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Use of system dynamics for proper conservation and recycling of aggregates for sustainable road construction

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ABSTRACT

A significant amount of mineral aggregates are used in constructing, rehabilitating and maintaining roads. As local (nearby) quarries get exhausted, aggregates need to be hauled from sources that are at ever-greater distances. Hence, over time the cost of trucking as well as the amount of emissions generated by trucking increases with a decrease of local natural aggregate stocks. The objectives of this study are to construct and utilize a system dynamics model of the depletion of a stock of natural aggregates due to pavement construction and maintenance, and determine the effect of using local and nonlocal aggregates, recycling and project cancellation (slowing growth) on the paving of roads. Long-term simulations are carried out with available aggregate stock, trucking distance and cost data. The quality of roads and a sustainability score, based on engineering, economic and environmental factors (emissions) are evaluated for different scenarios. An optimal combination of the use of local and nonlocal recycled aggregates, recycling and project cancellation is recommended. The proposed system dynamics model could be utilized by agencies to plan for the proper utilization of aggregate resources for road development and maintenance/rehabilitation projects.

1. Introduction

Good quality roads are essential for the economic growth of a nation. While much of the investment in the developing countries is used for constructing new roads, in much of the developed world the major emphasis is on the maintenance and rehabilitation of an existing and mature road network. Because of soaring energy costs, material costs and budget shortfalls, as well as increasing concerns about emissions and environmental pollution, there is a huge backlog of pavement maintenance and rehabilitation projects in nations such as the US. On the other hand, there are vigorous, on-going, discussions on how to sustainably maintain existing road assets that have been created by huge investments. A sustainable method for properly maintaining pavement is the topic of many on-going research studies around the world.

Aggregates constitute the bulk of the different layers of a typical road pavement structure and pavement construction is the single largest market for the natural aggregate (sand, gravel and crushed stone) industry. Typically sub-base and base courses are made completely out of aggregates, whereas aggregates constitute more than 80% and 90% of Portland cement concrete and asphalt pavements, respectively (Tepordei, 1999). More than 30,000 t of aggregates could be required per kilometer of a new asphalt pavement highway (NYCMA, undated). The continuous use of huge amounts, adoption of specifications for higher quality, and more restrictions on the opening of new sources can lead to a scarcity of natural aggregates. Already, a severe shortage of quality aggregate is prevalent in many parts of the US and in many areas of the developing world. This scarcity of aggregates now forces truck, rail and marine delivery of materials from great distances, which increases costs, traffic, and the emission of air pollutants. One example of particulate emissions are those from diesel engines, which have been identified as carcinogenic and harmful to the human health, even at occupational and environmental levels of exposure. An increase in cost and emissions can lead to a slow-down of road maintenance

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and rehabilitation of roads, which will in-turn lead to a rapid fall in the quality of roads, and related harmful effects on transportation (e.g., accidents).

An alternative to the use of natural aggregates is the recycling of reclaimed asphalt pavement (RAP) material for new roads, and existing road maintenance and rehabilitation. Recycling can slow the depletion of natural resources, and there are a number of research studies being carried out to determine the extent to which RAP can be used in new paving materials without compromise. The option of recycling, together with the availability of local and non-local aggregates, must be considered during the planning of road construction projects. Because there are many interconnected factors in the use of natural aggregates in road construction, such consideration can best be made with the help of a holistic approach such as system dynamics computer simulation modeling.

2. Objectives and scope

The objectives of the study that are reported in this paper are to:

(1) Develop a proper system dynamics model of the depletion of aggregate stock due to road construction and maintenance, with specific emphasis on the increase in haul distances due to depletion of local aggregate stocks.
(2) Explore different options for conserving and recycling aggregate resources in the future so as to minimize cost and emissions and hence enable sustainable road construction.

3. Background

3.1. Aggregate industry: Importance and impact

Aggregates are crucial resources for infrastructure development activities such as road building and concrete production. For example, 1 m^2 of built area consists of about 2 t of aggregates; the construction of one house uses up to 400 t of aggregates; the construction of 1 km of motorway requires up to 30,000 t of aggregates and the construction of 1 m of railway for a High Speed train (TGV) uses up to 9 t of aggregates (Miliutenko, 2009). Although aggregate sources are widespread, they do not occur everywhere. Moreover aggregates may not meet specifications, aggregate quarries could be shut down, and potential reserves may not be reachable because of conservation rules or encroachment (Langer, 2011). Furthermore, the permitting of new aggregate sources can take anywhere from 5 to 10 years (California Department of Transportation (CDOT), 2007). Therefore, there is a critical need during the development of road (and any other aggregate intensive) construction projects for decision makers to understand the issues surrounding aggregate resource availability so that they can strategically plan and ensure a proper supply in the future (Meininger and Stokowski, 2011).

The global production of aggregates amounts to 15 billion tonnes per year, with a predicted annual increase in demand of 4% (Miliutenko, 2009). In the US a record production of 2.3 billion tonnes was noted for 1996, and an increase rate of 1% (conservative estimate) was predicted. It has also been predicted that between the years of 2000 and 2020, the US would produce a total of 36.5 billion tonnes of aggregates (Tepordei, 1999). The predicted cumulative amount of aggregate production in the first quarter of the twenty-first century exceeds the total amount that was mined in the 100 years of the twentieth century (Tepordei, 1999). Langer (2011) also reports similar values, and shows an actual production amount of 3 billion tonnes in 2008, and a total production of approximately 23 billion tonnes between the years of 2000 and 2010. A few other estimates of production and use are as follows.

- The production of aggregates in Ontario is predicted to vary between 100 and 200 million tonnes annually, and the projected demand in urban areas is 1.5 billion tonnes in the next 25 years (Binstock and Carter-Whitney, 2011).
- Only about 43% of an existing reserve of 3.4 billion tonnes in a major portion of Ontario (areas 2, 3 and 5) has been reported to be of high quality (suitable for concrete and asphalt) (Ontario Ministry of Natural Resources (OMNR), 2009).
- Minnesota uses about 4.5 million tonnes of aggregate every year for maintenance activities of its approximately 213,000 km of roads (Aggregate Resources Task Force, 1998).
- A study on the aggregate resource of a seven county-metropolitan area in Minnesota (area with the highest demand for aggregates) shows 1.7 billion tonnes of aggregates remaining (in 2000), down from an estimated original available stock of 5.7 billion tonnes. The exhaustion of all resources is predicted by the year 2029 (Southwick et al., 2000).
- California used approximately 162 million tonnes of aggregate every year between the years of 1981 and 2010 (Clinkenbeard, 2012).

Although the extraction of aggregates from pits or quarries is a necessity for supporting the growth and proper maintenance of infrastructure, especially roads, it can cause major impacts on the environment. Extraction removes natural vegetation, topsoil and subsoil, leads to the loss of animal wildlife, biodiversity and aquatic systems, lowers water quality, and results in a loss of recreational areas (Binstock and Carter-Whitney, 2011). Furthermore, it causes noise, dust and vibration and hence affects adjacent ecosystems and communities in a negative way.

3.2. Aggregate transportation: Impact and concerns

Of the several steps in the use of aggregate from quarries (planning/permitting, royalties and taxes, capital expenses, transportation, labor, energy, mining and processing), transportation is the most costly component (Langer, 2011). Trucking remains the most popular method (>90% of shipments) for the transportation (hauling) of aggregates, as it allows flexibility in shipment by easily responding to changes in demand and schedule. The other advantages of trucking include relatively less initial capital investment, no requirement for any specialized unloading equipment, the ability to move trucks to different loading locations and to use any existing road infrastructure. However, the trucking of aggregates is a high impact activity; it uses fuel, leads to emissions, generates noise and dust, and can cause major damage to roads. Of course, the greater the hauling distance the greater the impacts (Binstock and Carter-Whitney, 2011).

The impact of aggregate hauling is well documented. For example, a report from California indicates that from 1981 to 2010, an average of 162 million tonnes of aggregates were consumed every year, resulting in approximately 7 million truck trips per year (each containing 22.5 t), a consumption of 179 million liters of diesel fuel and 468,000 t of emitted carbon dioxide every year (for an average haul distance of 40 km, and a 80 km round trip) (Clinkenbeard, 2012).

It has been reported that the cost of aggregate hauling increases by 100% for an increase of trucking distance of 40 km, with a cost of approximately 10 cents per km-tonne of aggregates for large semi-trailer trucks. Other estimates of the increase in cost due to hauling in the literature include: