RESEARCH AND ANALYSIS

A Dynamic Integrated Analysis of Truck Tires in Western Europe

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Summary

By evaluating tires from a perspective of industrial metabolism, potential novel and practical ways to reduce their environmental impact can be found. This may be achieved by focusing on technological issues such as choosing materials, designing products, and recovering materials, or by looking at institutional and social barriers and incentives such as opening waste markets or changing consumer behavior. A model is presented for the life cycle of truck tires in Western Europe that is dynamic in nature and values both environmental and economic consequences. Various scenarios are simulated including longer tire lifetimes, better maintenance of tire pressure, increased use of less-expensive Asian tires, and increased use of fuel efficiency-enhancing tires ("eco-tires"). Tentative results indicate that, among other things, more than 95% of the overall environmental impact during the life of a tire occurs during the use of the tire, due to the impact of tires on automotive fuel efficiency. Better maintenance of tire pressure and use of eco-tires produce greater environmental and economics benefits than more-durable and/or less-expensive (Asian) tires. These results imply that the emphasis in environmental policies related to tires should shift from the production and the waste stages to the consumption stage. It also suggests that the focus on materials throughput and associated improvements through factor 4 or factor 10 advances in reduction in mass are less important than the quality of the tires and their management.

Introduction

An economy consumes materials and energy inputs, processes them into useful forms, and eliminates the wastes from the process, in a manner similar to organic systems. This can be seen as metabolism and is sometimes referred to as “industrial metabolism” (Ayres and Simones 1996). Research in industrial metabolism aims at finding novel and practical ways to reduce the environmental impact per person and per monetary unit of economic activity. This may be achieved either by focusing on technological issues such as choosing materials, designing products, and recovering materials, or by looking at institutional and social barriers and incentives such as opening waste markets or changing consumer behavior (Ausubel 1998).

Industrial metabolism can be usefully applied at many different levels: global, national, sector, company, site, and household (Janssen and van den Bergh 1999). The most common level of application of industrial metabolism is the sector level. A specific material is selected and traced through the economy, starting at the extraction level and ending at the waste disposal point. A drawback of these standard models is the fact that economic and environmental indicators are presented separately. Conventional models also tend to limit their focus to only one segment in the life cycle (e.g., production, consumption, or waste management), thereby ignoring the interaction between up- and downstream processes.

This article presents a case study on tires in western Europe that incorporates the complete life cycle. Each stage in the European life cycle of tires poses its own problems. Because of the increased number of vehicles, the mountain of used tires has grown dramatically during the last decades. Every year, approximately 800 million scrap tires are disposed of around the globe. This amount is expected to increase by approximately 2% each year (UNCTAD 1996; EEA 1995). The production stage is important because the tire industry is the world’s largest consumer of natural and synthetic rubber. Burger and Smith (1997) estimate that 60% of the approximately 18 million tons of global rubber production in 2000 will be used for the production of automobile tires. The consumption stage is even more important because a significant share of the environmental impact during the life of a tire takes place during the usage of tires (Nicoletti and Notarnicola 1999). This is an important fact to be aware of, especially given that most environmental action groups focus mainly on waste issues. It should be kept in mind, however, that bringing about improvements in the life cycle is different from identifying the main contributors in the absolute sense. For example, it may be more difficult to generate fuel-efficient driving behavior than a cleaner waste processing option. Scenario analysis helps to understand this policy dimension.

The main goal of this article is to determine the economic, environmental, and social effectiveness of various scenarios that are indicated by industrial and policy stakeholders to represent the most important, anticipated changes in the western European tire life cycle in the coming decades. Obviously, in reality, these scenarios are not exclusive, but are most likely to occur in a parallel manner. We present here a simulation model that is dynamic in nature, integrates the complete life cycle, and incorporates environmental impacts into its economic analysis.

The article is structured as follows. To explain the context of the tire life cycle, a qualitative description of the tire cycle in Europe is provided in the second section. Policies and other issues are also discussed. The methodology of “dynamic integrated analysis” is explained in the third section. A dynamic systems model is introduced for the analysis of the truck tire cycle. The results of various scenarios examined with this model are presented in the fourth section. In the final section, conclusions and recommendations are formulated.

Tires in Europe

In this section the general background of tires in Europe is discussed. Besides evaluating the tire cycle, we summarize the main developments and policy issues that should ideally be addressed in the model.

The tire life cycle traditionally comprises five main stages, which include extraction, production, consumption, collection of used tires, and waste management. A simplified version of the tire cycle for a region is depicted in figure 1.

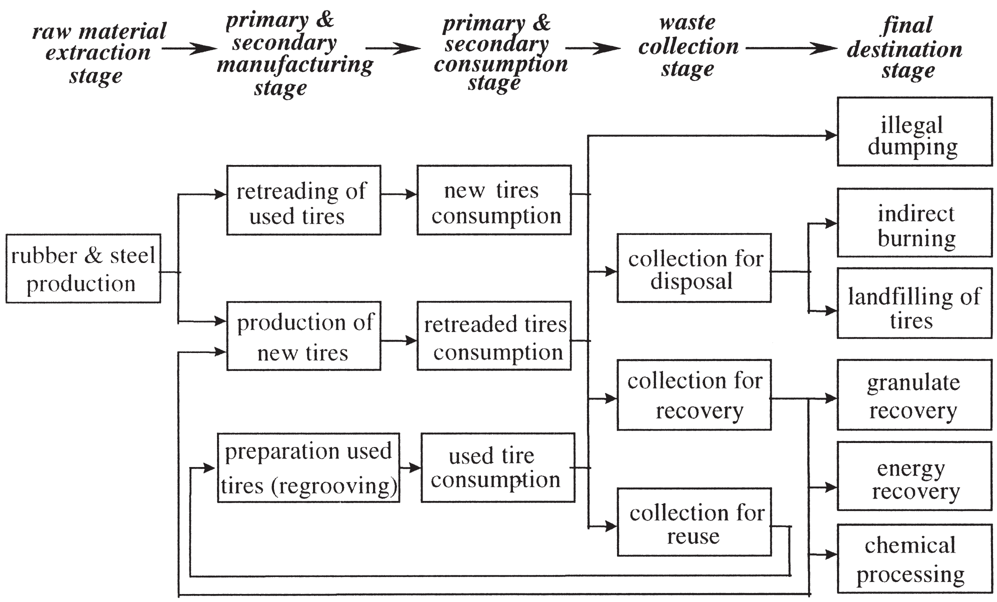


Figure 1 The life cycle of a tire.

Extraction

In the extraction stage, the generation of the basic components of a tire takes place. The components consist of synthetic and natural rubber, textile, steel, and chemical additives. The proportions in which these components are used depend heavily on the specific characteristics of the tire. This is clearly demonstrated if we look at the ratio between natural and synthetic rubber in tires: Generally, truck tires have a larger natural rubber content than do passenger car tires. An alternative component for rubber is "reclaim," which is the material recovered from used rubber products. Because its physical properties (i.e., elasticity, flexion, and chemical resistance) are not as good as in new rubber, the proportion of reclaim in tire applications is limited to 10% (Guelorget et al. 1993).

Natural rubber comes from the sap collected from *Hevea brasiliansis* (rubber tree) plantations. Synthetic elastomers are obtained from petroleum and coal, which require several stages to produce. The most important chemical additive is zinc oxide, which is used as an activator. Carbon black is added to further improve the rubber properties, prevent oxidation, and provide greater abrasion resistance. All the input materials are finally mixed and vulcanized using sulfur. Vulcanization is a thermochemical process that gives the tires their performance characteristics during the use of the product: It is important for their consumption, but it makes further processing in post-consumption stages more difficult.

Production

To understand the manufacturing stage of the tire, one should be aware of the composition of the tire. A tire roughly consists of the casing or carcass that forms the skeleton of the tire, and the tread that consists mainly of rubber and in most cases, therefore, can be renewed (e.g., retreading). As shown in figure 1, a tire can be produced in three ways: as a new tire, as a retreaded tire, and as a reused tire. The manufacturing of a new tire is a complicated process requiring a high level of technology. Therefore, the scale of operation is also relatively large, exceeding 50,000 metric tons[1] per year. Labor accounts for 30% of the total costs (U.S. EPA 1995).

The second option for tire manufacturing is through the retreading of a used tire casing.[2] Retreading involves stripping the old tread from a worn tire and reclothing the old casing with a tread made from new materials.[3] Retreading brings environmental benefits, as it extends the tire life span. It saves 80% of the raw materials and energy necessary for production of a new tire and reduces the quantity of waste to be discarded. Although the price of retreaded tires is between 30% to 50% lower than the price of a new tire, they deliver the same mileage as new tires (Ferrer 1997; ETRA 1996).

Although it is not truly a manufacturing option, the third alternative for generating tires is to prepare partly worn tires for reuse. This may involve regrooving, a procedure in which a new pattern is grooved into the tread base that remains after the original pattern has been worn away by use. This technique is carried out primarily on truck tires because these are designed with significant tread thickness. If the process is carried out correctly, about 30% extra mileage will be obtained for only 2.5% of the cost of a new tire (World Tire Industry 1997). Retreaders oppose direct reuse and regrooving because it makes further retreading more difficult, more expensive, and, in most cases, even infeasible. Depending on the remaining tread depth, discarded tires are also reused directly. Drivers replace tires before the minimum tread depth is reached. These tires generally enter international trade for direct reuse. From an environmental perspective, direct reuse and regrooving prolong the life span of a tire. The increased imports of reusable tires, however, may also increase the waste burden due to the short life span of reusable tires. Moreover, increased risks for accidents may result from driving on worn-out tires.

Consumption

Driving behavior and tire maintenance are the main factors in the consumption stage. Improvements in tire manufacturing over the past 40 years have more than doubled the mileage of tires, yet this technical limit is rarely met. Quick acceleration, not observing speed limits, abrupt braking, and not taking into account the state of road surface are all forms of driver behavior that cause the original tread to dwindle at a great rate. Currently, steel-belted radial passenger tires last about 65,000 kilometers (about 40,400 miles). If these tires are properly inflated, rotated, and otherwise cared for, a lifetime of 95,000 to 128,000 kilometers may be achieved. A tire loses up to 10% of its weight before disposal. Most of the material lost comes from the tread, which is made of rubber only. If the casing is in a good state once the tread is finished, tires can generally be retreaded. Although no scientific proof has been found, retreads historically have a poor public image. Yet, most retreaders claim that there is no quality difference between new tires and retreads (U.K. Environment Agency 1998).

Driving behavior and the neglecting of tire pressure also have a major impact on energy consumption. The fuel used to overcome the rolling resistance of the car tire accounts for 15% of the total fuel consumption. If tire pressure is not monitored this share may increase to more than 20%. A test in the United Kingdom proved that only 22% of cars and trucks are driven with the correct tire pressure. The majority of the drivers underinflate their tires by 10% to 15% (U.K. Environment Agency 1998). Another issue in the consumption stage is the introduction of energy-efficient tires (often labeled as "eco-tires" or "smart tires"). These can save up to 6% of a vehicle's fuel.[4]

Collection and Waste Management

The collection of tires is considered to be a separate stage in the life cycle. Used tires are accumulated after replacement or when scrapping a vehicle. Various parties are involved. Generally, tires are collected in tire service centers. Consumers pay a limited fee to the service center for proper disposal of the used tire. For example, in the Netherlands, consumers pay approximately € 2 per tire (€ 300 per metric ton) for disposal.[5] In turn, the service center passes part of that fee (roughly 50%) on to the broker, who separates the reusable and retreadable tires. The broker may then export the tires for either reuse or retreading. A portion of the tires is marketed to domestic retreaders or other recovery agents, such as cement kilns.

The final destination stage describes the ultimate location where used tires arrive. In this article, the term "used tire" defines a tire at the end of its first life cycle. Two subtypes of used tires are distinguished: The "part worn tire" is a used tire that can be either directly reused or retreaded; the "worn-out" or "scrap" tire is a used tire that cannot be reused for its original purpose, but may have a further use as a material or for energy. As shown in table 1, the configuration of options to process used tires varies widely within Europe.

Worn-out tires are generally used for materials recovery. The options for recovering the materials in tires include mechanical grinding, cryogenic grinding, and pyrolysis. In mechanical grinding, scrap tires and tire-related rubber waste are reduced into a powder of various particle sizes. After grinding the materials, the steel and textile are removed. In the cryogenic grinding process the whole tires are cooled down, using liquid nitrogen, to below the glass transition temperature. The cooled rubber is reduced to a very fine powder. This process enables rapid separation of textile, steel, and rubber. In view of its environmental performance, grinding is an energy-intensive process and has relatively high dust emissions. The economic and environmental advantages of grinding are that it generates recyclable rubber and useful by-products, such as steel and textile, which also can be recycled. The most common application of the granulate is in rubberized asphalt. Although this application seems to be a promising outlet for recycled rubber, it is not widespread in Europe because of its relatively high cost.

Chemical processing of size-reduced tires, such as pyrolysis, produces monomers. The resulting material is submitted to a further thermomechanical or high-pressure steam processes where additives are incorporated depending on the final product requirements. Although the end product is inferior to virgin rubber, it can still be used as a component in high-value commercial applications requiring high-performing rubber, such as tires, bicycle tires, automotive molded parts, soles, and heels. Chemically recovered rubber is approximately half the price of virgin rubber. Using recovered rubber can be economically feasible for the tire industry, especially when production waste is recycled and reused within the factory where it is generated. This might result in additional savings from the elimination of disposal fees and transportation costs.

The high energy content of tires has led to several applications of post-consumer tires for energy recovery. For example, many worn-out tires are used as a supplemental fuel in cement kilns. Depending on the technology used, tires can compose up to 25% of the total fuel of cement kilns. A major advantage of using worn-out tires in cement kilns is that it does not generate solid waste because the ash residues from the tire combustion are bound to the final product. Furthermore, sulfur emissions are not a major concern as the sulfur is transformed and bound into gypsum, which is added to the final

Table 1 Processing options of used tires in Europe, 1996

	Percentage of total quantity processed by individual options						
Country	*Quantity (metric tons)*	*Retreading*	*Physical application***	*Material recovery*	*Energy recovery*	*Landfill*	*Net-Export*
Belgium	70,000	11	8	14	25	42	n.a.
Czech Rep.	60,000	27	5	8	25	35	n.a.
Denmark*	19,000	26	8	14	9	49	0.5
France	375,000	20	7	7	15	47	4
Germany	600,000	20	n.a.	14	45	21	n.a.
Italy	260,000	22	n.a.	15	23	40	n.a.
Netherlands	65,000	37	n.a.	8	32	0	23
Norway	33,000	4	n.a.	n.a.	42	44	10
Spain	139,000	25	8	9	1	58	n.a.
Sweden	60,000	5	7	12	64	5	7
UK	370,000	31	5	11	27	26	n.a.

*Includes only tires for motorcycles, cars, and vans; n.a. = data not available.

**Physical application is the practice of utilizing used tires as objects in their original form. Applications include tires as coastal protection, children's swings, or cover materials in agriculture.

Source: Rosendorfová et al. (1998).

product (Jones 1997). In Europe, the United States, Japan, and Korea, cement kilns are among the most common end users of tires for their energy content. In some countries, such as Austria, France, Germany, and Sweden, up to 65% of the total quantity of used tires is incinerated in cement kilns. In an alternative to cement kilns, totally dedicated tires-to-energy power plants have been built in Europe.[6]

Traditionally, landfilling has been the most common method for disposal, mainly due to the low price of landfilling. Two forms of disposal can be identified: disposal in a landfill and disposal in a monofill. A scrap tire monofill is a landfill that stores tires only. When disposed of in landfills, scrap tires occupy a large amount of space and remain intact for decades, posing increased environmental and public health risks related to possible leakage and the danger of uncontrolled burning. Furthermore, when whole tires are buried in a landfill they trap air and have a tendency to migrate to the top of a closed landfill, breaking the landfill cap and causing costly damages to the landfill cover, which increase the instability of sites. Also, used tires easily trap rainwater and therefore create a favorable environment for insects such as mosquitoes, which increase the risk for malaria (U.S. EPA 1995). The European Commission recently accepted a directive that bans the disposal in landfills of whole tires by 2003, and of shredded tires by 2006 (European Commission 1997).

Monofills are more desirable than landfills, as they facilitate material and energy recovery in the future. After the European ban on landfills is operational, monofills will form a temporary solution in those European countries where capacities for processing used tires are limited. The potential advantage of such monofills is that they can be reconsidered as future used tire collection sites and distribution centers. Examples from Canada and the United States, however, show that monofill sites frequently become abandoned without processing the stored tires. Monofills also are a serious source of fire outbreaks (U.S. EPA 1995).

A Dynamic Integrated Analysis

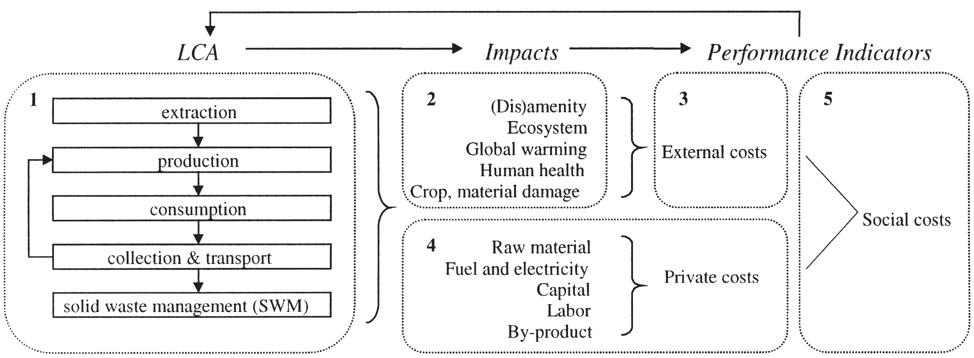
The tire life cycle generates substantial environmental burdens. Improvements in environmental performance can be achieved in several stages of the life cycle. Such improvements, however, can be interdependent. Changes in one part of the life cycle may have positive or negative consequences for another part. For example, by developing economically feasible waste management options for used tires, retreading becomes less attractive. The net impact for the environment may therefore be negative. Similarly, improving driving behavior for reasons of fuel consumption can increase the lifetime of a tire, which subsequently reduces the environmental pressure of the production stage.

In addition to the interaction between the stages in the life cycle, trade-offs between economic and environmental effects may occur. Each potential environmental improvement in the life cycle has consequences for the economy. For example, enhancing public awareness with regard to proper tire pressure requires funds for public campaigns, but at the same time generates substantial economic benefits in the long term as a result of reduced fuel consumption. Therefore, allocating the scarce resources available for environmental management, policy, or production measures should be analyzed in terms of the economic, as well as the environmental consequences.

Method

We present a system dynamics model developed to analyze the life cycle of truck tires.[7] The model is calibrated for the period 1990–1999 and predicts developments for the period 2000–2020. The region selected includes Germany, the Netherlands, the United Kingdom, Belgium, France, and Luxembourg. In order to cover the essential economic and environmental aspects of the tire life cycle, the model combines various analytical tools that are generally used separately in the field of industrial ecology. These tools include:

- *System dynamic approach* (SDA): SDA simulates the dynamics of flows and stocks of tire-related materials by using nonlinear differential equations and time delays. The purpose of SDA is to study the developments of the truck tire life cycle by incorporating technological and behavioral changes over the long term.



Domain of the Methods
- Lifecycle Assessment (LCA): 1 and 2
- Economic Valuation (EVA): 3
- Cost-benefit Analysis (CBA): 4 and 5
- System Dynamic Approach (SDA): 1, 2, 3, 4 and 5

Figure 2 General structure of the model.

- *Life-cycle assessment* (LCA): LCA accounts for the environmental effects of each process in the life cycle of truck tires in physical terms.
- *Economic valuation* (EVA): EVA quantifies the environmental effect in monetary terms. The purpose of EVA is to estimate the external benefits of specific environmental improvements in the tire life cycle.
- *Cost-benefit analysis* (CBA): A traditional CBA determines the desirability of a change or intervention in the system on the basis of private costs only. In this project, the CBA has been extended by also including external effects. This allows for trading off economic and environmental objectives.

Figure 2 shows the main structure of the model, representing one time step. The domain of each method applied in the project has been indicated. The outcome of the model is determined in an iterative process. Policy interventions or other types of shocks change the conditions surrounding the tire life cycle. As a result, private, external, and social costs change next. This, in turn, leads to a change in the configuration of the life cycle. Subsequently, economic conditions may change.

The main output variables of the model are private, external, and social costs (i.e., costs to society).[8] Private costs are defined as costs that are directly accounted for in the truck tire life cycle. These consist of costs of using materials, capital, transport, energy, and labor. By-products from the tire life cycle that fulfill a service outside the tire life cycle, such as energy from burning tires in cement kilns, are deducted from the financial costs. As an example of the cost structure, table 2 illustrates the financial costs of production of a retreaded tire.

External costs are those costs that are caused by activities of agents in the tire life cycle that have an impact on the well-being of another agent, but are not reflected in the cost borne by the former agent. The classic example of external costs is that of an upstream factory polluting a river that has a negative impact on catches in a downstream fishery. In deciding how it will produce and, consequently, how much pollutant it will emit to the river, the upstream factory will not take this effect into account. As a result, costs external to the factory will be born by the downstream fishery sector. Similar effects may occur in the tire life cycle.

Figure 3 presents the procedure of the calculation of the external costs. First, physical input-output matrices for each process in the life cycle are linked in order to calculate the overall emission levels resulting from the materials flows in the life cycle (see appendix 1). Second, these physical levels are converted into impact levels.

Table 2 Cost structure of the retreading of one metric ton of truck tires (1997)

Category	*Type*	*Unit*	*Quantity*	*Price (€/unit)*	*Costs (€)*
Material	Retreadable tire	Ton	1	700	700
	Tread	Ton	0.361	2,000	722
	Other inputs	Ton	0.006	500	3
	Water	m^3	2.536	1	3
Energy	Electricity	MWh	0.3	324	97
Labor	Skilled	Man-year	0.004	34,500	138
	Unskilled	Man-year	0.01	17,500	175
Capital	Operational		–	–	55
	R&D		–	–	10
	Depreciation		–	–	30
Transport	Inputs and outputs		–	–	50
Total cost					1,983

Source: Ferrer (1997); Rosendorfová et al. (1998).

Standard impact coefficients for the various countries involved are applied, assuming average conditions for population density and age distribution, for example.[9] Five major external impacts are taken into account: human health, global warming, (dis)amenity effects, disturbance of ecosystems, and damage to crops, buildings, and materials. Finally, the impact levels are converted into monetary values.

In this last step of economic valuation of the external effects, the measure of the monetary value is the willingness to pay (WTP). The WTP is defined as the maximum amount of money a person is willing to pay to obtain a good or service. An individual's WTP for a good is a reflection of his preferences for this good relative to other goods. There are various techniques to measure the WTP. First, values can be based directly on market values of productivity. The example in figure 3 shows how emissions of sulfur dioxide can decrease the attractiveness of an archaeological site, thereby reducing the income of tourism. Second, values can be based on market prices for surrogate products or services. To maintain the same level of tourism, the archaeological site can be converted into an entertainment park. The involved costs are attributed to the emissions from the power plant. Third, individual preferences (WTP) may be revealed through interviewing techniques. This enables the capturing of the more indirect values. For example, in the case of the archaeological monument, besides the reduction in tourist income, numerous people, who never intend to travel to the site, will experience suffering from the damage. Interviews can reveal these values.

A large number of empirical studies conducting economic valuation for external effects in western Europe are available. These studies have been used to compile a list of standard values for the most important impacts in the tire life cycle. Similar to the translation of emissions to impacts, assumptions about, for example, income levels and property values are made in translat-

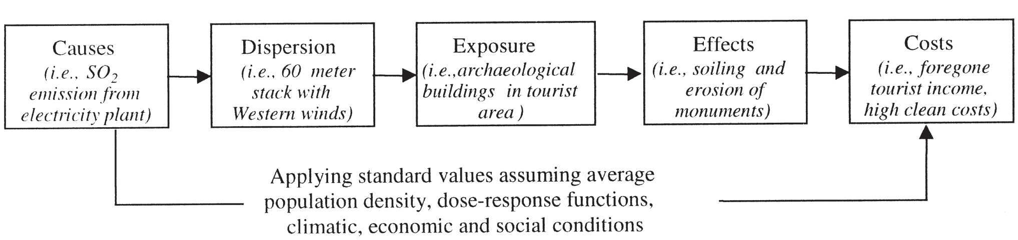


Figure 3 Monetization of environmental impact using standard values.

ing impacts into values. In appendix 2 an overview is presented of the levels and sources of the main external values applied in this study.

Two additional general remarks need to be made about the private and external costs. First, the configuration of the costs differs and changes over time for most processes in the tire life cycle. For example, because labor productivity gradually increases over time, the share of labor costs in the overall costs of new and retreaded tires declines. Ultimately, these price changes lead to shifts in demand and subsequently lead to reallocation of processes in the tire life cycle. Second, the types of costs vary across the stages in the life cycle. Production costs involve materials, labor, and capital. Consumption costs only include the fuel consumption attributed to the tire friction with the road surface. Transport costs include the capital and fuel required for the transport of tire-related materials in the tire life cycle. The waste stage involves, for example, the costs of land use and waste treatment.

In the final step of the overall method, the social costs are determined by summing the private and external costs. An optimal configuration of the tire life cycle is achieved for the society as a whole by minimizing the social costs in western Europe. This integration of private and external effects is uncommon in most life cycle studies. A strong advantage of this approach is that it enables the comparison of the benefits of some environmental improvement with the associated costs.

What is the position of this *dynamic integrated analysis* in the field of industrial ecology? Although each methodology is commonly used in its own disciplinary field, the combination of these tools has, to the authors' knowledge, not been performed before. Studies that approximate this approach are, for example, the *Systems approach* by Leach and colleagues (1997) and the *Impact pathway approach* by the European Community (EC 2000). This approach differs in that, although both studies monetize the external effects arising throughout the life cycle of a material or a product, the trade-off with private costs has not been made. Another example of a comparable approach is the *Economic Input-Output Lifecycle Assessment* (EIOLCA) developed at Carnegie Mellon University (2000). The difference between dynamic integrated analysis and EIOLCA is that the former takes into account the dynamic aspects in the economy and the environment, whereas the latter takes a snapshot at one moment in time and assumes constant prices. In conclusion, dynamic integrated analysis is a novel combination of existing methods.

Scenarios

Five scenarios have been tested and compared with the current situation (the base case). These scenarios are indicated by industrial and policy stakeholders to represent the most important anticipated changes in the tire life cycle in the coming decades. The exact content of the scenarios is based on interviews with agents in the waste management industry (Rosendorfová et al. 1998), reports on government involvement (U.K. Environment Agency 1997), and personal communication with tire manufacturers.

Base case scenario: Technological improvements are extrapolated based on the current rate of change: The durability of tires improves from 250,000 kilometers in 1990 to 300,000 kilometers in 2020, and the fuel efficiency of trucks improves by 1.5% annually. Consumer behavior remains unchanged in the base case: Tire pressure remains 10% lower than the ideal pressure.

Eco-tire scenario: Increasingly, tire companies are introducing tires that promote energy efficiency. These so-called eco-tires are more expensive than standard tires—on the order of €15 to €25 per tire—but consume up to 5% less fuel. The potential savings are therefore significant. The durability and the safety of these tires is similar to those of regular tires. Because these new types of tires have been around for only a few years, their present market share is minimal. To promote the use of eco-tires, public campaigns should be held. In the simulated "eco-tire scenario," the market share of the eco-tire increases from 0% in 1997 to 40% by 2020.

Pressure scenario: The majority of cars and trucks currently are not driven with the correct tire pressure. As a result, the rolling resistance of the tire is much higher than the optimal level, leading to a much higher fuel consumption and a more rapid wearing out of the tire. In the "pressure scenario," consumers gradually improve pressure and reduce underinflation from 10% in 1997 to 0% by 2020.

Lifetime scenario: The durability of tires has improved significantly in the last decades. Due to technological improvements in the tire, the lifetime of a car tire increased from an average of 24,000 kilometers in 1975 to 48,000 kilometers in 1990 (KPMG 1990). For truck tires, similar advances have taken place. Increased lifetime decreases the need for new tires and thus has a diminishing impact on environmental damage. The "lifetime scenario" simulates a gradual increase in the lifetime of truck tires from 250,000 km in 1990 to 400,000 km by 2020.

Asian tire scenario: It is expected that the largest expansion in primary tire production will occur in the newly industrialized Asian economies. For example, Asia already had the largest market share by 1990, about 12%, of primary truck tire production in the world. It is expected that the market share of world truck tire production in Asia will increase to 32% by the end of 2020 (Smith 1995). The reason for this significant growth comes from lower prices, due to proximity to the major natural rubber suppliers and due to cheaper labor and energy costs. These inexpensive Asian tires are said to be less suitable for retreading, although no scientific evidence of this has been found. Market penetration of inexpensive Asian tires may therefore lead to an increased environmental burden, due to the higher portion of nonretreadable tires. The Asian tire scenario simulates a gradual increase of the share of nonretreadable tires in the European market from 10% in 1990 to 40% by 2020.

A Dynamic Model of the Life Cycle

This section describes the basic equations of the simulation model that quantify the stocks and flows of tires within western Europe. The life cycle of tires, as depicted in figure 1, is simulated in terms of metric tons of tires. The allocation decisions during the life cycle are based on prices and technical constraints such as the ability to retread a tire.

The projected demand for tires is given as a scenario of tons of tires with the lifetime characteristics of new truck tires in 1990. Next, the projected demand is corrected for the consequences of change in lifetime. Prices of new, retreaded, and reused tires determine in which way the demand of tires will be met, taking into account the availability of reused and retreaded tires. After the consumption phase, used tires are collected and allocated to disposal, reuse, or recovery, based on prices and technical possibilities of recovery and reuse. The same holds for allocation of recovered tires to different forms of recovery. Each ton of produced tire finally ends up either in a landfill, or as recovered materials or energy. In this way, the model takes into account the mass balance of the tire life cycle. The simulation of the physical cycle of tires provides information for estimating the external, private, and social costs, as shown in figure 2. In the following section, the basic equations in the model are briefly discussed.

Production of Tires

Prices determine the demand for the type of tire. Using a multinomial logit function with price p_i and the sensitivity parameter β, the market share m of each tire type $i \in \chi$ is determined, where χ is the set of different types of tires. The multinomial logit function is used to describe the accumulation of the individual choices from consumers for a particular type of tire. The higher the value of β, the more sensitive the market share is to price differences among different types of tires.

$$m_{d,i} = \exp(-\beta \cdot p_i) / \sum_{j \in \chi} \exp(-\beta \cdot p_j) \qquad (1)$$

Demand for each specific tire type, $X_{d,i}$, can then be formulated as the market share times the total demand, X_{dt}. This amount is corrected by the fraction of average lifetime of a tire, l_a, divided by the lifetime of the specific type of tire, l_i.

$$X_{d,i} = m_{d,i} \cdot X_{dt} \cdot \left(l_a / l_i \right) \qquad (2)$$

Because of safety regulations, legislation restricts the reuse of tires, which is simulated by assuming a maximum fraction (i.e., limit) of tires being supplied by reused tires. The demand for other types of tires is based on prices.

The production, P_i, of reused tires (or retreaded) tires is the minimum of the available tires, $X_{v,i}$, collected for reuse (or retreading) and the demand for reused (or retreaded) tires.

$$P_i = MIN\left(X_{v,i}, X_{d,i}\right) \quad (3)$$

The production of new tires is then the total demand less the production of reused and retreaded tires. The stocks of the different type of tires, X_i, increase due to the production of tires, P_i,and decrease through depreciation of tires using a lifetime, l_{ti}:

$$dX_i / dt = P_i - X_i / l_{ti} \quad (4)$$

This lifetime is assumed to be a function of tire pressure γ, average lifetime in traveled distance (km) φ, and the average distance traveled per year (km/year), η.

$$l_{ti} = f\left(\gamma\right) \cdot \varphi / \eta \quad (5)$$

where the function *f(g)* defines that the maximum lifetime of a tire is met at an optimal tire pressure. If the pressure deviates from the optimal pressure, the lifetime declines.

The Treatment of Worn-Out Tires

Each year, a number of tires are depreciated. The total amount of fully depreciated (worn-out) tires, X_o, is defined as the sum of the tire stock divided by the lifetime of the different tires. These worn-out tires are allocated among illegal dumping, collection for disposal, collection for recovery, and collection for reuse. This results in a set of options, ψ. This allocation is based on price differences: The worn-out tires are allocated to the cheapest possible option. This decision process of many individuals is simulated by a multinomial logit function. The price of each option, *i*, for worn-out tires, $p_{o,i}$, and parameter α determine the market share of treatment of worn-out tires, $m_{o,i}$.

$$m_{o,i} = \exp(-\alpha \cdot p_{o,i}) / \sum_{j \in \psi} \exp(-\alpha \cdot p_{o,j}) \quad (6)$$

Besides prices, the ability of worn-out tires to be retreaded or reused determines the allocation of worn-out tires. Therefore, the price-dependent allocation has been corrected for this factor. When demand for reused tires is higher than technically possible, only the share of technically possible tires, $\kappa_{r,i}$, is reused. The amount of tires collected for reuse is then defined as:

$$X_r = X_n / l_n \cdot MIN\left(\kappa_{r,n}, m_{o,r}\right) + X_c / l_c \cdot MIN\left(\kappa_{r,c}, m_{o,r}\right) \quad (7)$$

with indices *r* for reuse, *n* for new, and *c* for recovery. Because both technical and price information are used to determine the reuse of tires, the price-dependent market share of equation (6) does not hold anymore. Therefore, the desired levels of the other destinations of worn-out tires are corrected by a factor ϕ, such that X_o is equal to the sum of the possible treatment of worn-out tires. This factor is defined as:

$$\phi = \left(X_o - X_r\right) / \left(X_o \cdot \left(1 - m_{o,r}\right)\right) \quad (8)$$

This leads to equation (9), where *i* consists of illegal dumping, collection for disposal, and collection for recovery.

$$X_i = m_{o,i} \cdot X_o \cdot \phi \quad (9)$$

The allocation of recovered tires in retreading, material recycling (granulate), energy recovery, and material reuse is defined in the same way as the allocation of worn-out tires to different treatments. Prices determine a desired allocation, which is corrected because of technical constraints. Retreading of tires is bounded by technical conditions, which depend on whether the worn-out tire was a new tire, a retreaded tire, or a reused tire.

Prices of Tires

The prices of retreaded and new tires consist of costs for materials, labor, energy, capital, and transport. A profit margin determines the final market price. The costs of materials consist of the sum of prices times inputs for all types of materials inputs. Labor costs contain wages paid for unskilled and skilled labor. Energy costs include the costs for electricity. Transport costs result from the distance traveled for each material or tire type times a fixed price per unit distance. Capital costs per ton of tire are equal to the capital output ratio *COR* times an annuity factor, plus operation cost and costs for research and development (R&D) and marketing. The annuity factor is defined as $\rho/(1 - (1 + \rho)^{-L})$ with ρ the interest rate, and *L* the economic lifetime of the capital stock. The *COR* is the amount of capital needed to produce a unit of output. The costs of operation, R&D, and marketing are fixed. Finally, the cost price is calculated with a profit margin factor to determine the market price. This profit margin factor is determined during (historical) calibration, and is assumed to remain the same in the near future.

Fuel Efficiency

The type and use of tires influence the fuel consumption of cars. An autonomous part of improvement in fuel efficiency is distinguished from an endogenous one. The autonomous improvement is determined by the expected technical advancement resulting from R&D activities in the tire industry. The pressure of the tire determines the endogenous part. The deviation of the actual tire pressure from the optimal pressure is negatively correlated at an increasing scale to fuel efficiency. Fuel consumption, F_C, is defined as the ratio of distance traveled per year by the average truck divided by the fuel efficiency, F_E, multiplied by a factor reflecting the difference between the actual γ and the optimal tire pressure γ_o, multiplied by a factor that attributes the fuel consumption to one metric ton of tires. In case of an optimal pressure of tires, 85% of fuel consumption is not related to the tire. This amount is subtracted from F_C to determine the tire-related consumption.

$$F_c = \left(kmyr / F_E\right) \cdot \left(1 + f\left(\gamma - \gamma_o\right)\right) / 4.5 \quad (10)$$

Asian and Eco-Tires

The stocks of tires are averages of different types of tires of different qualities. The distribution of different types of tires among the various stocks is assumed to be homogeneous. Because the lower retreadability of Asian tires and the improvement in fuel efficiency resulting from using eco-tires are a main focus of this analysis, Asian and eco-tires are treated differently. The fraction of Asian and eco-tires in the various tire stocks is explicitly monitored in order to correct for the different technical characteristics of these tires.

For Asian tires, the maximum recovery rate and production costs are different than for other tires. An important impact of eco-tires is the improvement of fuel efficiency. Therefore, the fuel efficiency is divided by a factor *a* representing this improvement. The higher the percentage of eco-tires in the stock of tires used by consumers, X_e^s, the higher the improvement in fuel efficiency. Fuel consumption for eco-tires, $F_{C,e}$, is defined as:

$$F_{C,e} = F_c / \left(1 + a \cdot X_e^s\right) \quad (11)$$

A limited amount of data is available in order to implement the model. Nevertheless, the model is able to reproduce roughly the materials flows for the period 1990–1999. Calibration of the model has been a combination of expert-based assumptions, and the adjustment of parameters such as α and β.

Results

The final outcomes of the scenarios are presented in various forms. First, the materials flows are reported in terms of demand and production of the various types of tires. Next, monetary costs are presented for each stage in the life cycle. The results are discussed in terms of private costs, external costs, and social costs. To verify how the various scenarios meet the European Union (EU) policy objectives on recycling as defined by the Priority Waste Stream Group on Tires, recycling indicators for the scenarios are also reported (European Commission 1993).

Material Flows and EU Targets

The model is driven by a given demand for road transport service in northwest Europe. Based on developments in the last decade, this demand is expected to grow approximately 0.3% per year. The demand for truck tires that results from this transport requirement varies depending on the technical and behavioral durability of tires. The lifetime of tires increases faster than the overall demand for shipment of freight. Therefore, the demand for truck tires declines for all scenarios including the base case (see figure 4a). The introduction of eco-tires and Asian tires does not have an additional impact on durability. Therefore, the overall demand for truck tires for these two scenarios coincides with the base case. Improving the management of the tire pressure leads not only to less fuel consumption but also to a longer lifetime of the tire. The most effective way to reduce demand is to intensify research in tire technologies, subsequently resulting in higher

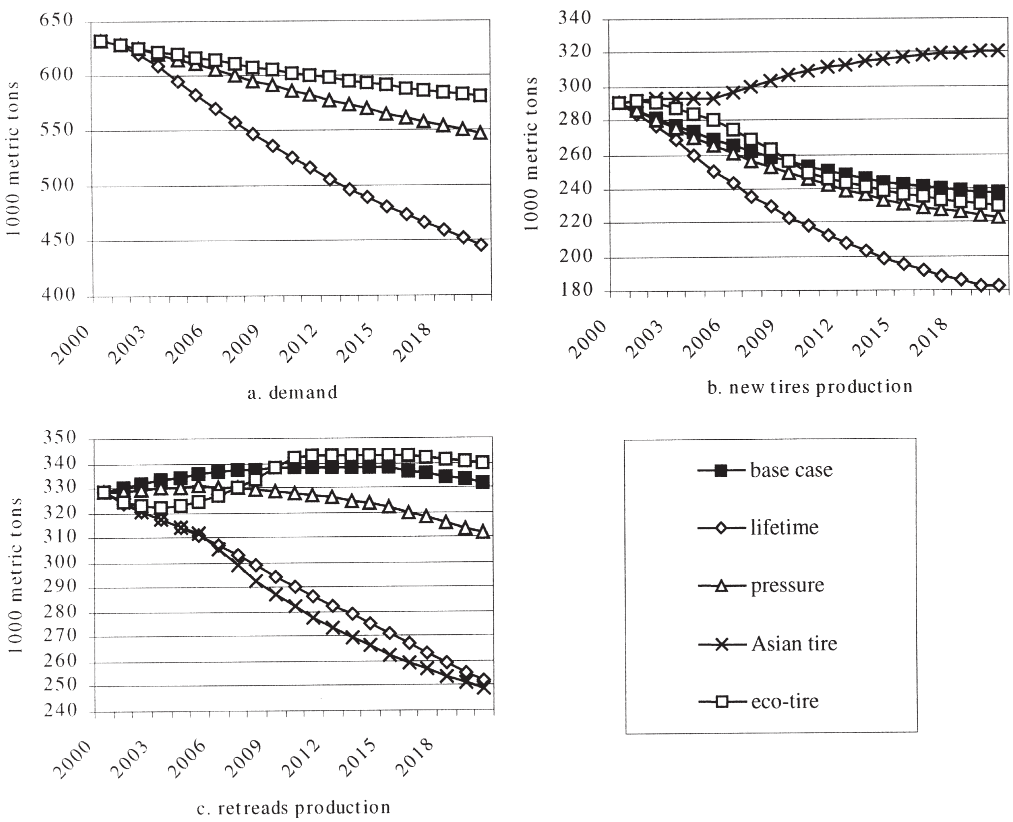


Figure 4 Main materials flows in the European truck tire cycle (2000–2020).

durability. If the lifetime increases from 250,000 kilometers in 2000 to 400,000 kilometers in 2020—rather than the anticipated 300,000 kilometers—the overall demand for truck tires declines by 150,000 tons by 2020.

The demand for truck tires is met through the production of new and retreaded tires. A net reduction in the demand for tires does not necessarily have to result in a net reduction in production of new tires. In this respect, the technical and economic level of retreadability is a crucial factor. Asian tires are considered to be nonretreadable. Despite the decrease in overall demand, the production of new tires in the Asian tire scenario starts to increase shortly after the introduction of Asian tires in 2000 (see figure 4b). In response to the reduced availability of retreadable tires, the retreading level declines most in the Asian tire scenario (see figure 4c). The lifetime scenario also shows a decrease in the level of retreading, this time not for reasons of reduced retreadability, but as a result of decreased overall demand. As the lifetime increases, the overall decrease in demand will eventually affect the new tire manufacturers as well as the retreading industry. The pressure scenario has a different impact. Because monitoring tire pressure prevents damage to the casing of the tire, improving pressure management has a positive effect on the retreadability of the tire. Therefore, the retreading industry is not negatively affected in the pressure scenario. The eco-tire scenario also demonstrates a typical growth pattern. Shortly after the introduction of eco-tires in 2000, retreading declines because the industry is not yet equipped to retread eco-tires. The adoption of these new technologies occurs gradually as its market grows. Therefore, the retreading curve is S-shaped.

To verify how the various scenarios meet the EU policy objectives on recycling as defined by the Priority Waste Stream Group on Tires, waste management indicators for the scenarios are also reported (European Commission 1993). The indicators that are ranked according to the waste management hierarchy include the prevention rate, the retreading rate, the recovery rate, and the landfill rate.

Prevention is aimed at the reduction in growth of "first-life" used tires. First-life tires are tires that result from primary tire manufacturing. According to the EU, this overall reduction is the end product of an improvement in the average lifetime of tires, which, with constant demand, should reduce the volume of first-life, used tires by 5%. The difficulty with this definition is that it is not clear what the baseline "demand" exactly stands for. The prevention rate can be calculated according to the demand level in 2000, or it can be based on the expected demand that results if business-as-usual developments in technology occur. This latter definition is represented by the base case. Compared to the level of 2000, the prevention accomplished in all scenarios meets the EU target. If the EU baseline is similar to the base case scenario, the Asian tire scenario and the eco-tire scenario do not meet this target. Both the lifetime and pressure scenarios do meet the target.

According to the EU, retreading should increase from 20% of the volume of used tires in 1990 to 25% in the year 2000. For truck tires, in particular, this implies an increase from 50% in 1990 to 60% in 2000. The target of 60% retreading is rather difficult to achieve, most likely due to technological limitations. In the Asian tire scenario especially, the retreading target will not be met according to the findings of this simulation.

Recovery of used tires should increase from 30% of the volume of used tires in 1990 to over 65% in the year 2000. For truck tires, this implies an increase from 35% in 1990 to 70% in 2000. Recovery includes using whole tires for other uses, using materials made from used tires, and burning used tires as a substitute fuel. The throughput in the waste stage in the tire cycle is the main determinant of the recovery rate. Because the retreading rate was low in the Asian tire scenario, the recovery rate is high.

The EU has decided to completely ban the disposal of whole tires in landfills or by incineration without energy recovery by 2003. This ban applies to shredded tires in 2006. Although landfilling clearly declines in the coming decades, the targets of the EU are not met in either scenario. In order to meet EU targets, specific policy measures should be undertaken to create incentives to ban landfill practices in Europe, without causing an increase in illegal dumping of used tires.

Social Costs

What is the overall impact of tires on European society? Figure 5 summarizes the social, private, and external costs of the various scenarios, respectively. Note that the *y*-axes of the graphs start at different levels to emphasize the distinctions among the scenarios. The external costs clearly outweigh the private costs. This implies that current prices, which correspond to the private costs, significantly do not reflect the true costs for society.

Many policy makers think that environmental improvements require financial sacrifices: That is, they think that the so-called win-win options, in which both the economy and the environment benefit, do not exist because the invisible hand of the market economy would already have utilized those options. The results presented in figure 5 demonstrate the opposite. The most environmentally benign scenarios also generate the best financial result. In other words, compared to the base case scenario, environmental benefits can be achieved at negative private costs.

Two reasons exist for this positive outcome. First, the stakeholders in the tire life cycle, particularly the consumers, do not always act in a financially rational manner. For them, it would be profitable to obtain eco-tires, yet the slightly higher purchase price prevents them from doing so. This explains the rapid increase in the market share of the Asian tire that is cheaper than the European tire. In a similar way, lack of awareness among drivers prevents the optimal management of the tire pressure, despite the fact that it is an extremely cost-effective measure. Second, markets do not clear in an instant. Divergences between demand and supply change prices, which in turn gradually steer the market toward equilibrium. Figure 5 shows the total ex-

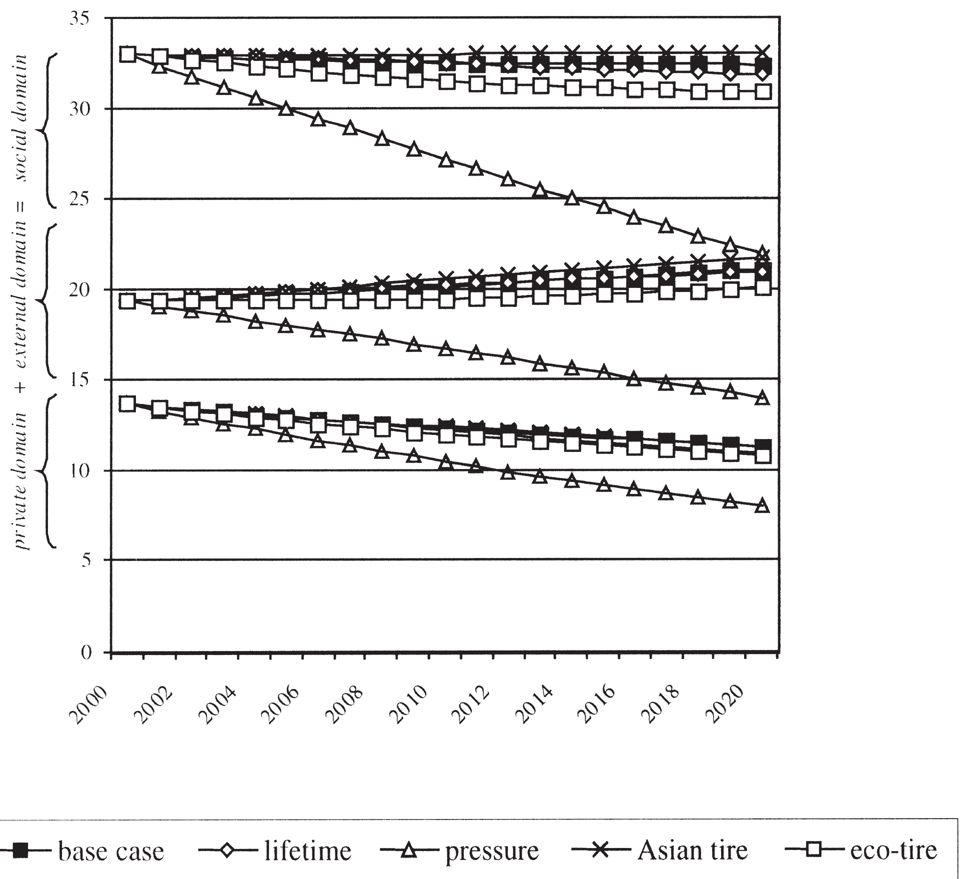


Figure 5 Overall social, external, and private costs (2000–2020).

ternal costs. Surprisingly the base case does not generate the highest environmental damage. Both the Asian tire scenario and the lifetime scenario perform worse. The higher environmental damage in the Asian tire scenario results from the lower degree of the relatively environmentally favorable tire retreading and the higher proportion of relatively more environmentally damaging new tire production. Also the external costs for waste management are higher in the Asian tire scenario.

The higher environmental damage in the lifetime scenario is rather counterintuitive. One would expect the lifetime scenario to be less environmentally damaging because, as was shown in figure 4a, the lifetime scenario generates a large reduction in demand for tires. This reduction, however, is not decisive in the external costs. In the base case scenario, an exogenous improvement of the fuel efficiency is assumed for each new tire produced. Because the lifetime is extended, the replacement of the tires is postponed. On average, more fuel-inefficient, old-fashioned tire types are in use in the lifetime scenario, causing a higher level of fuel consumption and, subsequently, higher environmental impact. In spite of the smaller throughput, the lifetime scenario generates more environmental damage.

The scenarios that focus on fuel consumption perform best in terms of both private and external costs. The most striking scenario is the pressure scenario. Simply by monitoring tire pressure more cautiously, significant financial and environmental gains can be achieved. No technological solution such as eco-tires or the development of tires with a longer lifetime can surpass this scenario. In other words, it is primarily the consumer, and much less the tire manufacturers that can contribute to environmental management. Of course, if the consumer purchases eco-tires and improves the tire pressure, environmental damage is reduced the most.

To understand the origin of the varying effects of the five scenarios, the external and private costs are analyzed in more detail in the following sections.

External Costs

Environmental research on tires focuses mostly on the waste stage of the lifecycle. Disposed tires draw significant attention, partly due to their bulkiness and conspicuousness. Also, the extraction stage in which natural and synthetic rubber are generated receives considerable attention. Although such partial studies are useful in solving environmental problems within one segment of the life cycle, these investigations are unable to expose the relative importance of their contribution. This can only be achieved by taking the full life cycle into account. The comparison of the external costs among the four segments of the life cycle in figure 6 confirms the earlier conclusion that the consumption stage is by far the most important stage.

Comparing the four parts of figure 6 shows that about 95% of the environmental damage related to tires is generated in the consumption stage. This environmental damage is completely caused by fuel consumption required to compensate for the friction of the truck tire. This friction is currently much higher than it should be as a

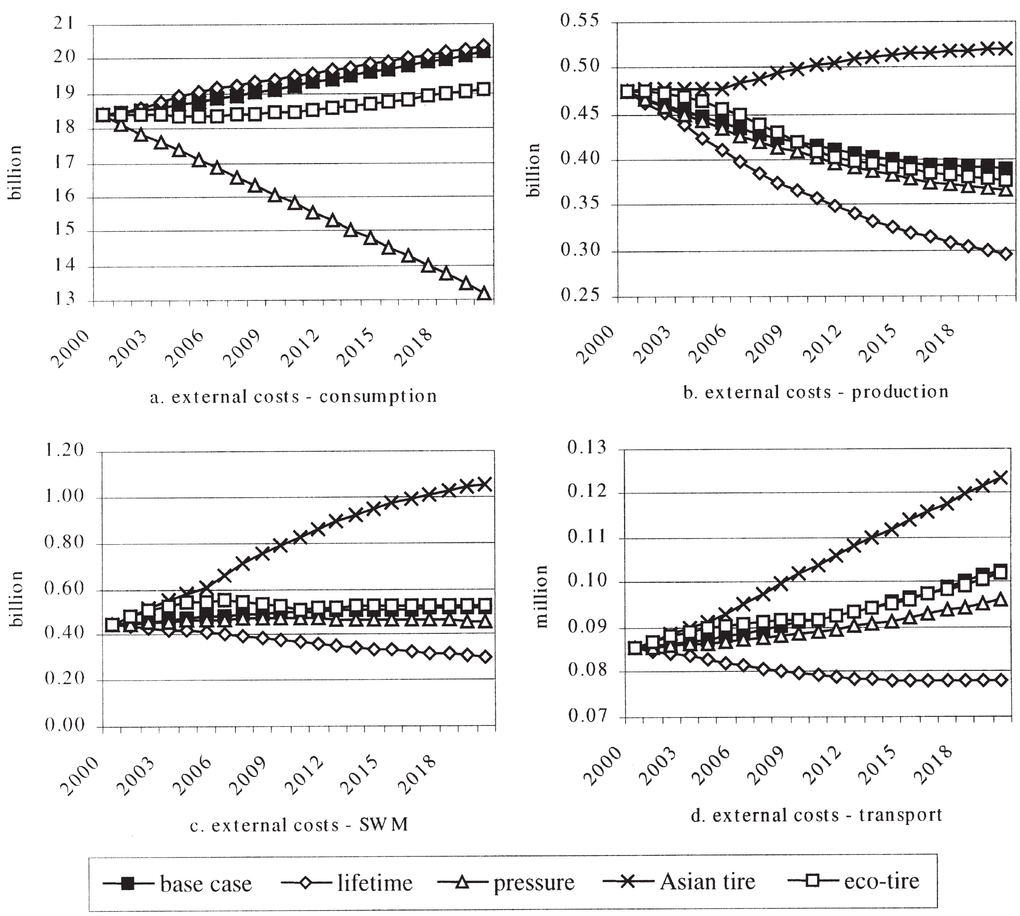


Figure 6 External costs by segment in the life cycle: (a) consumption; (b) production; (c) solid waste management (SWM); (d) transport.

result of underinflation of the tire. Environmental improvements should, therefore, primarily be sought by improving driving behavior and tire maintenance. Alternatively, eco-tires can be introduced. Extending the lifetime of the tire also implies that the technical improvements in fuel efficiency are postponed. Therefore, the external costs of the lifetime scenario are higher than those of the base case scenario. Asian tires do not have an impact on fuel consumption.

There are two reasons for the external costs (see figure 6b) to vary in the production stage: the overall level of production and the proportion of retreads in the overall production. The environmental damage of new tire production is higher than that caused by retreading (note that both retreading and new tire manufacturing are included in the production stage). As was shown in figure 4a, the overall demand, and thus production, in the base case, Asian tire, and eco-tire scenarios coincide. Because the Asian tire leads to less retreading, the environmental impact in production is worse than in the base case. For the eco-tire, a similar pattern evolves in the early years after the introduction, but as the retreading of eco-tires picks up, the environmental impact becomes lower than in the base case. In other words, promoting retreading is good for the environment, although the gain is not substantial. The main reduction in the external costs in the production stage is achieved by reducing the production volume. Both the lifetime and pressure scenarios are effective in this respect.

The external costs in the SWM stage in figure 6c show a wide variation for the different scenarios. After 2000, the quantity of disposed tires declines in the base case scenario due to the decrease in the overall demand for tires. Improvements as a result of lifetime extension of tires have the most positive impact on the environmental impact of the SWM stage. Because better management of the tire pressure also leads to a longer lifetime of the tire, this scenario also registers a significant reduction in the level of disposed tires. The Asian tire scenario generates the highest level of worn-out tires and, therefore, performs worst. In the first instance, the introduction of eco-tires also leads to higher disposal levels. As the retreading industry gradually adopts the new techniques for handling eco-tires, the level of disposed tires declines again.

Figure 6d depicts the external costs in the transport stage. The absolute level of these costs is small compared to those of the other stages. This result argues against environmental action groups that desire to keep production activities local in order to avoid transport. Transport does not seem to make any difference in the case of tires. The Asian tire scenario generates the highest transport externalities because the transport requirement particularly related to the transfer of worn-out tires is larger than in the other stages. The main source of externalities in the transport stage results from the SWM stage.

Figure 7 shows the disaggregation of the external costs by type of environmental impact. Because the external costs of eutrophication are lower than one million €, this graph is excluded in figure 7. Again, one quadrant, human toxicity, dominates by accounting for more than 95% of the total external costs. This high level is due to the strong relation of human toxicity with transport-related emissions caused in the consumption stage. It is particularly the emission of particulate matter (PM_{10}) and nitrous oxide (NO_x) that causes the negative impact on human health.

Global warming is also mainly caused in the consumption and the SWM stages through emissions of carbon dioxide (CO_2) and methane (CH_4) (see figure 7b). The cost pattern is similar to the damage for human health.

Damage to crop, forest, and materials has a significant negative net cost because the ozone-depleting effect of NO_x has a positive impact on crop yield and exceeds the negative impact of VOC and SO_2 on crop yield. Therefore, figure 7a and figure 7c show similar patterns in opposite directions (mirrored pattern).

Finally, the development of disamenity costs, caused mainly by the presence of landfills and incinerators and, to a lesser extent, by transportation-related traffic congestion, reveals a pattern similar to the external costs of the SWM stage (see figure 7b and figure 7d). Due to the increased burden of used tires, the disamenity effect is particularly large in the Asian tire scenario and small in the lifetime scenario.

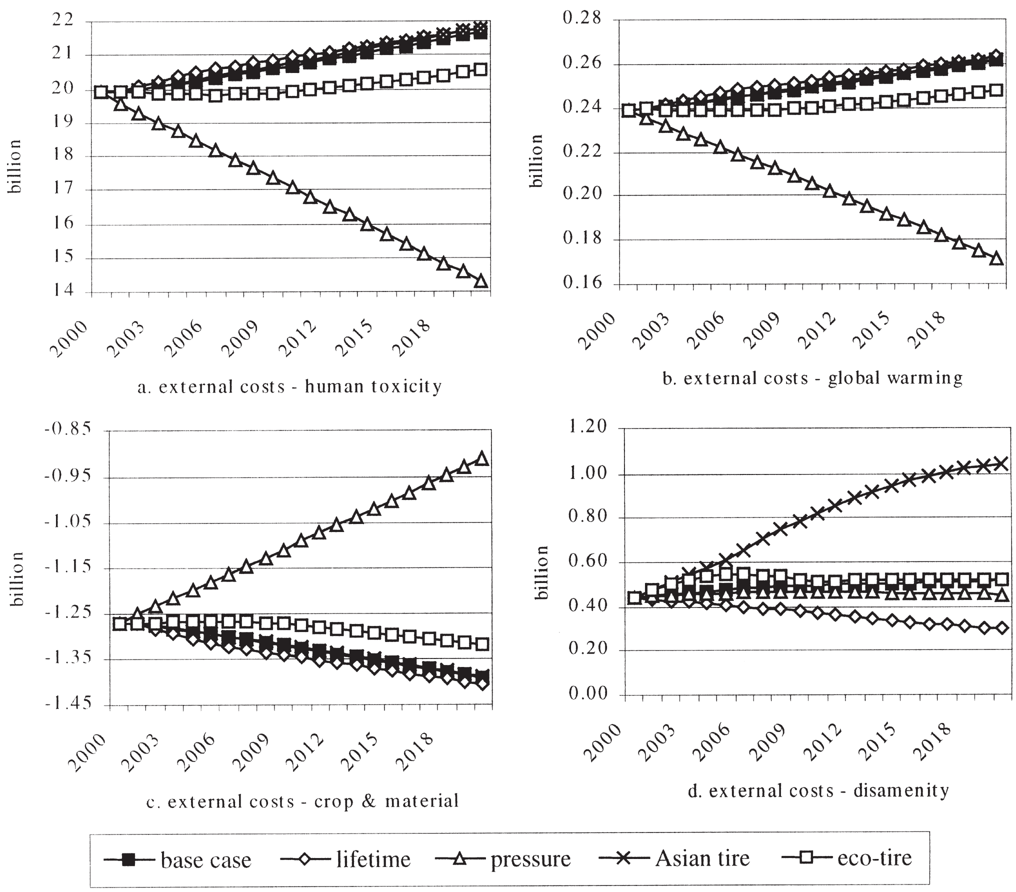


Figure 7 External costs specified by environmental problem: (a) human health; (b) global warming; (c) acid rain; and (d) disamenity.

Private Costs

As shown in figure 8a, the consumption stage is the largest contributor not only to external costs, but also to private costs. Approximately 70% of the total private costs are generated during this stage. The costs in this stage are solely determined by fuel consumption. Labor and capital costs do not play a role. The base case, lifetime, and Asian tire scenarios come out as the most costly situations. This proves that minor changes in fuel efficiency dominate the overall financial performance of the life cycle. Also visible is the larger improvement resulting from pressure management as compared to the introduction of eco-tires. The combination of both strategies obviously generates the largest financial gain.

Figure 8b shows that, due to the reduced level of consumption, tires with a long lifetime generate the least aggregated production (purchasing) costs. It is not in the interest of tire manufacturers to pursue this scenario. Their main goal is to maximize sales and profit. Because eco-tires are more costly and do not lead to a reduction of the market, the tire industry is more likely to pursue this scenario. Besides serving the interest of the industry, this scenario also serves the interest of the society as a whole. The improvement of pressure management only leads to a small market reduction.

The negative costs of the SWM stage, shown in figure 8c, are mainly the result of the generation of by-products, such as rubber granules for the production of rubber tiles and tire-derived fuel for energy consumption in cement kilns. Because the Asian tire scenario generates the largest throughput, it also generates the highest benefits in the recycling industry as well as the highest costs in the waste management sector. The oppo-

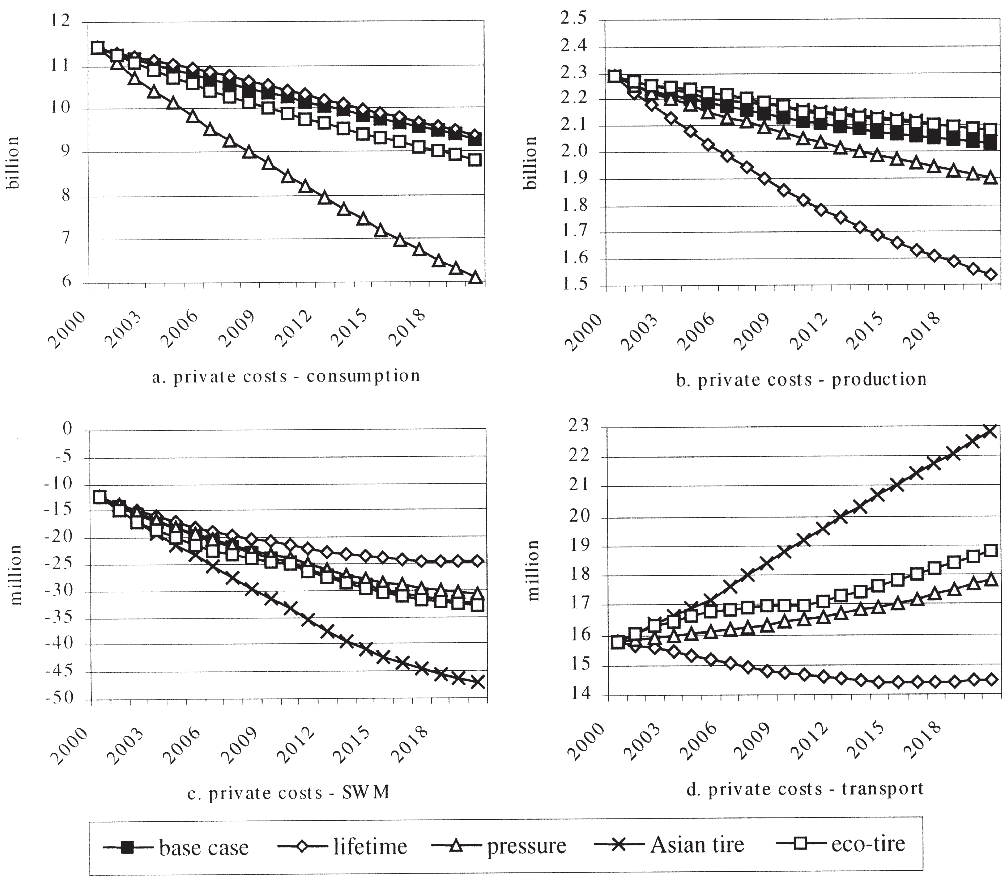


Figure 8 Private costs by segment of the truck tire life cycle: (a) consumption; (b) production; (c) solid waste management (SWM); (d) transport.

site occurs in the lifetime scenario that generates the smallest throughput. Also, the private costs in the transport stage are strongly related to the throughput in the sector (see figure 8d).

Conclusions

The simulation model presented in this article describes the dynamic life cycle of truck tires in western Europe. It is suitable for deriving qualitative insights into the long-term dynamics of the life cycle by incorporating the economic and environmental effects occurring in the extraction, production, consumption, and waste management stages. Various scenarios that represent potential future conditions have been simulated. It should be noted that the characteristics of the methodology used do not justify precise quantitative predictions. Distributions within the truck tire market, such as the variation between different tire types and brands, have been averaged. Despite this restriction, several convincing conclusions can be drawn from the model simulations.

Although most policy interventions in the tire life cycle focus on waste managers and tiremanufacturers, the consumer is the most powerful stakeholder when it comes to improving the environmental performance. In fact, the consumer can achieve this at negative financial costs. By improving the monitoring and management of tire pressure, environmental gains can be realized that would not be attainable by technological or economic changes in the other stages. The second best option—utilizing eco-tires rather than the normal tire—also lies within the domain of the consumer and can be achieved at negative financial costs. In summary, the environmental improvements in the tire cycle with the highest potential are both win-win options. Deficiency in driver-awareness and lack of accessible pressure equipment may be reasons why consumers are not already realizing these options. Public campaigns supported by government and industry should attempt to reduce this ignorance.

Obviously, the role of tire manufacturers is still of crucial importance in creating a more sustainable tire life cycle. By improving the durability and fuel efficiency of tires, significant improvements can be achieved. From the perspective of the tire manufacturer, it is more rational to focus on fuel efficiency because this avoids loss of sales market. In introducing eco-tires to the traditional market, however, it is important that the retreading industry simultaneously make the shift to these new tires. Retreading techniques require certain modifications that are economically feasible only if the retread market for eco-tires has sufficient volume. Therefore, the government could play a role in developing and promoting new retreading techniques for eco-tires.

The waste stage of tires also deserves additional attention. Eventually, every tire will reach the end of its functional life, and so it is important to utilize the tire waste as efficiently as possible. Clearly, landfilling of tires cannot be considered an efficient waste management option. The difference in efficiency between material recycling and energy recovery, however, is too small to recommend one over the other. To create incentives for the individual member countries, the European Commission defined strict targets that need to be met early in the next millennium. These targets define concrete levels for the various waste management options. Most of the scenarios seem to be in line with these targets.

An overall conclusion is that the result of this study conflicts with the philosophy of the "factor 4" school of thought,[10] which reasons that reducing throughput in the economy is the most efficient way to slow down environmental degradation. It is not the mass of the tires in use, but the quality of the tires and their management that are decisive in the reduction of environmental pressure caused by the tire life cycle.

Acknowledgments

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Notes

1. One metric ton = one megagram = 1.102 short tons. Throughout this article, the term "tons" refers to "metric tons."
2. Two technologies are used: hot and cold retreading. Combining heat and pressure, "hot retreading" takes place in a mold that creates a new tread design. In cold retreading, the tread is molded and cured in advance and then chemically bound to the prepared casing.
3. Today, retreading is more common for truck tires than for passenger car tires. The retread rates of truck tires and passenger tires are approximately 80% and 20%, respectively (U.K. Environment Agency, 1998). Car tires can be retreaded only once, truck and bus tires three to four times, and aircraft tires eight times. In practice, truck tires are retreaded fewer times (an average of 1.5 times in the Netherlands, and 2.5 times in eastern Europe).
4. An external effect that, due to lack of reliable data, has been ignored in the consumption stage is the solid residue arising from the wearing of tires that is left on roadways and then presumably washed into surface waters (see U.K. Environment Agency 1998 for more information).
5. "€" is the symbol for the euro, the new European currency. In late 1999, at the time this study was conducted, 1 € was equivalent to 0.95$ (U.S.). In the meantime, the euro has diminished in value. By May 2000, 1 € was approximately equivalent to 0.89$ (U.S.).
6. The largest plant in Europe is Elm Energy Wolverhampton, UK, with an electricity output of 175,000 MWh and a consumption of 94,000 tons of worn-out tires per year, which is about 15% of the country's total used tire generation (U.K. Environment Agency 1998).

7. Beyond this point, the term "tires" refers to "truck tires."
8. The underlying data applied in the model are too extensive to report in this publication. Interested readers can contact the authors for more detailed insight into the data.
9. To accurately determine the environmental impact, the concentration levels of each pollutant should be determined taking into account the physical properties of the site. For example, an air pollutant emitted during sea freight will do less harm than the combustion of rubber in a densely populated area. It is beyond the purpose of this model, however, to take into account this level of detail. Therefore, average values for western Europe are applied. For further reading on site dependency of environmental effects see, for example, Potting et al. (1998).
10. See Von Weizäcker et al. (1997) and Reijnders (1998) for more information on the "factor 4" school of thought.

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Appendix 1 Technology Matrix

The technologies applied in the model are based on best available technologies (BAT) for all processes in the cycle. Associated with each process is a vector, also known as a technology matrix, which describes the various inputs and outputs. Table 3 gives an example of a technology matrix for tire retreading. The individual processes are linked through a series of mass balance equations that stipulate that total mass of materials used equals total mass of materials produced. The transportation logistics are also taken into account. By linking the various stages in the cycle through a series of materials balance flow equations, the level of raw, intermediate, final, and pollutant goods used and produced can be computed.

Appendix 2 External Values

The contribution of the range of pollutants to the external costs is expressed in monetary terms. These values have been derived from various studies. An overview of these studies is provided in Van Beukering (2000). Table 4 summarizes the selected values applied in this study.

Table 3 Example of a technology matrix for tire retreading

		Quantity	*Unit*
Input	Partly worn tires	1.00000	Metric ton
	Tread	0.36133	Metric ton
	Cement	0.00618	Metric ton
	Water	0.00254	Metric ton
	Labor	0.01633	Man-year
	Electricity	1,080	MJ
Output	Tires	0.97623	Metric ton
	Rubber from buffing	0.09984	Metric ton
	Refused tires	0.04596	Metric ton
	HC	0.00191	Metric ton
	PM_{10}	0.00002	Metric ton

Source: Rosendorfová et al. (1998, 110).

Note: The emissions resulting from the use of electricity are not included in this table. These emissions are accounted for elsewhere in the model.

Table 4 Externalities: new estimates

Impact category	*Pollutant*	*Value*	*Unit*
Global warming[a]	CO_2	2.40	€/metric ton
	N_2O	748.3	€/metric ton
	CH_4	44.9	€/metric ton
Human health[b]	SO_2 production	7,204	€/metric ton
	NO_x production	3,432	€/metric ton
	PM_{10} production	23,683	€/metric ton
	VOC production	734	€/metric ton
	HC production	602	€/metric ton
	SO_2 transport	6,401	€/metric ton
	NO_x transport	3,154	€/metric ton
	PM_{10} transport	87,258	€/metric ton
	VOC transport	602	€/metric ton
	CO transport	0.71	€/metric ton
	Benzene transport	554	€/metric ton
	Accidents transport	32	€/1,000 HGVkm[d]
Crop material damage[b]	SO_2	215	€/metric ton
	NO_x via ozone	–697	€/metric ton
	VOC via ozone	642	€/metric ton
Disamenity[c]	Nonhazardous waste	37	€/metric ton
	Hazardous waste	370	€/metric ton
	Congestion	171	€/1,000 HGVkm
Ecosystem[b]	BOD	240	€/metric ton
	COD	240	€/metric ton
	TSP	24	€/metric ton
	N	4,000	€/metric ton

[a] Tol (1999).

[b] EC (2000).

[c] Brisson and Pearce (1995) for disamenity values of landfilling and Brossier (1996) for external costs of congestion.

[d] Heavy good vehicle kilometers (HGVkm).