transportation LCAs.

A related deficiency of conventional LCA is the failure to specify clearly the counterfactual, or alternative world, with which a specific policy (say, a specific policy regarding ethanol) is being compared. It is conceptually impossible to evaluate a fuel such as ethanol "by itself;" rather we must estimate the difference between doing one thing rather than another. These differences between alternative worlds are a function of the initial conditions in each world, the initial perturbations (or changes), and dynamic economic, political, social, and physical forces. Yet no transportation fuelcycle study, old or new, has any sort of serviceably modeled counterfactual, or alternative world -- most likely because such a model requires something like general economic equilibrium analysis, at the least, and fuelcycle analysts are not familiar with general equilibrium models.

Comparing conventional LCAs of transportation and climate change with the ideal model: production and consumption of energy and materials, and use of land (PCEM).

Although virtually all LCAs of transportation and climate have focused intensively on the energy and materials part of PCEM, and data and methods of analysis in this area have improved over the past 15 years, there remain serious omissions and oversimplifications, which by themselves undermine any claims of definitive knowledge of the effects of transportation policies on climate.

Perhaps most seriously, many recent studies have ignored energy and materials associated with building and maintaining fuel production and distribution infrastructure, transportation equipment, farm equipment, and so on, even though some analyses indicate that such energy and materials usage *might* be a non-trivial fraction of total fuelcycle energy and material usage. For example, my own recent analysis suggests that the simple, first-order GHG emissions associated with building and servicing pipelines, ships, trucks, and tractors -- but not fuel-production facilities -- might be about 3% of the total, simple, first-order GHG emissions in the corn/ethanol fuelcycle. Whether or not these are included can make a difference of two to three absolute percentage points in the comparison of ethanol with gasoline. In addition, a few studies indicate that emissions associated with the fuel-production facilities might be of the same order of magnitude, although there is much uncertainty. Thus, all told, emissions associated with construction and maintenance of facilities might be on the order of 5% of fuelcycle GHG emissions, and shift the standing of ethanol, for example, relative to gasoline, by as much as five percentage points (although this appears to be a maximum, and 3% might be more likely).

The story with energy and materials does not end here. There are many sources of primary, basic data on the energy intensity of various feedstock production and transport processes (e.g., oil recovery, coal mining, natural gas transport, and petroleum shipments) yet no analysis makes use of all of them, and many analyses make use of few or none of them. On the basis of my own work, and the work of others, I surmise that the difference between using primary data in an appropriately detailed input/output flow model, and using literature-review estimates in a more aggregated approach, can amount to a percent or two of simple, first-order, fuelcycle GHG emissions.

More uncertain, and more important, are estimates of the energy intensity of fuel production (e.g., petroleum refining, ethanol production) and the energy efficiency of motor vehicles. Most analysts acknowledge the latter, and even check the sensitivity of their results to assumptions regarding the relative efficiency of motor vehicles. Many analysts, too, are aware of the importance of assumptions regarding the energy intensity of, say, corn-to-ethanol production. But even though there are plenty of analyses and models of, for example, refinery input and output and refinery energy usage, under different economic scenarios, no recent transportation LCA, as far as I know, uses such models, or even the results of the such models run specifically for fuelcycle policy evaluation. This weakness may again have a nontrivial impact on the results. For example, my analysis suggests that uncertainty as regards refinery energy production is at least three absolute percentage points in the fuelcycle analysis.

Finally, but of potentially great quantitative significance, conventional transportation LC models ignore (or treat too simply) changes in land use related to the establishment of biomass grown to make biofuels. The replacement of native vegetation with biofuel feedstocks and the subsequent cultivation of the biomass can significantly change the amount of carbon stored in biomass and soils, and thereby significantly change the amount of CO_2 removed from or emitted to the atmosphere compared with the no-policy alternative. An ideal representation of land-use changes would involve an integrated model of land-use characteristics, land productivity, and commodity prices, constraints on use of land, and other factors. To my knowledge no transportation LCA embodies such a model. My own relatively simple but conceptually comprehensive treatment of the impact of land-use changes suggests that *a proper treatment of land-use changes could change CO_2-equivalent emissions from transportation lifecycles by ten or more percentage points in some cases.*

Comparing conventional LCAs of transportation and climate change with the ideal model: prices

All energy and environmental policies affect prices. Changes in prices affect consumption, and hence output. Changes in consumption and output change emissions. Price effects are ubiquitous.

Research done by the U. S. Department of Energy (DOE) and Oak Ridge National Laboratory indicate which kinds of price effects are likely to be important. First and foremost, perhaps, are those that involve the price of oil. The substitution of a non-petroleum fuel for gasoline probably will reduce the price of crude oil. A reduction in the world price of oil will stimulate increased consumption of petroleum products, for *all* end uses, *worldwide*. Analyses by DOE have shown that the additional worldwide oil consumption induced by the lower prices is quite large compared to the initial substitution in the U. S. transportation sector.

Whatever the exact magnitude of these price effects, they are potentially important enough that they ought to be taken seriously in an evaluation of the impact of transportation policies on climate. There is no way to escape this conclusion. We cannot dismiss the effects because they occur outside of the U. S., or outside of the transportation sector, because in an analysis of global warming, we care about all emissions, everywhere. We cannot dismiss price effects on the grounds that a policy will not really affect price, because in principle even the smallest change has a nonzero-probability of leading to a nonzero affect on price. (In any event, if the price effects really are so small, then the policy must be so unimportant or ineffective as to have no affect on climate worth worrying about anyway.) And we certainly cannot argue that all such price effects are likely to be substantially "similar" for all policies, and hence of no importance in a *comparison* of alternatives, because this clearly is not the case: policies related to LPG, which can be made from crude oil, may have an effect different from policies related to natural gas, which is a substitute for oil, and different again from policies related to new fuels derived from biomass, which has little to do with oil.

The economic modelers will be quick to remind us that the web is even more complex. For example, a large price subsidy, such as is enjoyed by corn ethanol, ultimately causes a deadweight loss of social welfare, on account of output being suppressed below optimal levels due to the inefficient use of [tax] resources. This loss of output probably is associated ultimately with lower greenhouse gas (GHG) emissions. Thus, in this case, a subsidy policy may have countervailing effects: on the one hand, there will be an increase in GHG emissions caused by increased use of petroleum due to the lower price of oil due to the substitution of ethanol, but on the other, there will be a decrease in GHG emissions due to the reduction in output caused by the economic deadweight loss from the subsidy. By contrast, an R & D policy that succeeds in bringing to market a new, low-cost fuel, will, on account of the more efficient use of energy resources, unambiguously improve social welfare.

It is easy to go on. For example, economists have pointed out that price effects might eliminate and even reverse the environmental benefits of EVs as estimated in simple fuelcycle analyses: if EVs are mandated, but are really quite costly, the resultant increase in the cost of vehicles will cause car buyers to delay purchase of new, clean, efficient vehicles -- to the possible detriment of the local and global environment.

As a final example, changes in prices are an important determinant of equilibrium uses of different types of land. The extent to which a new biofuel program displaces native vegetation, existing agricultural production, unproductive set-aside land, or something else, matters a great deal in analyses of lifecycle CO_2-equivalent emissions, because of the different carbon-storage characteristics of these ecosystems. In the real world, this displacement ultimately is determined strongly by prices of land and commodities derived from land.

Prices in the context of "joint production." Nearly as important are price effects in cases of joint production. It is well known that corn-ethanol plants, for example, produce goods other than ethanol. A policy promoting ethanol therefore is likely to result in more output of these other goods, as well as more production of ethanol. What is the impact on climate of the production of the other goods? The only way to answer this question is to model the market for the other goods to see, in the final equilibrium, what changes in consumption and production occur in the world with the ethanol policy. If the production of the other goods is large compared with the production of ethanol, then we reasonably may expect that the effect on climate of the production of the other goods is not trivial compared to the "first order" effect of using or making ethanol. No transportation LCA done to date has used a full global equilibrium model to determine the impact of coproducts on world markets.

The same issue of joint production arises in petroleum refineries. But even though these sorts of effects are well known and widely studied, no engineering fuelcycle analyst has done, or incorporated, an appropriate economic analysis of these effects, in any fuelcycle. Most have used so-called "apportioning" or "co-product displacement" schemes, which bear no real formal relation to the general equilibrium analysis of alternative policies.

Minor effects of prices. Finally, there are a practically infinite number of what are likely to be relatively minor effects of price changes. For example, different fuelcycles use different amounts of steel, and hence have different effects on the price and thereby the use of steel in other sectors. The same can be said of any material, or of any process fuel, such as coal used to generate electricity used anywhere in a fuelcycle. It might be reasonable to presume that in these cases the associated differences in emissions of GHGs are a second-order effect on a second-order process (e.g., that the price effect of using steel use is no more than 10% of the "first-order" or direct effect of using steel, which itself probably is less than 10% of fuelcycle emissions), and hence relatively small. On the other hand, we might be surprised, and sometimes many individually quite small effects add up (rather than cancel each other). For these reasons, it would be wise for fuelcycle analysts to investigate a few classes of these apparently minor price effects. (It is possible that some input-output [I/O]energy analysts have done this already, although most if not at all I/O studies used in LCA assume that prices are fixed.)

Comparing conventional LCAs of transportation and climate change with the ideal model: emissions and the climate environmental systems

The ultimate objective of LCAs of GHG emissions in transportation is to determine the effect of a particular policy on global climate. This requires a number of steps beyond the macro-economic modeling of commodity production and consumption discussed above: identification of gases that are emitted from fuelcycles and can affect climate directly or indirectly; identification of sources of emissions of the identified direct and indirect GHGs; estimation of emission factors for the identified sources; modeling the effect of "indirect" GHGs on "direct" GHGs; and representation of the effect of direct GHGs on climate. None of these steps are as well characterized as one might like, and as a result one might reasonably have little confidence in the soundness of the overall representation of the climatic effect of a particular policy.

i). Identification of emitted GHGs. The more researchers study climate, the more they learn about the gases that affect climate. As a result, the list of identified GHGs has grown considerably since early fuelcycle analyses, and can be expected to continue to grow.

The authors of the early studies of net fuelcycle CO_2 emissions were well aware that other gases, emitted at various stages in fuelcycles, affect climate. Shortly after the early fuelcycle CO_2 fuelcycle studies were done, other fuelcycle analysts began to include other GHGs, first methane (CH_4), then nitrous oxide (N_2O). These three are referred to as "direct" GHGs, because they affect climate directly, as themselves, rather than indirectly via an effect on *other* gases. Ozone (O_3) also affects climate directly, but is not emitted as such from fuelcycles; rather, its concentration is influenced by other gases that *are* emitted from fuelcycles: nitrogen oxides (NO_X), carbon monoxide (CO), nonmethane organic compounds (NMOCs), hydrogen (H_2), and others. By 1990 NO_x, CO, and NMOCs had been identified as "indirect" GHGs because of their effects on ozone. In 1993, I included them in my first LCA model, weighting them by the IPCC's "global warming potential" (GWP) factors.

More recently, aerosols have been identified as direct and indirect GHGs, and work is proceeding to identify which kinds or components of aerosols affect climate most. The most recent research indicates that sulfate aerosols tend to cause global cooling, but that the black-carbon (BC) component of aerosols has a very strong global warming effect. [The latest version of my Lifecycle Emissions Model (LEM) includes BC and sulfate from particulate matter (PM)] The list of GHGs undoubtedly will continue to grow as researchers identify more GHGs, direct and indirect.

ii) Identification of sources of GHGs. Not surprisingly, the more we look for sources of GHGs, the more we find. Sometimes the newly identified or quantified sources are surprisingly significant. For example, in the case of the soy/biodiesel lifecycle, emissions of N_2O from nitrogen fixation by soybeans may be enormous – on a par with CO_2 emissions from fuel combustion. In fact, including these emissions in an LCA of biodiesel may result in biodiesel emitting considerably *more* CO_2 –equivalent fuelcycle emissions than petroleum diesel, rather than considerably less as is estimated in conventional LCAs. Although this source has been identified and even quantified in IPCC emission-inventory guidelines for years, it has not been included in any biodiesel LCAs performed to date (other than my own).

iii) Estimation of emission factors. In many cases, data on GHG emissions are lacking or of poor quality. For example, even if one identifies N_2O emissions from nitrogen fixation (mentioned above), one still is faced with considerable uncertainty regarding the appropriate emission factor for this source.

Because CH_4 emissions typically are multiplied by a CEF of on the order of 10 to 30, and N_2O emissions by a factor of 250 to 350, a doubling or having of assumed emissions of these gases can have a large impact on the calculated CO_2-equivalent total. Unfortunately, in many cases there are so few real emissions data that we are happy if we have reason to believe that we know emissions to within a factor of two. For example, nitrous oxide emissions from vehicles might contribute as little as 3% or as much as 10% of simple, first-order fuelcycle emissions. (Only a year or so ago, this range might have been about 2% to 15% -- so we do make progress!) Moreover, virtually all analysts assume that all vehicles emit the same amount of N2O, even though in many cases this assumption probably will prove to be appreciably in error.

Another often poorly characterized source of emissions is changes in carbon sequestration in biomass and soils as a result of changes in land use related to the establishment of biomass used as a feedstock for biofuels. Generic data on the carbon contents of soils and plants are available, but there can be much variation about these generic means from site to site. The uncertainty inherent in carbon-storage factors related to land use can change lifecycle CO_2-equivalent emissions by several percentage points.

Finally, there has been less research into emission factors for newly identified (but potentially important) GHGs, such as black carbon (BC). First-cut comprehensive emission-factor databases and emissions inventories for BC have been published only recently. In many cases, the uncertainty in BC emission-factors is 50% or more. Given the possibly quite large CO_2-equivalency factor for BC (on a mass basis, it may be well over 1000), this degree of uncertainty in emission-factor estimates translates directly into a large uncertainty in the effect of BC emissions on climate.

iv) The effects of indirect GHGs on direct GHGs. The difficulties with emission factors may be serious, but at least they are familiar to most fuelcycle modelers. By contrast, this fourth step -- modeling the environmental flows and fates of the emissions – is unfamiliar to most fuelcycle modelers. The problem is not that nothing is known about these flows and fates, for indeed quite bit is known; rather, the problem is that nobody seems to have the complete, integrated picture of all of the interactions that ultimately affect climate.

The complexity and possible importance of these environmental interactions are nicely illustrated by the nitrogen cycle, one of the more complex of the pollutant/environment/climate pathways. Virtually all fuelcycles produce very large amounts of NO_x. Some biomass fuelcycles -- particularly the corn/ethanol cycle -- also produce large amounts of inorganic nitrate. These nitrogen compounds undergo a number of transformations, in a variety of media, and have several different kinds of effects on climate.

In sufficiently hot engines, atmospheric nitrogen is burned to NO. Emitted back to the atmosphere, NO is oxidized to NO_2 and then photolyzed back to NO, in a complex series of reactions that involve NMOCs, CO, and OH-, and CH_4, and affect the ozone (O_3) equilibrium. In the upper portions of the troposphere, O_3 is direct, radiation-absorbing greenhouse gas. This is the first climatic effect of nitrogen in the cycle as I have arbitrarily begun it.

NO_2 eventually oxidizes further to nitrate, and then is converted to nitric acid, which in the presence of ammonia (NH_3) is neutralized to ammonium nitrate. Ammonium nitrate is an aerosol; in general, aerosols affect climate by scattering and absorbing solar radiation and changing the dynamics of cloud formation. On balance, the effects of nitrate aerosols might actually lead to global cooling.

Ambient nitrate, however, precipitates from the atmosphere, usually dissolved in water. This nitrogen deposition leads to a new cycle of climatic effects. Acidic deposition can harm plants, and thereby reduce biotic sequestration of CO_2. However, the nitrates also are nitrogen fertilizers, which stimulate plant growth, and hence sequestration of atmospheric CO_2, in biomes that are nitrogen limited. Only a few years ago, researchers demonstrated that nitrogen fertilization explained a then-“missing” CO_2 sink. They also have indicated that carbon sequestration stimulated by nitrogen deposition greatly exceeds carbon oxidation caused by acid-nitrogen deposition.

The cycle continues. Some of the nitrate denitrifies to N_2 or N_2O, the latter being an extremely potent “greenhouse” gas. A conversion to N_2O of only a few percent of the N can have a significant impact on CO_2-equivalent fuelcycle emissions.

Some of the nitrate gets carried to lakes and oceans, and eventually is sequestered as inorganic nitrogen. In oceans, the nitrogen dynamics are quite complex, and apparently not completely understood, but involve nitrification, denitrification, N_2O production, and nitrogen fertilization.

Nitrogen fertilizer that becomes organic nitrogen in plants eventually can become organic nitrogen in animals. Some of this organic nitrogen will be excreted as urea, uric acid, or ammonia, waste products which continue down further branches of the nitrogen cycle, generally with effects on climate and human health. Ammonia, for example, is a precursor to the aerosol ammonium nitrate.

Might any of this make a difference? My preliminary calculations indicate that the climatic effect of changes to the nitrogen cycle may be on the order of 3-5% of fuelcycle CO_2-equivalent emissions of CO_2, CH_4, and N_2O. This 3-5% excludes the impact of N_2O from the use of fertilizer, which itself is roughly another 3-4% in the some fuelcycles.

Given the large nitrogen flows in some biomass fuelcycles, and the possibility that the nitrogen cycle will have a total effect equivalent to 5-10% of fuelcycle emissions, it is evident that a complete analysis of the climate impacts of energy policies ought to include a total nitrogen-cycle balance, with all of the relevant fates (especially nitrogen fertilization, and denitrification to N_2O), fully specified. My current model traces most of these effects of nitrogen but in many cases only crudely and with poor data.

By comparison, the pathways for CH_4, CO, NMOCs, and N_2O are at least a bit simpler (the N_2O cycle appears to be quite simple). However, the aerosol (PM) pathways are quite complex and, as we shall see momentarily, potentially quite important in LCAs of CO_2-equivalent GHG emissions.

v) The effect of direct GHGs on climate. Once we have estimated the final, net changes in emissions of climate-relevant gases, we either can run global climate models to estimate the effect of the emissions on climate (this is most accurate but also the least convenient and the most costly), or else we can convert non-CO_2 emissions to an "equivalent" amount of CO_2, in essence using the results of simplified climate models. Most fuelcycle analysts have used the IPCC's global-warming potentials (GWPs), which tell us the grams of a gas that produce the same integrated radiative forcing, over a specified period of time, as one gram of CO_2, given a single pulse of emissions of each gas. Typically, analysts use the GWPs for a 100-year time horizon.

But as some economists, and indeed some of the original developers of GWPs themselves pointed out, the IPCC GWPs should not be used in any analysis that purports to be, or contribute to, anything like a cost-benefit evaluation. The 100-year

GWPs give radiative forcing 99 years from now the same weight as radiative forcing tomorrow, but give no weight at all to radiative forcing 101 years from now. Neither ordinary people nor cost-benefit analysts evaluate the future in this way; rather, people and analysts weigh the future against the present by discounting the future at some typically nonzero rate. Intuitively and analytically useful CEFs should incorporate a discount rate. (Again, some of the original analysts in this area also developed GWP expressions with a discount rate.)

Furthermore, because we do not care about the radiative forcing or even the mean global temperature per se, but rather about the actual physical, economic, social, and biological impacts of climate change, CEFs ideally should be estimated on the basis of equivalent *impacts*, rather than equivalent temperature change. The most natural numeraire for impacts, of course, is their dollar value[3].

Thus, if one does not run a model of climate and climate-impacts to estimate the effects of changes in emissions of "greenhouse" gases, for each policy scenario to evaluated, one should use CEFs that equilibrate on the present dollar value of the impacts of climate change. Ideally, these present-value CEFs would be derived from runs of climate-change models for generic but clearly specified policy scenarios.

Researchers have begun to develop such CEFs, and the simple ones developed so far (including some developed for the LEM) can differ from the IPCC 100-year GWPs by at least 10%. I would not be surprised if sophisticated present-value CEFs, developed with advanced climate and economic models, differed from the IPCC GWPs by 20% -- a potentially important difference.

More importantly, estimating and applying CEFs for gases for which the IPCC has not developed GWPs can have a significant effect on lifecycle CO_2-equivalent emissions. For example, recent sophisticated global modeling indicates that BC might cause a large radiative forcing, second only to that of CO_2. Applied in the context of LCAs of transportation fuels, the CO_2-equivalent of BC emissions can have startling results: for example, it can completely eliminate the energy-efficiency benefits of diesel compared to gasoline, and make diesel vehicles *worse* for climate than gasoline

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[3] In addition to these problems of incorporating an arbitrary time cutoff and defining equivalence with respect to radiative forcing rather than with respect to impacts, the IPCC GWPs have the problem of estimating equivalence for a one-time unit emission of a gas given constant concentrations of all gases, as opposed to considering a more realistic pattern of emissions changes over time.

vehicles. Few if any transportation LCA models (apart from the LEM) include BC as a GHG.

TOWARDS A MORE COMPREHENSIVE MODEL

This overview has identified major deficiencies in the development and application of conventional LCAs of transportation and climate. In this concluding section, I delineate a more comprehensive and accurate model.

If we wish the results of lifecycle analysis of transportation to be interpretable and relevant, then lifecycle models must be designed to address clear and realistic questions. In the case of lifecycle analysis comparing the energy and environmental impacts of different transportation fuels and vehicles, the questions must be of the sort: "what would happen to [some measure of energy use or emissions] if somebody did X instead of Y," where – *and here is the key* – X and Y are *specific and realistic alternative courses of actions.* These alternative courses of actions ("actions," for short) may be related to public policies, or to private-sector market decisions, or to both. Then, the lifecycle model must be able to properly trace out all of the differences – political, economic, technological -- between the world with X and the world with Y. Identifying and representing all of the differences between two worlds is far more complex than simply representing the replacement of one narrowly defined set of engineering activities with another.

As noted above, current lifecycle models do not put the questions they address clearly, and are not capable of tracing out all of the effects of clearly put questions. A major part of the problem is that there always will be *economic* differences between world X and world Y that do affect energy and emissions but that present lifecycle models do not account for.

To begin to develop a more realistic lifecycle evaluation framework, we must understand how public or private actions regarding transportation fuels might affect prices and ultimately emissions. In general, actions may affect prices directly, for example by changing tax rates, or indirectly, by affecting the supply of or demand for commodities[4] used in transportation. In an integrated and complex global economy, changes in the prices of important commodities ultimately will affect production and consumption of all commodities in all sectors throughout the world. In the final equilibrium of prices and quantities, there will be a new global pattern of production and consumption. Associated with this new pattern of production and consumption will be a new pattern of emissions of criteria pollutants and greenhouse gases. The difference between the global emissions pattern associated with the transportation action being evaluated and the global emissions pattern without the action may be said to be the "emissions impact" of the action being evaluated.

Hence, I propose that rather than ask what would happen if we replaced one very narrowly set of defined activities with another, and then use a technology lifecycle model to answer the question, we instead ask what would happen in the world were to take one realistic course of action rather than another, and then use an integrated economic and engineering model to answer the question. This juxtaposition reveals three key differences between what we current conventional approach and the expanded approach that I believe is likely to be more accurate (Table 1):

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[4] Actions may affect demand or cost functions directly, for example by mandating production or consumption, or indirectly, for example by affecting incomes and hence household consumption decisions.

Table 1. Comparison of the conventional lifecycle approach in transportation with an expanded approach

Issue	conventional approach	Expanded approach
The aim of the analysis	Evaluate impacts of replacing one limited set of "engineering" activities with another	Evaluate worldwide impacts of one realistic action compared with another
Scope of the analysis	Narrowly defined chain of material production and use activities	All major production and consumption activities globally
Method of analysis	Simplified input/output representation of technology	Input/output representation of technology with dynamic price linkages between all sectors of the economy

Ideally, then one would construct a model of the world economy, with sectoral and geographic detail where we think it is most important for evaluating energy policies (e.g., world oil production and demand; vehicle production in the U. S.; agricultural markets for crops and biomass). Within the sectors we would have detailed input/output data and emission factors for the processes now modeled in fuelcycle analyses.

One could do this either by expanding an economic/policy-evaluation model into an integrated economic/fuelcycle/climate model, suitable for the all-in-one evaluation of the impact of energy policies on climate, or by adding to an engineering fuelcycle model demand and supply functions or simple price, quantity, and elasticity parameters. Either way -- whether starting from "economic" or from "engineering-fuelcycle" models -- it is a formidable project.

The policy-manipulable inputs to such an integrated economic/engineering model might be things like projections of the cost of fuels or vehicles, taxes or subsidies on fuels and vehicles, mandates regarding the supply of certain types of vehicles or fuels, demand side restrictions or inducements, environmental constraints, demographic and macroeconomic variables, and representations of consumer preferences. The major outputs of interest might be emissions, energy use, vehicle travel, GNP, and the like. In principle, all emissions could be monetized, and a total change in social welfare estimated. If one chose not to monetize all of the outputs, then one simply would report all of the different outputs, and leave commensurability and overall evaluation for someone else. In this case, one would make compound statements of this sort: "policy-option 1 results in lower greenhouse-gas emissions than does policy-option 2, but also lower vehicle miles of travel and lower GNP".