On the Objectives of Industrial Engineering from the Perspectives of the Energy Efficiency

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Received 14 May 2014
Accepted 20 July 2014

Abstract

The focus of Industrial engineering has always been efficiency. While industrial engineering has contributed significantly to the improvement of productivity and quality of life, the objective function in the models used in industrial engineering normally measures of efficiency of products or processes. However, the efficiencies of products or services are normally indirect measures of quality of life. Therefore, this paper will illustrate some discrepancies between what we *measure* and what we *need* in some aspects of energy efficiency. In manufacturing, transportation, and services, energy efficiency has improved tremendously using the current measures in food processing, in fuel efficiency of cars and trucks, or in heating and air conditioning. However, the total energy consumption per capita in developed countries remains high. The improvement in products and processes may not be reflected in serving human needs. For example, while car fuel efficiency has improved many times in the last 100 years, commuting times become longer and longer. Commuting time is directly related to our livelihood in modern cities, as measured in some basic elements of Maslow's hierarchy of human needs. This paper intends to draw attention to the measure or objective function in optimizations through the perspectives of energy efficiency. We first gather information on improvements in energy efficiency in cars, food supply chains, and heating and air conditioning systems in commonly accepted measures. We will then contrast them with the improvements in satisfying human needs. The evidence reveals interesting food for thought for industrial engineering and for engineering and science in general. In addition, we developed an energy efficiency measure for commuting that is directly linked to our needs, demonstrated its usage with some examples, and provided ideas for future research. We hope our measure on energy efficiency in commuting would lead to new measures or objectives for industrial engineers in product design, manufacturing, transportation, process design, and city planning.

Keywords: Energy efficiency, human needs, commute, industrial engineering, energy consumption, commuting time.

1. Introduction

Industrial Engineering always focuses on efficiency, and improvements in efficiency contribute significantly to the improvement of productivity and quality of life. However, efficiency measures are often associated with products or processes, such as cars or air conditioning. Therefore, when the production capacity was scarce, the efficiency measures of products or process lined up well with the efficiency of serving human needs. However, when the production capacity is in excess or abundance, as in many parts of the developed and emerging economies, the product- or process-based efficiency measures may no longer line up well with the efficiency of serving human needs.

In this paper, we consider the energy efficiency as an example in which the product or process efficiency may not be directly linked to the efficiency of serving human needs. The rapid improvement in human lives is due in large part by the increased ability of converting stored energy into useful power by human beings. Before the large-scale use of stored energy, many human needs were not satisfied.

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Steam engines powered the Industrial Revolution in the 18th century. It was the internal combustion engines and the electric motor that brought more power to more places to satisfy more human needs. After about one hundred years with the newly found power, human have increased their productivity and production capacity tremendously. The increase has tipped the balance between production capacity and natural resources. Previously, natural resources were plentiful, but the scarce production capacity could not provide sufficient products and services to satisfy human needs. Today the opposite is true: the efficient and abundant production capacity in products and services leads to scarcity in natural resources. One only needs to see the smog in many cities around the world, to struggle to find drinkable water from natural sources, or to observe how far or how challenging is it to get oil to appreciate the scarcity of the natural resources.

Modern life requires a lot of energy per person. Pessimists worry that energy resources will run out, while optimists believe that the ingenuity of human beings will always find new ways to generate power to maintain the growth. However, every source of renewal energy has its challenges. In the wake of the tsunami-damaged nuclear facilities in Japan, Germany voted to shut down their nuclear power plants. Wind and solar energy have their own limitations. Drastic changes are needed to achieve higher percentages of renewable energy sources by 2050[1].

Because it is difficult to supply enough power from renewable sources, industrial engineers should focus on the energy efficiency of energy generated. If the entire world consumes as much energy per capita as the US, Canada and UAE, as the trend is moving toward, will there ever be enough renewable energy? Human beings have made great progress in the energy efficiency of products such as cars and lighting, or of processes such as heating, food production, and processing. However, energy consumption per capita in the United States does not decrease much even with significant efficiency improvement in products and services. Even with these significant efficiency improvements, globally, energy demand is estimated to increase by over 35% by 2030 and over 70% by 2050[2].

One way to reduce energy consumption without lowering the level of service to human needs is through a variety of mechanisms geared to change people's behavior: subsidies, taxes, direct feedback, campaigns, and education[2]. Another way is to introduce measures of efficiency that directly link the energy consumption with human needs. Such measures would allow people or organizations to set objectives that link the energy source to the ultimate usage. This is a rather radical notion and will surely raise new questions, arguments and discussions, which I hope this research will trigger.

2. The Energy Flow and Human Needs

Globally, the energy demand is categorized into industry, transport, building, and other categories[2]. The Energy Information Administration (EIA) presents the energy flow of the United States in Figure 1[3]. The starting points are energy sources, and the ending points are Transportation, Industrial, Residential and Commercial. The goal of transportation energy efficiency defined by the US Department of Energy is "to work with industry to develop and deploy advanced transportation technologies that reduce the nation's use of imported oil and improve air quality." The goal of residential energy efficiency is "to develop cost-effective solutions that dramatically reduce the average energy use of housing while improving comfort and quality." With these goals, the efficiency of cars, lighting, heating, and air-conditioning have been drastically improved. However, energy use has not reduced much, as will be shown later.

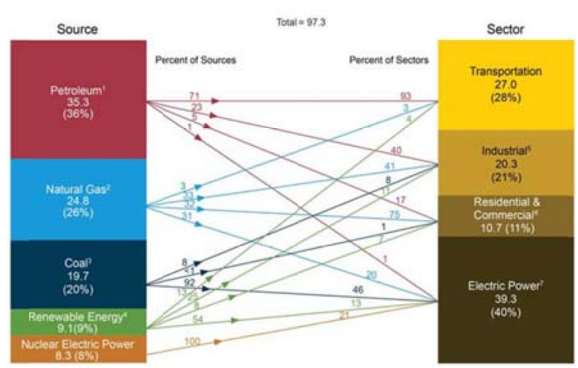

Fig. 1. EIA Primary Energy Consumption by Source and Sector, 2012.

Human needs and wants are complex. They can be short term or long term, physiological or psychological, and such needs can conflict with each other. Maslow's pyramid of human needs, proposed in 1943[4] and updated in 1970[5], is well known and has been discussed and quoted extensively. We will use elements in Maslow's pyramid as a starting point in this paper.

In Maslow's pyramid of human needs, the most basic needs are physiological, such as air, water and food. If the physiological needs are met, the need for safety emerges. In short term, the safety includes protection from danger, including anything from weather to assault. In the long term, safety includes livelihood, a means of securing the necessities of life - a job for most city dwellers. Once safety needs are met, people need belongings and love: friends, family, organizations, and social circles. The next level in the pyramid is esteem, which people need for reputation, attention, status, recognition, and a sense of achievement. Those who have achieved a high level of esteem may engage self-actualization or self-fulfillment, as do dedicated artists, athletes, educators, activists, or philanthropists.

Today, the immediate physiological needs of the middle class in developed countries and emerging economies are met by high productivity in society, which also provides excellent service to short term safety needs such as shelter from weather and assault. However, high productivity can actually have a negative impact on long term physiological needs such as health because of over eating and lack of physical activities.

Livelihood: One major factor that affects livelihood is the commute to work. Thanks in part to job specialization, many people have to commute to work, and that commute needs energy. Even biking consumes energy in the bike supply chain and in peddling. However, energy consumption in peddling is also generally good for most people in the city for long term health as long as the duration is acceptable and safe.

Currently, the most relevant measure for energy efficiency related to commute is fuel efficiency in cars. In next section, we will show that the improvement in fuel efficiency in cars has not always translated into satisfying some aspects of commuting needs.

Food: Industrialization improved energy efficiency in food production per calorie or other nutritional units, and in transportation per unit weight per unit distance. However, the increased production and transportation capacity also increased volume and distance and added many intermediate steps in processing, transport and refrigeration. Many aspects of these steps negatively impact the service to human's long-term needs, such as health. However, the increased production and transportation capacity also increased volume and distance and added many intermediate steps in processing, transport and refrigeration. Many aspects of these steps negatively impact the service to human's long term needs, such as health.

Another safety needs is shelter. Modern commercial buildings provide heating and air conditioning to protect humans from bad weather and to provide an environment conducive to higher productivity. Over the years, the building codes have helped to regulate the improvement of insulation, new lighting systems have helped to reduce energy consumption per unit of light generated, and new heating, ventilation and air conditioning rating systems have helped to improve energy efficiency with their respective measures. However, energy consumption in commercial buildings per employee and per unit space has not decreased.

In this research, we explore what efficiency measures or objective functions can directly link energy consumption and human needs in some specific areas.

3. Energy Efficiency in Cars

Engineers and scientists have made great improvements in car efficiencies. Table 1 compares the Ford Model T with the Ford Fiesta 2014 model, the closest car in size with to the Model T. In about 100 years, the fuel consumption, weight, and top speed almost doubled, respectively. Each parameter requires more energy to achieve. The total increase in efficiency, combining all three parameters, can be considered to have improved over 8 times!

Table 1. Comparison of Ford Model T and Ford Fiesta.

	Ford Model T	Ford Fiesta 2014	Approximate Improvement
L / 100 KM	11.2 - 18.1	6.0 - 8.1	~2
Weight (KG)	544	1,192	~2
Top speed	64 – 72	145	~2

Even in the last 30 years, the improvement in car fuel efficiency is still significant, thanks to microprocessors and new technologies. A comparison of the Honda Accord between 1983 and 2014 is shown in Table 2.

The overall improvement can be considered more than doubled.

Table 2. Comparison of Honda Accord: 1983 vs. 2014.

	1983	2014	Approximate Improvement
L / 100 KM	11.3	7.8	45%
Weight (KG)	955	1,614	70%
Speed	N/A	N/A	>1*

* No meaningful values can be used. However, the speed limit in 1983 was 55 miles per hour in the United States. In 2014, most highway speeds are much higher. Because of this, better acceleration, and higher horsepower of cars, the actual top speed is much higher in 2014 than in 1983.

The US EPA reports significant improvement in the fuel efficiency of production weighted passenger cars for nearly 40 years[6], shown in Figure 2.

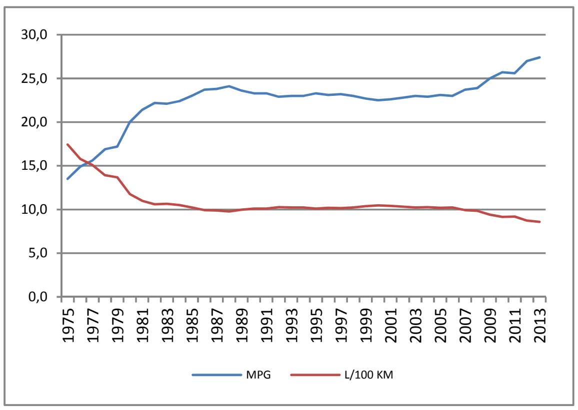

Fig. 2. Fuel efficiency improvement 1975 – 2013, USEPA 2013 Report.

Similar efficiency improvements are also achieved in light trucks and sport utility vehicles.

Most people would agree that commuting is a chore, but because it is necessary for livelihood, it is one of the most important usages of cars. USDOT conducted a national household travel survey in 2009[7], which shows that people drive instead of walking or using public transportation mostly to reduce time or increase safety. However, studies in Germany show another result: that life satisfaction decreases with increased commuting time[8]. Since commuting often occurs during rush hour, the commuting time and energy consumption should both be higher than 28% of the distance travelled. Here, the efficiency that directly links energy to human needs is time savings in commuting. Therefore, objectives for energy efficiency in commuting should be to reduce the time.

How much fuel efficiency improvement translates into improvement of commuting time in last 35 years? Figure 3 shows the commuting times based on surveys conducted by the US Census in 2009[9] and the USDOT survey[7]. In both data sets, the commuting times have become longer.

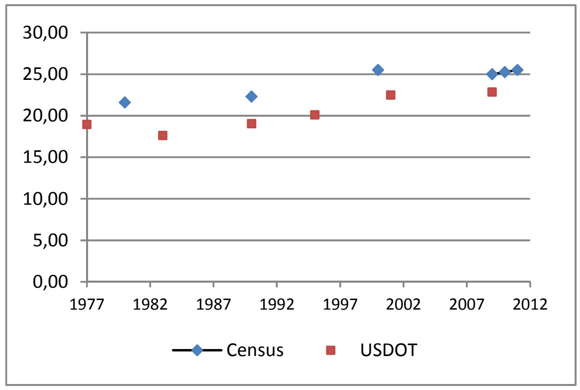

Fig. 3. Commuting time changes from 1977 – 2012.

A study based on a survey of 982 residents in Guangzhou, China[10] shows that the percentage of people who are satisfied with using private automobiles and individual transport (walking or bicycling) were 51.52% and 73.86% in 2007. The commuting times are 30.2 and 38.9 minutes. According to China's New-Urbanization Report 2012, published by the sustainable development strategy research group under the Chinese Academy of Social Sciences, the commuting time by car in Guangzhou has increased to 48 minutes. Interestingly Guangzhou won the ITDP 2011 Sustainable Transport Award.

There are many reasons for the lack of improvement in using energy to reduce commuting time as a particular human needs: urbanization, city sprawling, zoning, population increase, economic development, etc.

However, can we start to think about how to use energy to reduce commuting time? Should industrial engineers use commuting time as optimization objectives in transportation system and process design?

Ironically, one of the improvements in cars and SUVs is acceleration. However, industrial engineers know that in stop and go traffic during rush hour, the improved acceleration of some cars increases the relative speed differences in successive cars because 1) some other cars do not accelerate well and 2) some cautious drivers would not accelerate fast. Such variation leads to slower average flow. Therefore, the EPA's change in fuel efficiency measures on cars to accommodate better acceleration,, which lead to more fuel consumption and longer commuting time.

Economically, the cost of fuel has about doubled in last 10 years in many parts of the world. However, the household income in developed countries has not increased in constant dollars. This means that commuting also deprives consumers' ability to satisfy their other needs.

How have improvements in transportation affected security, another important human need in Maslow's Hierarchy? Security related to transportation can include fatality rates, injury rates, accident rates, etc. The IRTAD Annual Report 2010[11] shows that the fatality and injury rate in most of the 29 member countries has been reduced significantly from 1970 to 2009, even as more people drive greater distances. In the United States, the highway fatality rate per 100 million miles travelled decreased over 90 percent from 1921 to 2011[12]. See Figure 4. The trend in non-fatal traffic injuries in the United States has fallen 50% from 1988 to 2012[13]. The report attributes the decline rate to vehicle design, law enforcement, etc.

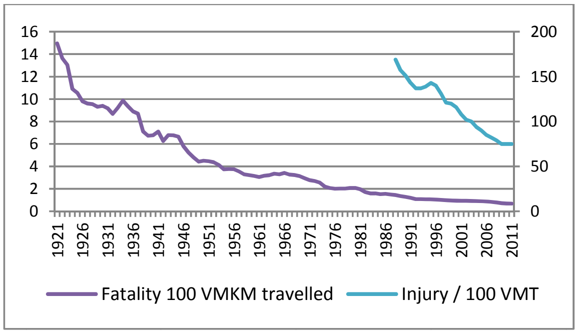

Fig. 4. Vehicle highway fatality and injury rate in 100 vehicle million KM traveled.

However, around the world, crashes on road led to over 1.3 million fatalities and 50 million injuries, of which 90% of the casualties are in low- and middle-income countries[13]. The percentages of fatalities by types of road users in different countries are shown in Figure 5.

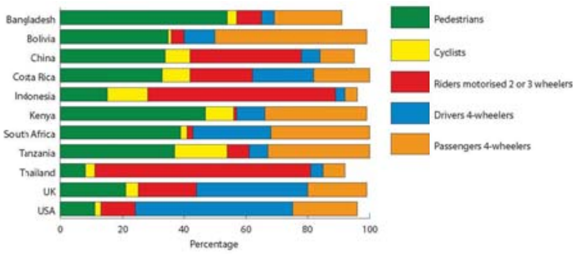

Fig. 5 Percentage of fatalities by different categories of road users.

4. Energy Efficiency in Food Supply Chain

Energy for our physiological need for food is consumed in agriculture, processing, packaging, transportation, sales, services (restaurants), and households (refrigeration, cooking). Energy use in food systems is significant compared to total energy use: 12.2% in 1997 and 14.4% in 2002 in the United States. From 1997 to 2002, even when the total energy consumption per capita is reduced by 1.8 %, the energy in the food system increased by 16%, shown in Table 4[14].

Table 3. Energy use change between 1997 and 2002.

	1997	Change by 2002
Total energy per capita	Base line	-1.8%
Total energy in food system	Base line	+16.4%
Energy in food as % of total	12.2%	14.4%

Figure 6 shows the magnitude, changes from 1997 to 2002 in energy use in different categories and changes in the annual percentage.

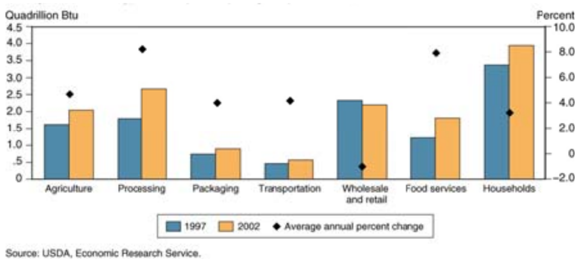

Fig. 6. US energy consumption and change by stage in the food supply chain.

The biggest increases in energy consumption have been in processing and food services. Increased consumption of processed and packaged food raises costs for transportation, storage, refrigeration, etc., and processed food and serviced food are also considered less healthy than fresh-cooked food at home. The increase in energy consumption in households might mean more cooking (better) or more refrigeration (less nutritious). Large increases in agriculture and transportation mean more consumption, which ironically is also a problem. In the US, and in terms of calories, the problem in food is abundance, not scarcity. Most people constantly have to control themselves to consume less, to forgo dessert, to reduce portion size, etc. The increase shows higher consumption, which is directly related to health problems, shown in Figure 7[15].

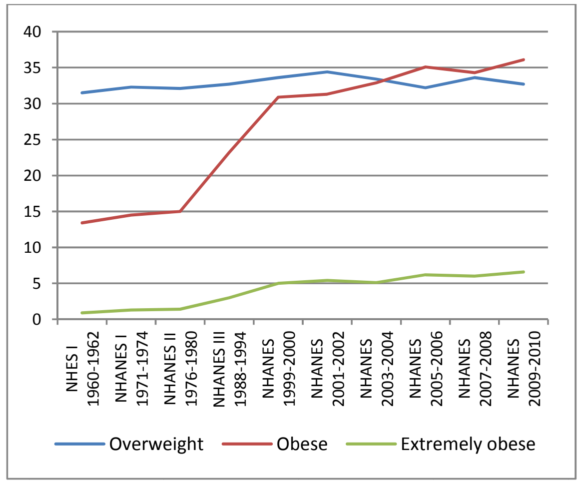

Fig. 7. The percentages of people that are overweight, obese, and extremely obese from 1960 to 2010. NHES is National Health Examination Survey, and NHANES is National Health and Nutrition Examination Survey.

People are also eating food higher in the food chain, which are more energy intensive than food low in the food chain. These are not in the best interest of health, which is a long term physiological need, and obesity can negatively impact love and esteem at higher levels of Maslow's pyramid of human needs. However, the energy used in this fundamental human need is not directly reflected in common energy efficiency measures.

5. Energy Efficiency in Commercial Buildings

Commercial buildings use power in heating and air-conditioning, lighting, IT systems, etc. These provide safety from heat and cold and a better environment for livelihood. All are basic human needs. In the 1992 EPAct legislation, the U.S. Department of Energy (DOE) was given a task to determine whether or not the most recent edition of a national model code (a building code), the ASHRAE Standard 90.1, would save energy compared to the prior edition (ASHRAE: American Society of Heating, Refrigerating and Air Conditioning Engineers). DOE assigned the task to the Pacific Northwest National Laboratory to conduct a study. The report shows that over the 24-year period, the estimated cumulative energy reduction is approximately 28%, shown in Table 3[16].

Table 4. The improved building code and estimated energy savings from 1980 – 2004.

Building code	% Energy Reductions
90.1-1980	Base line
90.1-1989	-15
90.1-1999	-4
90.1-2004	-11.9
Cumulative	-28.1%

The building code specifies many factors, one of which is related to windows. Double-pane and even triple-pane windows provide better insulation and are much more popular now. The EIA report shows that the use of less energy-efficient single-pane windows are down to less than 20%, while the use of more energy efficient double or triple-pane windows reached approximately 80%, as shown in Figure 8.

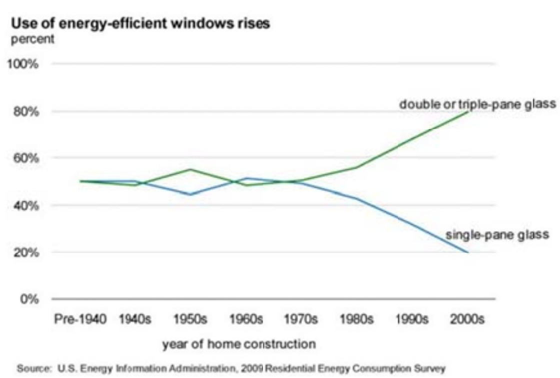

Fig. 8. The increasing use of double or triple-pane glass.

The efficiency of air conditioning systems is defined by Seasonal Energy Efficiency Ratings (SEER) by the Air Conditioning, Heating and Refrigeration Institute (AHRI). The average SEER rating of air conditioners sold went from just above 7 to almost 11 from 1978 to 1997[17], shown in Figure 9. This should translate into approximately 30% savings in electricity. With the building code, including increased usage of the double or triple-pane windows, one would expect more significant savings in energy. However, the residential electricity usage increased about 60% from 1982 to 1990 and then decreased 15% from 1991 to 1997. In commercial use, shown in Figure 10, the energy consumption per square meter and per employee reduced some from 1979 to 1986[18], then basically remained stagnant.

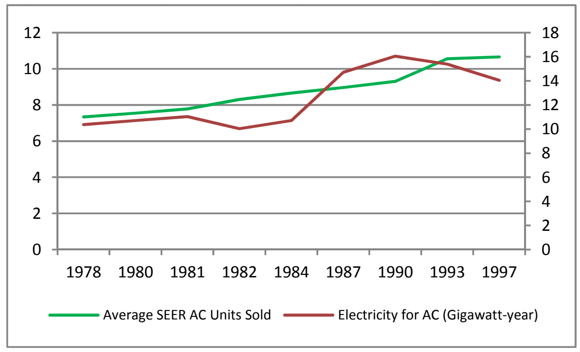

Fig. 9. The increase of SEER numbers and electricity used.

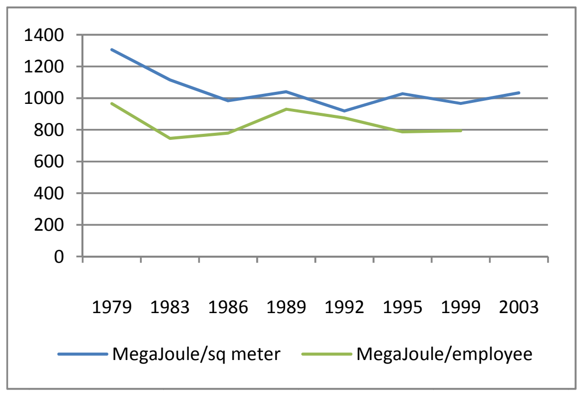

Fig. 10. The energy use per square meter and per employee.

One possible reason for lack of improvement in commercial buildings could be the increase of energy consumption by computers and IT infrastructure. However, until 2003, the energy use in computers was only approximately 4% of the total in commercial buildings[19]. The percentage may have increased in more recent years due to data centers. The estimated use of electricity in data centers doubled from 2000 to 2005 to 1% of the total and was estimated to double again by 2011[20]. Still, the percentage is not big enough to change the entire energy picture yet.

6. Summary of Observations

Over the years, various sectors of industry have made significant improvements in energy efficiency on products and processes in traditional measures. However, the EIA data in Figure 11 shows that the energy consumption per capita has not decreased much. The data from 1949 to 2010 are based on the EIA Annual Energy Review Report, 2011[21]. The data from 2011 to 2014 are based on the EIA Annual Energy Outlook 2014[22]. Until 2008, there was no significant decrease. From 2009 to 2011, the per capita consumption decreased, partially due to high energy costs and the recession. Since 2012, the per capita energy consumption has been stagnant. This lack of improvement occurs in parallel with the significant reduction in energy intensive manufacturing activities in the United States (concrete, metals, plastic, etc.). Of course, as society changes, energy demand changes. For example, air-conditioning is much more common now than 60 years ago, and energy consumption in IT systems, home appliances, etc. are higher. However, how much does this help issues of human need?

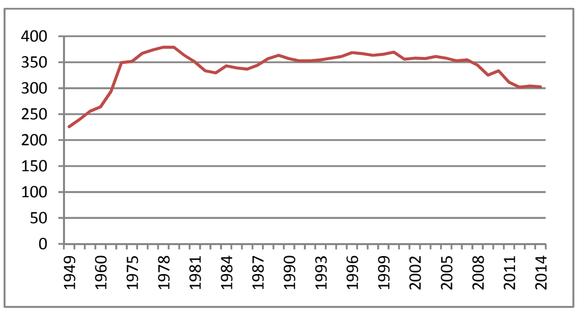

Fig. 11. Energy consumption per capital from 1949 to 2014.

In car making, food supply chains, and HAVC systems, the industries in silos can achieve significant improvement in energy efficiency. However, if measured against specific human needs, such as reduction in commuting times, in highway fatality rates, in good working conditions, or in health provided by food systems, how much improvement have we achieved? Which country, city, or community is doing better? It seems to be useful to add measures that close the loop from the energy source toward human needs. These measures can be used as objective functions for Industrial Engineers to design and operate systems that improve energy efficiency toward our needs. We will attempt to show examples below.

7. The use of Commuting Time as Energy Efficiency Objective

Commuting is a basic needs for livelihood and a long term safety issue in modern life. Commuting constitutes 28% of automobile travel in distance in the United States[7]. Normal walking speed can only cover about 5 kilometers in an hour, a big chunk of one's disposable time in a day, and so unacceptable to most people. Therefore, some faster mode of transportation is necessary: bicycles, motorcycles, buses, trains, and cars. These means require different levels of energy and offer different commuting times and levels of security.

Most commuters travel by car in order to save time and increase safety. The Toronto Board of Trade[23] considers commuting time so important that it uses the category consistently on its scorecard of competing cities. Other cities also report commuting time and safety as an important quantitative metric. Many reports also list the importance of energy consumption. However, no one considered the use of energy as an input to save commuting time or safety. The energy efficiency in commuting time can be modeled as an input-output system, as shown in Figure 12. The input is the energy consumption E for commuting. The output is commuting time reduction. One way to define commuting time reduction is to use the time reduction from walking to work for a given distance. A simpler definition is to use the inverse of commuting time as the output.

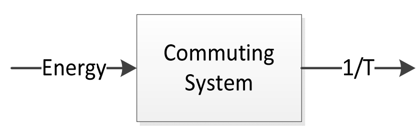

Fig. 12. The relationship between energy input and commuting time output. Mathematically, this is

$$e_{Tcommute} = \frac{\text{Inverse of commute time}}{\text{Energy Input}} = \frac{1}{E^{t}T}$$

Where

E The energy consumption in commuting. For a community, one can take the average. The unit can be GJ/trip. It can include both operating energy and embedded energy in the infrastructure and equipment.

T Commuting time in minutes or seconds. The first is more customary in commuting, and the second is the commonly used scientific unit.

t A constant exponent assigned to weigh the other factors, such as area of the region or population density. The simplest form is $t = 1$.

This macro level energy efficiency measure depends on many factors, such as mode of transportation, road network, city planning, terrain, population density and area.

We demonstrate the usefulness of this measure with cities that are either passenger car or public transport centric. Since this measure is new, it is challenging to find the data toward this measure. We managed to get data sufficient to achieve rough estimates of energy consumption in operations, meaning excluding the energy consumption in constructions. Our results should provide useful insight into the energy efficiency of public transportation versus private automobiles. The operating energy efficiencies in commuting time for the cities in which passenger cars dominate the commute are shown in Table 5. They are listed in the descending order of percentage of passenger car commuters.

Table 5. Passenger car energy efficiency in commuting time in select cities.

	% Auto	L/100 KM	Comm Time	Speed KM/hr	Speed KM/min	L/min	GJ/min	Occu-pency	GJ/trip	$E_{Tcommute}$
US	90.0%	8.11	22.9	46.5	0.774	0.0628	0.0022	1.13	0.0442	0.990
Dallas	95.6%	8.11	26.5	43.1	0.719	0.0583	0.0020	1.13	0.0476	0.793
LA	89.2%	8.11	28.1	43.1	0.719	0.0583	0.0020	1.13	0.0504	0.708
Seattle	85.6%	8.11	27.5	43.1	0.719	0.0583	0.0020	1.13	0.0494	0.736
Chicago	83.7%	8.11	30.7	43.1	0.719	0.0583	0.0020	1.13	0.0551	0.591
Toronto	71.2%	8.11	40.0	43.1	0.719	0.0583	0.0020	1.21	0.0671	0.373
Montreal	70.5%	8.11	38.0	43.1	0.719	0.0583	0.0020	1.21	0.0637	0.413
Sydney	67.0%	8.11	33.0	43.1	0.719	0.0583	0.0020	1.10	0.0627	0.469

In Table 5, the columns % Auto and Comm Time are from the Toronto Board of Trade[23]. The commuting time in the entire US is from the USDOT National Household Travel survey of 2009[7]. Fuel efficiency is converted from 29 miles per gallon (MPG) from the CAFÉ 2009 total fleet data reported in NHTSA NVS-220 (2013)[24]. The travel speed and travel time in the US are based on the USDOT Survey[7]. All other cities are based on the same report using MSA (Metropolitan Statistical Area) data for a population of more than 3 million. Occupancy data for US cities is also from the NHTSA report. The occupancy data for Toronto, Montreal are from McLeod[25]. The Occupancy and Comm Time for Sydney are from the Bureau of Transport Statistics of New South Wales[26].

The second group includes the three cities with the highest percentage of commuters using public transport, listed in the Toronto Board of Trade[23].

Table 6. Public transport energy efficiency in commuting time in select cities.

City	% Non Auto	Total Energy GWh/yr	Total Energy GJ/Yr	Passengers/day, in 1000	GJ/passenger trip	Comm Time min	$E_{Tcommute}$
Hong Kong	89.2%	1,344		4,300	0.00892	37.6	2.94
Paris	73.7%		9,548,184	12,000	0.00218	30.0	5.22
London	59.8%	1,163		3,033	0.00111	37.0	2.44

In Table 6, the column % Non-Auto is from the Toronto Board of Trade[22]. The Total Energy and Passengers/day in Hong Kong is from the MTR Sustainability Report Summary[27]. The Total Energy and Passengers in Paris are from the Paris Transport Authority report[28]. The Total Energy and Passengers/day in London are from Facts and Figures[29]. The Comm Time for Hong Kong and London are from the Toronto Board of Trade report[22]. The commuting time in Paris is from a comprehensive survey report[30]. The travel time in Hong Kong is from Tse and Chan[31].

The report[30] includes more specifics. The commuting time of 30 minutes used in the table is for suburban commuters, probably more comparable to the situation in Hong Kong and London. In the city center, the commuting time is 17 minutes, which will almost double its efficiency. Commuting in the suburbs is dominated by automobiles and therefore not included. The total energy given was 41,878 thousand ton oil equivalent (ktoe). We assume that was the electricity consumed. The main power source in France is nuclear. To be consistent, we applied the coal fired power generation efficiency calculated for HK or London at 34%[32], which was approximately the average in the US coal fired power plant.

We also computed operating energy efficiency for the bus rapid transit (BRT) public transport system in Bogota, Colombia. Since the procedure of estimation is similar to those of private cars: using fuel efficiency, occupancy, and travel time, it does not fit in either table above. Therefore, we included the results separately in Table 7.

Table 7. Public commuting energy efficiencies in Bogota Colombia.

	% Non Auto	L/100 KM	Commute time	Speed KM/hr	Lit/min	GJ/min	Occupency	GJ/trip	$E_{Tcommute}$
Bogota	81%	24.0	44.6	26.7	0.1068	0.0037	60	0.0028	8.11

The % Non-Auto is from the ESMAP Report[33]. The L/100 KM is based on manufacturer published fuel efficiency for the 48-seat Volvo bus, which is commonly used. The commuting time is estimated based on two sources. The first is the commuting time reduction of 21 minutes from the World Urban Forum[34], and the second is the commuting time reduction of 32% from the Energy Efficient cities Initiative[35]. Based on these two data points, we estimated the prior commuting time was 21 / 0.32 = 65.6 and the new time is 44.6 minutes. The peak hour occupancy is 98[35]. We used a more conservative number of 60 in the calculation. ESMAP also reported that the average speed is 26.7 KM per hour. The system serves over 1.65 million passengers a day in which 15% of the passengers previously traveled by private car[36]. The reduction in cars should also reduce the car commuting time from 42.7 min. McCarney estimated that the overall commuting time dropped by 21 minutes for all commuters[34].

The reason that the efficiency in Bogota is so much higher than other public transport systems is its very high occupancy rate. The data for Bogota is during the peak time, while the data for Hong Kong, Paris and London are for anytime.

Energy efficiency in commuting time can be improved two ways: 1) by energy savings or 2) by time savings. Energy efficiency can be used to compare cities based on competitiveness and city design and to compare cities based on different years to show improvement or different systems to show advantages. The measure can also be used for individuals to show their personal energy conservation and satisfaction. Although the data were crude estimates, the drastic differences allow us to draw the conclusion that public transportation is much more energy efficient than private cars in operational energy efficiency in commuting times. The average efficiency of the seven auto-centric cities is 0.58. The coefficient of variation, or the ratio of standard deviation and mean, is 0.29. The average and coefficient of variation for public transport systems in the four cities is 4.68 and 0.32, almost an order of magnitude higher than auto commuting!

We did not consider the embedded energy in cars, roads, tunnels, tracks, and other infrastructure. However, it is reasonable to argue that the energy consumption of infrastructure for bus systems, or even rail systems, should not be higher than the passenger car infrastructure.

There are other factors such as comfort. The attractiveness of passenger cars is that not only is it a transporter, it is also a shelter that provides comfort, privacy, and entertainment, although few would consider being stuck in traffic as much comfort or entertainment. None the less, it is difficult to resist the temptation for cars. However, we also need to consider how much more energy is consumed to achieve this marginal comfort and entertainment.

Another measure of the transportation system is safety. Hong Kong's MTR system reported its safety record in 2008, 2009 and 2010, shown in Table 8[37]. The data suggests an extremely high level of safety. In the US, the highway fatalities in 2009 reached 33,963. If we normalize using the population of the US and Hong Kong, this will be 779, only about 2.3% of the fatalities in US! We did not find reliable data in other cities. In 2009, the CDC estimated traffic injuries at 2.3 million (CDC, 2009), and using NHTSA's report of 2,932,374 million vehicle miles (NHTSA, 2010), we can estimate 0.49 per million KM - a very impressive number. However, in Hong Kong, using 34.05 per 100 million passenger journeys and 10 KM per journey, the injuries in Hong Kong are 0.03405 per million KM, only 7% of the US injury level!

Table 8. The fatalities and injuries in Hong Kong public transportation system.

	Transporter Type	2008	2009	2010
Fatality, number per year	Bus	0	1	0
	Heavy rail	1	0	0
	Light rail	0	3	1
	Total	1	4	1
Injuries (requires hospitalization) per 100 million passenger journeys)	Bus	7.53	11.16	7.51
	Heavy rail	8.4	7.56	7.94
	Light rail	12.34	15.33	12.3
	Total	28.27	34.05	27.75

The BRT in Bogota, along with other policies, also increased safety in Bogota. Road injuries were reduced by 15%, and the fatalities by 40% from 1999 to 2006 (Cohen, 2008).

Similar efficiency measures can be developed for safety as for commuting time. However, we could not find good data for the other cities studied. Further data and study should suggest better measures.

8. Energy Efficiency in Food and Buildings

Food is one of the most important fundamental physiological needs. It is also most intimidating: as the saying goes: "we are what we eat." Food directly impacts our health and wellbeing. However, food is also very complex, impacted by culture, history, geopolitical systems, etc. A simpler dimension in food can be calorie and other nutritional intake. Some minimum amount of food energy is needed to sustain life; more is needed for health and livelihood. However, too many food calories deteriorate our long-term health, which is a basic need. Interestingly, in the middle class around the world today, the majority of people worry more about taking in too many calories than not enough. Too much calorie intake leads to health problems, the opposite of human need. This suggests that there exists an "optimum" value of calorie intake.

Therefore, the energy efficiency in food supply chains can be fundamentally different from energy efficiency in commuting: too much production of food can be bad, while the shorter the commuting time, the better.

Housing is also complex, impacted by culture, history, and geopolitical systems. A simpler measure can be size. House size may also depict similar properties as food. Individuals often want a particular size or other characteristic directly related to energy. A house too large requires too much maintenance and can negatively impact how often you interact with loved ones who occupy the same home. Similarly, too much heating or air conditioning makes a house too hot or too cold. Therefore, energy efficiency in housing shares similar characteristics with those in food supply, the topics for future research.

9. Summary

This paper points out that the great improvements in energy efficiency in cars, housing, and food supply chains may not always translate into improvement in energy efficiency to satisfy human needs. We substantiate this observation with evidence from commuting, food, and housing.

We proposed a specific measure of energy efficiency on commuting time and compared between different cities and between passenger cars and public transport. The energy efficiency in commuting time can be a powerful measure to compare performance in different years to show improvement, among different cities to encourage competition, in different systems to show advantages of system design, or by individuals to justify personal choices. Specific measures such as fuel efficiency, heating and air conditioning, and food labeling have yielded energy conservation in silos. We hope this measure would further the cause of energy conservation by channeling the valuable energy into what we humans need. For example, this measure can be used to provide a more objective and concrete measure for the ITDP Annual Sustainable Transport Award. It will direct the cities to put the fund to where it really matters.

We also provide suggestions on energy efficiency for commuting security and some characteristics for food and housing. These are more difficult and will be the topics of future research.

We hope this paper will provide food for thought on energy efficiency and spark new development, new measures, and new policy to focus on more direct measures that address how energy efficiency relates to human needs, as reflected in Maslow's Hierarchy of Human Needs. Once the basic physiological needs are satisfied, human beings seek higher level needs such as security, love, friendship, esteem, reputation, and personal satisfaction. Some of these may not need much energy. Nowadays, there are high income people who proudly drive fuel efficient cars and have small, energy efficient homes to gain esteem or personal satisfaction. Many people volunteer to help others. Therefore, the objective functions for engineers and others should adapt to this change in the resource-scarce and productivity-abundant society throughout many parts of the world. Today, scarce resources such as air and water are free, while the products from abundant production systems are expensive, which will lead to unsustainable systems. Industrial Engineers can make great contributions using analytics to link the use of scarce resources to human needs.

Acknowledgements

I would like to thank Professors Bartholdi for his help. I would also like to thank my students Kyungha (Diana) Lim and Emilie Wurmser for their help with foreign language sources.

References

1. R. Teske, T. Pregger, S. Simon, T. Naegler, V. Graus, and C. Lins, Energy Revolution 2010 – a Sustainable World Energy Outlook, *Energy Efficiency*, **4** (3) (2011) 409-433.
2. W. Graus, E. Blomen, and E. Worrell, Global Energy Efficiency Improvement in the Long Term: a Demand- and Supply-Side Perspective, *Energy Efficiency*, **4** (3) (2011) :435-463.
3. U.S. Energy Information Administration, Annual Energy Review, (2012), accessed on March 20, 2014, www.eia.gov/totalenergy/data/annual/pecss_diagram.cfm.
4. A. Maslow, A theory of Human Motivation, *Psychological Review*, **50** (4) (1943) 370 – 396.
5. A. Maslow. Motivation and personality, 2nd Ed. New York: Harper & Row, (1971).
6. US EPA, Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 – 2013, http://www.epa.gov/otaq/fetrends-complete.htm, accessed on March 20, 2014.
7. US DOT Federal Highway Administration, 2009 National Household Travel Survey – Summary of Travel Trend, (2011), accessed Sept 6, 2011. http://nhts.ornl.gov/publications.shtml,
8. A. Stutzer and B. Frey, (2007) "Commuting and Life Satisfaction in Germany" Informtionen zur Raumentwicklung (In English), BBR publishing, 2/3, pp 179 – 189.
9. B. McKenzie, and M. Rapino, Commuting in the United States 2009: American Community Survey Reports. US Census Bureau, Accessed September January 28, 2012. http://www.epa.gov/otaq/fetrends-complete.htm.
10. S. Zhou, L. Deng and H. Meiyu, Spatial Analysis of Commuting Mode Choice in Guangzhou, China, *Chinese Geographical Science*, **23**(3) (2013) 353-364.
11. IRTAD, IRTAD Annual Report, International Traffic Safety Data and Analysis Group, Road Safety 2010 Accessed Feb. 20, 2012, http://www.internationaltransportforum.org/irtadpublic/pdf/10IrtadReport.pdf,
12. NHTSA, Analysis of the Significant Decline in Motor Vehicle Traffic Fatalities in 2008, DOT HS 811 346, accessed July 10, 2011, http://www-nrd.nhtsa.dot.gov/cats/listpublications.aspx?Id=229&ShowBy=Category,
13. K. Watkins, and D. Sridhar, Road Traffic Injuries: The Hidden Development Crisis, A Policy Briefing for the First Global Ministerial conference on Road Safety, Moscow, Nov. 2009, Accessed Feb. 20, 2012,

http://www.makeroadssafe.org/publications/Documents/road-traffic-injuries-kevin-watkins.pdf

14. P. Canning, A. Charles, S. Huang, K. Polenske, A. Waters, Energy Use in the U.S. Food System, Economic Research Services in USDA, (2010), http://www.ers.usda.gov/Publications/ERR94/ERR94.pd, Downloaded April 20, 2011.
15. C. Fryar, M. Carroll and C. Ogden, Prevalence of Overweight, Obesity, and Extreme Obesity Among Adults: United States, Trends 1960–1962 Through 2009–2010, CDC Publication and Information Products, (2012), accessed on April 19, 2014 http://www.cdc.gov/nchs/data/hestat/obesity_adult_09_10/obesity_adult_09_10.htm.
16. D. Belzer, S. McDonald and M. Halverson, A Retrospective Analysis of Commercial Building Energy Codes: 1990 – 2008," Prepared for DOE Contract DE-AC05-76RL01830, Pacific Northwest National Lab, (2010), accessed May 20, 2011. http://www.energycodes.gov/publications/research/documents/codes/Retrospective_Commercial_Buildings_Codes_Analysis.pdf,
17. US EIA, Trends in Residential Air-Conditioning Usage from 1978 to 1997, (2000), Accessed May 17, 2011, http://www.eia.gov/emeu/consumptionbriefs/recs/actrends/recs_ac_trends.html.
18. US EIA, Residential Energy Consumption Surveys 1978-1982, 1984, 1987, 1990, 1993, and 1997, (2000) http://www.eia.gov/emeu/consumptionbriefs/recs/actrends/recs_ac_trends.html, Accessed May 2, 2011.
19. US EIA, Annual Energy Review 2009, Report No. DOE/EIA-0384 (2009), Release Date: August 19, 2010, Accessed June 5, 2011, http://www.eia.doe.gov/emeu/aer/consump.html,
20. A. Howard and J. Homes, Addressing Data Center Efficiency: Lessons Learned from Process Evaluation of Utility Energy Efficiency Program, *Energy Efficiency*, **5** (1) (2012), 137 – 148.
21. US EIA 2011 Annual Review, accessed on April 19, 2014, http://www.eia.gov/totalenergy/data/annual/pdf/sec1_13.pdf .
22. US EIA Annual Energy Outlook 2014, accessed April 19, 2014 http://www.eia.gov/oiaf/aeo/tablebrowser/#release=AEO2014&subject=2-AEO2014&table=2-AEO2014&region=1-0&cases=ref2014-d102413a,.
23. Toronto Board of Trade, Toronto as a Global City: Scorecard on Prosperity – 2010, accessed on Feb 7, 2012, http://www.bot.com/AM/Template.cfm?Section=Scorecard&Template=/CM/HTMLDisplay.cfm&ContentID=4449.
24. NHTSA, NVS-220, Summary of Fuel Economy Performance (Public Version), (2011), accessed Dec 12, 2013, http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/April_2013_Summary_Report.pdf.
25. M. McLeod, (1999) Auto Passenger Travel and Auto Occupancy in the GTA, Data Management Group Joint Program in Transportation, University of Toronto, (1999) accessed Feb 20, 2012, http://www.dmg.utoronto.ca/pdf/reports/1996to2000/auto_pass.pdf.
26. Bureau of Transport Statistics of New South Wales, 2009/10 Household Travel Survey, (2011), accessed on April 14, 2013, http://www.bts.nsw.gov.au/ArticleDocuments/79/R2011-09-HTS-Report.pdf.aspx?Embed=Y, accessed on April 14, 2013.
27. MTR Corporation, Sustainability Report Summary, (2009), accessed on Dec. 10, 2011, http://www.mtr.com.hk/eng/sustainability/2009rpt/MTR_SRSummary_Eng_FINAL.pdf.
28. Paris Transport Authority (RATP), Activity and Sustainability Report, (2010), accessed Dec. 15, 2011. http://www.ratp.fr/en/ratp/n_23731/journalists/
29. Transport for London, Facts and Figures, (2011) accessed Dec. 15, 2011, http://www.tfl.gov.uk/corporate/modesoftransport/londonunderground/1608.aspx#techinfo.
30. Y. Caenen, C. Couderc, J. Courel, and C Paulo, (2010) Les Franciliens consacrent 1:20 par jour à leurs déplacements, (2010), accessed January 4, 2012 (in French). http://www.iaurif.org/fileadmin/Etudes/etude_696/Franciliens_transports.pdf,
31. C. Tse, and A. Chan, Estimating the Commuting Cost and Commuting Time Property Price Gradients, Regional Science and Urban Economics, **33** (6) (2003) 745-767.
32. T. Hansen, Operating Performance Rankings, 2010 Top 20 Power Plants, Electric Light&Power, accessed Feb. 7, 2012 www.elp.com/index/display/article-display/4158273877/articles/electric-light-power/volume-89/issue-6/features/operating-performance-rankings-2010-top-20-power-plants.html.
33. ESMAP EECI Good Practices in Cities Case Study, 2009, http://www.esmap.org/esmap/sites/esmap.org/files/CS_Bogota_020310_0.pdf, accessed Feb. 9, 2012.
34. P. McCarney, Background Paper of World Urban Forum III, (2006), accessed Sept. 8, 2011, http://www.unhabitat.org/cdrom/docs/wufiii_background_en.pdf.
35. ChinaBRT, accessed on February 19, 2012, http://www.chinabrt.org/en/cities/bogota.aspx.
36. G. Menckhoff, Latin American Experience with Bus Rapid Transit, Institute of Transportation Engineers Annual Meeting, Melbourne, (2005), accessed Sept. 10, 2011, http://siteresources.worldbank.org/INTURBANTRANSPORT/Resources/340136-1153689836373/ITEMelbourneBRT-LAExperience.pdf,.
37. MTR Corporation, Sustainability Report, (2010), accessed February 19, 2012, http://www.mtr.com.hk/eng/sustainability/2010rpt/sr10/reporting-performance_why-we-report.php.