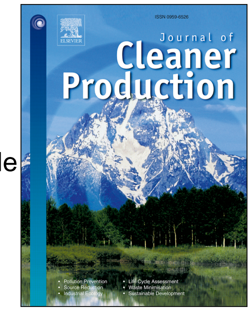
Accepted Manuscript



Analysis of alternative road construction staging approaches to reduce carbon dioxide emissions

Jan Krantz, Weizhuo Lu, Tim Johansson, Thomas Olofsson

PII: S0959-6526(16)32078-9

DOI: 10.1016/j.jclepro.2016.12.023

Reference: JCLP 8598

To appear in: *Journal of Cleaner Production*

Received Date: 19 November 2015

Revised Date: 2 December 2016

Accepted Date: 6 December 2016

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1. Introduction

Road construction projects generate considerable amounts of greenhouse gas (GHG) emissions such as carbon dioxide (CO_2) due to the large-scale use of heavy duty diesel (HDD) construction equipment (Hajji and Lewis, 2013), as well as extensive earthworks and earthmoving operations (Kenley and Harfield, 2011). The Swedish Transport Administration (STA) has declared that a reduction of energy use and associated CO_2 emissions in road construction should be a priority (Trafikverket, 2012). Despite this, previous studies have largely disregarded emissions of CO_2 occurring at construction sites according to Davies et al. (2013), Kenley and Harfield (2011), Kim et al. (2011). Instead, the primary indicators of construction performance are construction time, costs and quality (Chan and Chan, 2004).

Some concepts of "efficiency" motivated the early approaches or rules of thumb used in road construction, such as *cut to fill*, used to keep earthworks processes within the construction site (Mawdesley et al., 2002) and *short haul first,* used to minimize mass hauls (Askew et al., 2002). Modern-day project managers use more systematized approaches in road construction, such as mass haul diagrams for visual aid (Jayawardane and Harris, 1990) and linear programming-based mass haul optimization methods (Easa, 1988). Mass haul diagrams and linear programming-based optimization have been adopted in some commercial planning software, such as TILOS and DynaRoad (Shah and Dawood, 2011). Linear programming-based mass haul optimization has been combined with geographic information systems (GIS) (Moselhi and Alshibani, 2009) and productivity simulation (Ji et al., 2011) in recent research. Although approaches like mass haul optimization offer potential to significantly reduce CO_2 emissions, research on the topic has so far been limited (Kenley and Harfield, 2011).

Research has also been conducted on single construction equipment, much of it focusing on measuring emissions or energy use with portable emissions measurement systems (PEMS) (Abolhasani et al., 2008, Frey et al., 2010), engine dynamometers (Babbitt and Moskwa, 1999) or chassis dynamometers (Yanowitz et al., 2000). Models such as MOVES (EPA, 2015) and California Air Resources Board's (2011) OFFROAD (now being replaced by equipment specific models) have been used for developing emission inventories and assessing energy use on national, state and local levels. The emission factors in these models are based on lab testing using engine dynamometers (Rasdorf et al., 2010). Emission inventory data have been used to assess emissions or energy use on a project level (Rasdorf et al., 2012). In fact, MOVES also allows estimation of project emissions based on equipment data selected from its equipment inventory database and user specified duration data (EPA, 2015).

Life-cycle assessment (LCA) approaches have been applied to road projects but have rarely included all life-cycle stages. For instance, Stripple (2001) did not include end of life treatment, Huang et al.