

Development of LCA-AIR – An Airport Pavement Life Cycle Assessment Tool

John Kulikowski¹, Mohammed Sawalha², Michael Sladek³, Jeffery Roesler⁴

Abstract

The demand to provide more sustainable facilities and infrastructure has increased over the past ten years. The ability to measure and quantify the environmental impacts of such projects is in higher demand. Life cycle assessment (LCA) studies/tools are developed for highway infrastructure and pavements but a limited number of studies have been developed for airports and few for their pavement facilities. This paper introduces a pavement LCA tool called LCA-AIR 1.0 to fill the necessary gap in quantifying sustainability strategies for airfield pavements. LCA-AIR incorporates the material production, construction/maintenance and rehabilitation, and use phases in the analysis. It uses standard indicators from TRACI to quantify these impacts based on two functional units (square yard and pounds-mile traveled). LCA-AIR showed that each phase contributed to the environmental impact but overall, the use phase produced the greatest LCA impact factors. The material production (MP) phase was heavily influenced by the binding agent (cement or asphalt). Brooming for foreign object debris (FOD) contributed significantly to the construction/maintenance and rehabilitation (CMR) phase. Use (U) phase was dominated by aircraft operations, particularly taking off and cruising. LCA-AIR currently does not consider the pavement end of life phase. An LCA example and corresponding environmental impacts for two different pavement types (Portland cement concrete and asphalt concrete) over the lifespan of a new airfield is provided to demonstrate the capabilities of LCA-AIR.

Introduction

In the United States the transportation sector generates 27% of total US greenhouse gas emissions (GHG) of which, aircraft account for 8.2% of the total (Federal Highway Administration 2015b). The US has an estimated 13,112 airports (Federal Aviation Administration 2015a). Airports world-wide (U.S.) process 3.3 billion passengers (838 million), 3.6 trillion passenger-miles (963 billion) and 55 million short-tons of freight annually, driving approximately 3.0% of the worlds GDP (International Civil Aviation Organization 2014; Senguttuvan 2011). Although the infrastructure quantity and areas are smaller than roadways, airports still have a significant environmental impact. In order to identify opportunities to reduce the environmental impacts of airport pavements, an LCA framework is required to first quantify the energy consumption and impact factors of current practices and operations.

¹ Chief, Airfield Pavement Evaluation Team; Air Force Civil Engineer Center; 119 Barnes Dr., Tyndall AFB, FL 32403; john.kulikowski.1@us.af.mil; 435-938-8507.

² Graduate Research Assistant; University of Illinois Urbana-Champaign; 205 N. Mathews Ave., Urbana, IL 61801; sawalha2@illinois.edu; 276-898-7430.

³ Masters Graduate; University of Illinois Urbana-Champaign; 205 N. Mathews Ave., Urbana, IL 61801; sladek1@illinois.edu; 815-861-4466.

⁴ Professor, University of Illinois Urbana-Champaign; 205 N. Mathews Ave., Urbana, IL 61801; jroesler@illinois.edu; 217-265-0218.

The ability to measure and quantify the environmental impacts of infrastructure and facilities is vital. Fowler and Rauch (2006) provide a thorough review of facility rating systems such as LEED, Green Globes, Green Star, GBTool, CASBEE, BREEAM, etc. Multi-disciplinary infrastructure projects use rating systems such as ENVISION to measure sustainability on a more comprehensive level (Institute for Sustainable Infrastructure & Zofnass Program for Sustainable Infrastructure 2015). More specific to transportation infrastructure and pavement facilities are rating systems such as Green Roads, INVEST, Illinois Tollway LCA Tool, etc. These rating systems help transportation agencies and other organizations find sustainable and innovative solutions to minimize their impacts on the environment. Currently, airport pavements do not have such rating systems. The Chicago Department of Aviation uses the *Sustainable Airport Manual* to guide project efforts to minimize environmental impacts for building facilities, maintenance materials, and parking areas (Chicago Department of Aviation 2013). This living document has evolved since introduction in 2003 and is based on the LEED rating system. However, this manual does not provide considerations for airfield pavements.

Project rating systems attribute points to specific actions taken during the design, construction, maintenance and operation of the facility but they do not quantify the environmental impacts resulting from the sustainability choices for a particular project. A life cycle assessment (LCA) is a method to quantify these environmental impacts from processes and projects throughout its life (Santero N. J. 2009). LCA studies/tools have been completed and developed for highway pavements, such as PaLate (Horvath 2004), PE-2 (Mukherjee & Cass 2011), Athena Pavements LCA (Athena Sustainable Materials Insitute 2013), and recently the Illinois Tollway tool, ICT-LCA (Al-Qadi et al. 2015) but airport pavement LCA studies and tools are needed. This paper presents the methodology and development of an airport pavement LCA tool called LCA-AIR. The initial development of LCA-AIR quantifies the environmental impacts of airfield pavement using the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts 2.1 (TRACI) categories established by the Environmental Protection Agency (EPA) (U.S. Environmental Protection Agency 2012). LCA-AIR can be used by airport owners, operators and engineers in their decision making process to make sustainable pavement choices based on quantitative comparisons.

Life Cycle Assessment Tool Framework

LCAs can consider the entire lifespan or a limited number of phases of a product, service or system with LCAs often completed to compare multiple products, services or systems. To ensure consistency in LCAs, the International Organization for Standardization (ISO) created two standards in 2006: ISO 14040:2006 and 14044:2006 (International Organization for Standardization 2006) with additional technical reports published to assist in application of the standards (International Organization for Standardization 2012). Other countries or regions have also published LCA standards such as PAS 2050:2011 by the British Standards Institute or EN 15804:2012 by the European Standard. ISO 14040 defines the four, high-level framework components of an LCA as seen below in Figure 1.

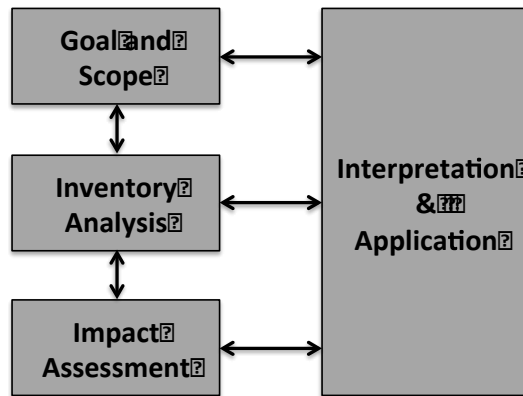


Figure 1: LCA framework (after ISO 14040).

The goal and scope includes the intended application and audience. The scope describes the boundaries, assumptions/limitations and the methodology for the assessment. Critical items in the scope are the functional unit, system boundaries, impact categories, allocation procedures, and data quality. The inventory analysis is critical and the most time consuming component. Balance must be struck on the analysis based on time to completion, available money, and data (quantity and quality). During this step, data is collected and analyzed in accordance with the goal and scope. The inventory data and sources determine the quality of the LCA. The inputs and outputs are assembled into a life cycle inventory (LCI) for each process defined in the project scope. Data used in the LCA can be primary and/or secondary. Primary data is collected at the source for each process in the product, service, or system. Secondary data is generic industry averages, which may come from databases or literature. Data quality is measured using indicators such as, technology (compatibility of technology at data collection time), time (age of data), geography (location of data sources), completeness (adequate period to even out normal fluctuations) and reliability (verifiability of measurements).

The impact assessment characterizes the inventory results into indicators (e.g. global warming potential, ecotoxicity, resource depletion, etc.) as defined in the goal and scope. These impacts are then related to their field. The interpretation includes the evaluation of information and results from the previous steps to analyze content, develop conclusions, assess limitations and formulate recommendations (Lewis 2013). As seen in Figure 1, the arrows are bi-directional, which depicts the iterative process of a LCA. The LCA can be refined at each step to ensure consistency and quality of the final product.

LCA-AIR Development Methodology

A standard airport configuration [runway (RW), parallel taxiway (TW), ladder TWs and apron] was selected for the initial tool development as seen in Figure 2. This airport serves as the basis for all processes needed to be considered in developing such a tool. Currently the LCA tool is limited to analysis of two runways, four taxiways and two aprons. Excel is used to provide the interface and database for this tool. Functional unit, system boundaries, impact categories, data quality and collection, and assumptions need to be stated to meet established standards. These are discussed briefly in the following sections.

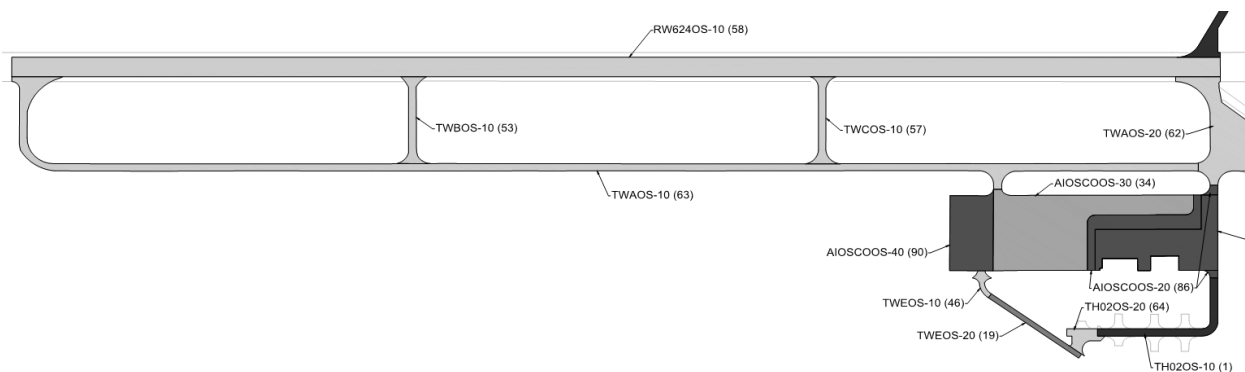


Figure 2 – Standard airport configuration

Functional Unit

The functional unit serves as the base unit to which the results are normalized. The function of an airfield is to provide operating space for aircraft in moving goods and passengers over its design life. Due to complexity of airports, two functional units are used. The first is square yards for all the processes except airplane operations. The second functional unit for aircraft operation is pound-mile traveled.

System Boundaries

The system boundary defines what processes, materials, and systems are included or excluded from the study. The system boundary in this study includes all the traditional life cycle phases of the pavement except the end of life phase. The system boundaries are consistent with LCA pavement frameworks published previously (Santos, et al. 2014; University of California Pavement Research Center 2010). Industry practice is to recycle the pavement materials at end of life. Due to the complexity of airports, their growth and land planning strategy, uncertainty exists for the pavement's final use and thus, recycling of pavement layer materials was currently not assumed. For highways, Santero et al. noted similar complexities in end of life and recycling allocations (Santero et al. 2011). A traditional highway LCA considers vehicle operations (fuel consumption) and not manufacturing, maintenance and disposal impacts. Similarly, LCA-AIR only considers flight operation for aircraft. Upstream impacts from aircraft manufacturing, facility construction and downstream impacts from aircraft maintenance and disposal were not included. Figure 3 below, shows the system boundary used in this study.

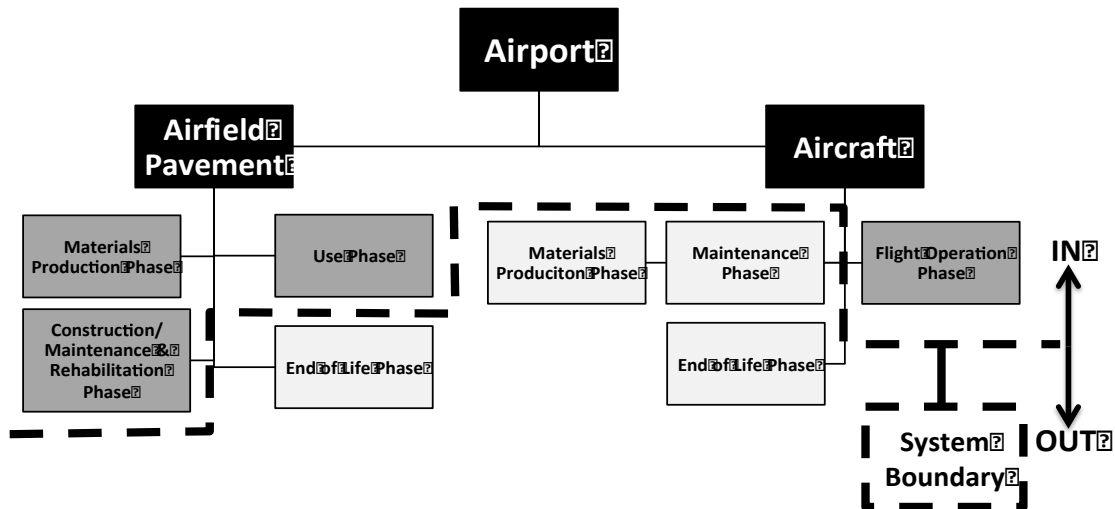


Figure 3: System boundary for LCA-AIR tool

Impact Categories

Impact categories are the metrics used to evaluate the impacts from different processes, materials, and systems. The TRACI and primary energy consumption impacts, with the units used in this LCA, are shown in Table 1.

Table 1: TRACI Environmental and Energy Impacts

Impact category	Unit
Ozone depletion	kg CFC-11 eq
Global warming potential	kg CO ₂ eq
Smog	kg O ₃ eq
Acidification	kg SO ₂ eq
Eutrophication	kg N eq
Carcinogenics	CTUh
Non carcinogenics	CTUh
Respiratory effects	kg PM _{2.5} eq
Ecotoxicity	CTUe
Fossil fuel depletion	MJ surplus
Primary energy consumption (renewable + non-renewable)	TJ

kg (kilograms), eq (equivalent), CFC-11 (Trichlorofluoromethane), CO₂ (carbon dioxide), O₃ (trioxidan [ozone]), SO₂ (sulfur-dioxide), N (nitrogen), CTUh (comparative toxicity unit-for human health), PM_{2.5} (particulate matter), CTUe (comparative toxicity unit-for ecotoxicity), MJ (megajoule), TJ (terajoule)

Data Collection

The data quality and accuracy greatly impact the results, especially when aggregated over a 40 year time period. Huang et al. (2009) presented essential parameters/data required in developing an asphalt pavement LCA tool for only the construction/maintenance phase. Multiple data

sources are used in the development of LCA-AIR. The MP and CMR phases use predominantly secondary data from the Ecoinvent database for materials and combustion of fuels (EarthShift 2013). Some material's impacts come from SimaPro databases (SimaPro (Version 7.3.3) 2012). Construction equipment efficiencies and productivity use direct manufacturer equipment data when possible and complimentary data from EPA's NONROADS (U.S. Environmental Protection Agency 2008a). The use of secondary data is appropriate for the scope of this tool as it is for the US and not a specific US geographic region.

Constraints and Assumption of LCA-AIR

The constraints and assumptions of the tool are the following:

- The main constraint of this study is the dependency on secondary data sources.
- Jet fuel consumption is modeled as kerosene combustion in industrial equipment.
- Construction and maintenance equipment only consider the diesel fuel consumed but equipment maintenance is not considered.
- Feedstock energy is not considered.
- Useful PCC pavement life with correct maintenance is considered to be 40 years.
- The end of life phase for the pavement is excluded. Prediction of pavement rehabilitation or airport reconfiguration decisions after 40 years has large uncertainty.
- New airfield construction requires soil removal to the depth of pavement structure.
- 90% of the maximum take off weight was used for each airplane type.
- Terminal and other aerial port infrastructure environmental burdens are excluded. These burdens include construction, energy use and waste generation from the terminal facilities, hangars, etc.
- The aircraft fuel consumption during flight at altitude is assumed to be constant. Air resistance is considered to be constant.
- The airfield light emitting diode (LED) lights are assumed to run 12 hours per day. In the use phase, snow removal activities consume fuel during plowing operations but de-icing chemicals and placement are not included in the LCA.
- For larger scale airfield projects a concrete or asphalt plant is located on the airfield. This study assumes a 25-mile haul distance for mixed concrete (PCC) and asphalt (AC). Construction activities are based on standard practices. Equipment productivities are based on average conditions and normal operator abilities.

Implementation of the LCA-AIR

The implemented LCA in this study follows the framework described above. Figure 4 below, shows the information flow for each phase. First, the geometric data and associated information (density, jointing, etc.) is entered for use in the material production (MP), construction/maintenance and rehabilitation (CMR) and use (U) phases. The processes for each phase are described below. Next, mix design material quantities are inputted to calculate impacts associated with the raw material extraction, processing, transportation to plant, mixing operations and transportation to the job site. Following the material inputs, the specific equipment for each construction tasks are selected. For example, land clearing may use dozers, front-end loaders and dump trucks. Based on the quantity of material to be removed, the associated productivity and fuel consumption rate are used to calculate the gallons of diesel consumed for each activity. From the quantity of diesel consumed the environmental impacts are then calculated. Lastly, information regarding airplane type, number of operations, snow removal, and lighting can be

entered. Using the aforementioned data the environmental impacts for each phase as well as the total impacts are calculated for each of the TRACI indicator categories in Table 1.

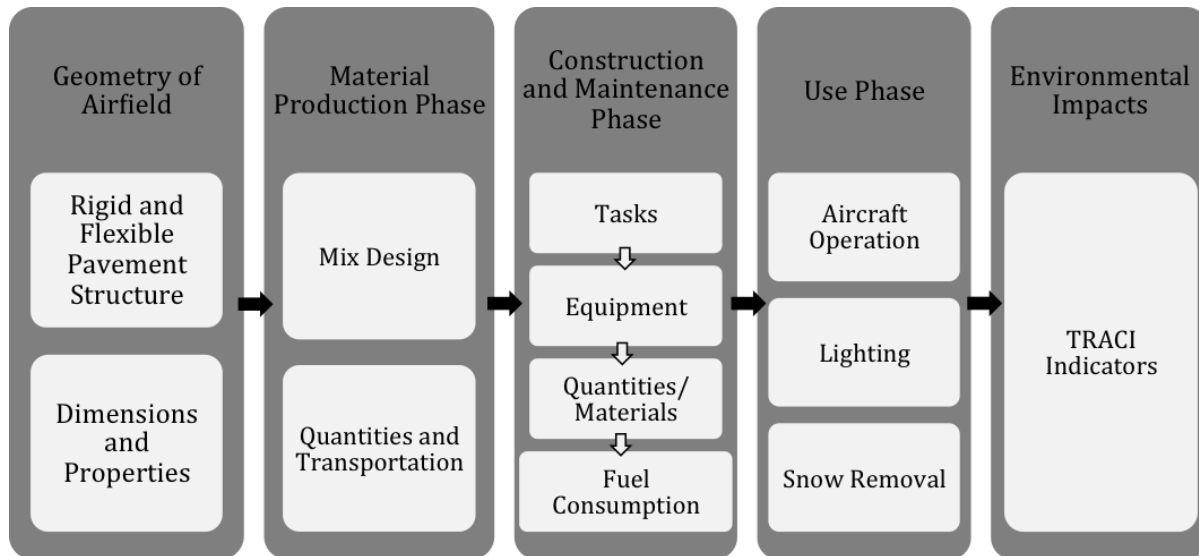


Figure 4: LCA tool overview

An airport in a northern climate was analyzed in order to include an option for snow removal in the tool. Table 2 shows the airfield feature dimensions (Figure 2). The operating aircraft are: B-747, B-777-200, A330-300 and B737-700. Annual departures for the aircraft follow: B747 with 900, B777 with 500, A330 with 1200, and the B737 with 1200.

Table 2: Case Study Feature Dimensions

Feature	Length (ft)	Width (ft)	*Total True Area (ft ²)
Runway	11,800	200	2,360,000
Taxiway A	14,200	75	974,592
Taxiway A - Holding Pad	60	375	342,168
Taxiway B	900	75	83,892
Taxiway C	900	75	81,225
Shoulders (AC)	28,400	50	1,420,000

*True area varies based on fillet dimensions

The environmental impacts for two different pavement structures (PCC and AC) were evaluated. The Federal Aviation Administration's (FAA) design program FAARFIELD is used to determine the pavement structure for a 40-year design life (Federal Aviation Administration, 2010). This extended design life has a higher initial cost than a standard FAA design life because of the increase in layer thicknesses. The PCC pavement life was assumed to be 40 years without major rehabilitation (includes some partial/full depth patch repair, joint/crack sealing, etc.) and the AC pavement structure has periodic rehabilitation (two mill/inlay operations, patching and crack sealing) over the 40-year life. Given the aircraft above, the flexible pavement consists of a five inch P-401 AC surface course, an 11 inch P-403 AC binder course over nine inches of P-209 crushed aggregate base and a subgrade California Bearing Ratio (CBR) of 10.

The rigid pavement consists of 16.5 inch P-501 PCC (flexural strength of 700 psi) with 20 foot panel sizes, over six inches of P-306 Econocrete, over six inches of P-209 crushed aggregate base and a subgrade k-value of 141 psi/in (Federal Aviation Administration 2014).

Environmental Impact Results And Discussion

LCA-AIR developed in this study is used to quantify the environmental impacts. LCAs commonly focus on energy consumed and global warming potential (GWP) for products or processes. All impacts are presented but energy and GWP are primarily considered for comparisons. This section presents the contribution to the impacts for selected phases (MP, CMR and U phase), and total impacts per functional units.

Material Production Phase Impacts

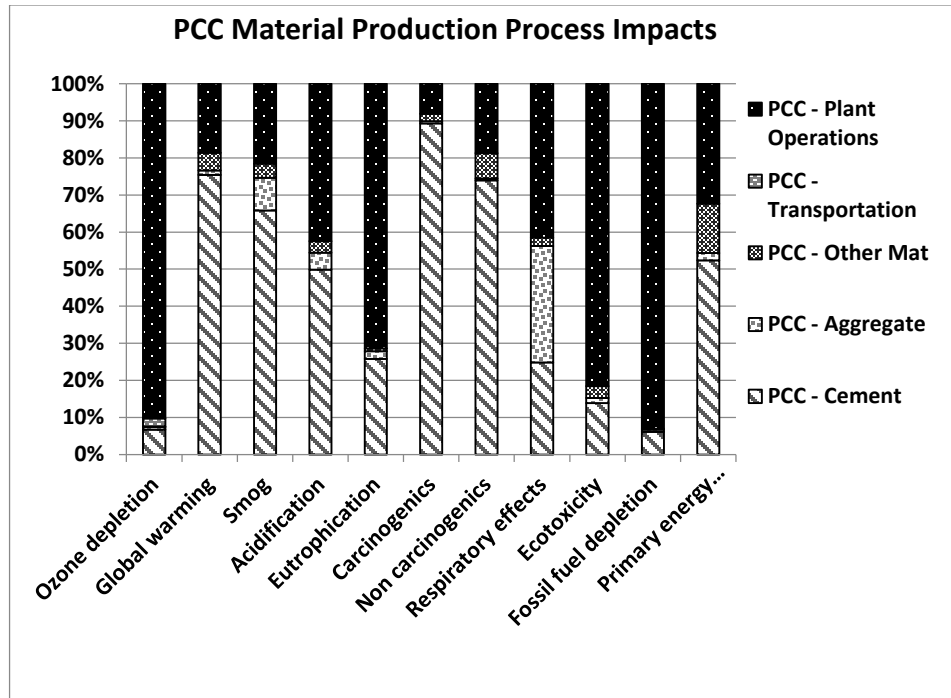
MP phase is broken down into the following five categories for PCC and AC: plant operations (all stages of mixing of PCC or AC), material transport to site, aggregate production (including recycled asphalt pavement and shingles), other material production (supplementary cementitious materials, steel, etc.), and cement or asphalt binder. The material impacts are independent of the mix design procedure (Superpave, Marshall, etc.) and are calculated as follows:

$$Total\ Impact_{material} = (V_{material}) \times (\gamma_{material}) \times (\varphi_{material})$$

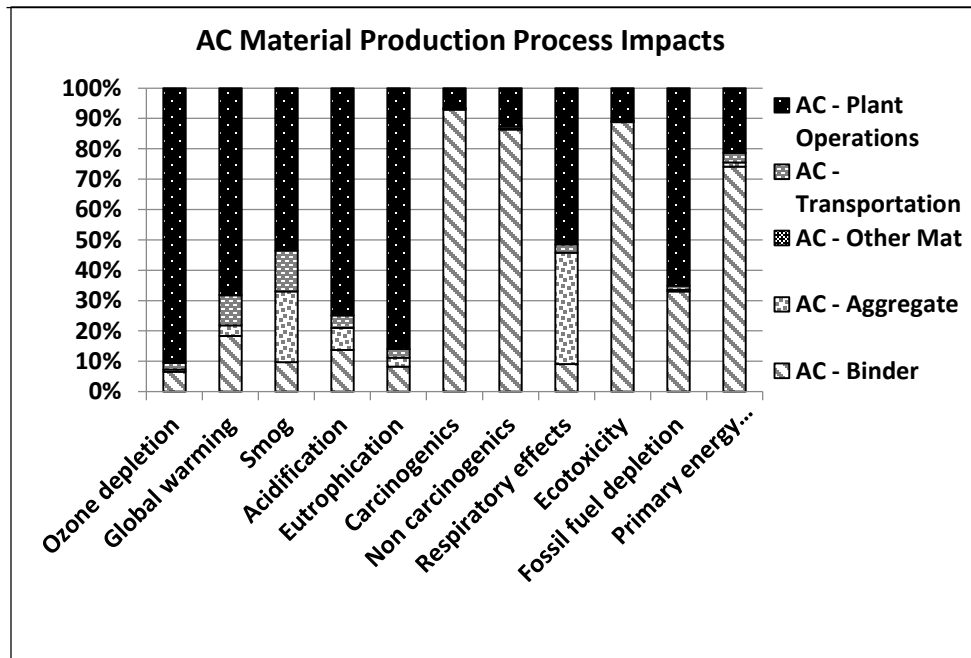
where, $V_{material}$ is the volume (ft³) of raw materials, $\gamma_{material}$ is the average material density (ft³/ton) and $\varphi_{material}$ is the Ecoinvent environmental impact value per ton. The impacts for each material, in each TRACI category, are summed together for a total impact per airport feature and phase. Although, roadways and airport pavement contain similar materials, the quantity per square yard differs. For both pavement types, Figure 5 shows the binding material (cement or asphalt) had the largest impact followed by plant operations.

For PCC in Figure 5a, the cement accounts for 50% of the energy consumed and 72% of the GWP produced. The calcination of limestone in the cement production process requires large amounts of energy and releases significant quantities of CO₂. For AC in Figure 5b, the binder accounts for 74% of the energy consumed and 18% of the GWP produced. The extraction and processing of binder is extremely energy intensive at the refineries. Large amounts of energy are required during the asphalt production process as aggregates must be dried and heated prior to mixing with the binder. The quantities for the remaining categories are shown in Figure 5.

This data highlights areas where a reduction in environmental impacts can be achieved. The use of recycled, co-products, and waste materials (RCWMs) in the mix should be a balanced focus, considering both durability and performance for a specific pavement. Giustozzi et al. provided a large-scale (60,000 m²) implementation of this concept, using 85% recycled and in-situ soil material in an Italian taxiway. In doing so, a reduction of 35% CO₂ emissions was achieved for the entire project (Giustozzi et al. 2012).



(a) PCC



(b) AC

Figure 5: Material production process impacts

Construction/Maintenance and Rehabilitation Phase Impacts

The CMR phase is broken down into 30 categories as shown below. Based on required CMR schedule, not all categories were used for this hypothetical case study.

- | | |
|-----------------------------|------------------------------|
| ▪ Land Clearing and Removal | ▪ Asphalt Patching |
| ▪ Excavation (Edge Drains) | ▪ Asphalt Overlay/Inlay |
| ▪ Grading | ▪ Tack Coat |
| ▪ Earthwork | ▪ Concrete Overlay |
| ▪ Soil Stabilization | ▪ Pavement Removal |
| ▪ Crushed Aggregate Base | ▪ Diamond Grind Surface |
| ▪ Asphalt Paving | ▪ Surface Treatment |
| ▪ Concrete Paving | ▪ Grooving |
| ▪ Joint Sawing | ▪ Restriping |
| ▪ Pavement Marking | ▪ Rubblization |
| ▪ Milling | ▪ Concrete Demolition |
| ▪ Cold In-Place Recycling | ▪ Rout and Seal Cracks |
| ▪ Hot In-Place Recycling | ▪ Full Depth Repair (PCC) |
| ▪ Full Depth Reclamation | ▪ Partial Depth Repair (PCC) |
| ▪ Rubber Removal | ▪ Joint Sealing |

The impacts for the CMR activities stems from the combustion of diesel in the equipment. The repair materials are also included in this phase. Figure 6 shows the maintenance activities and associated fuel consumption for both pavements. The following equation was used to determine the fuel consumed and the impact from its combustion for each piece of equipment.

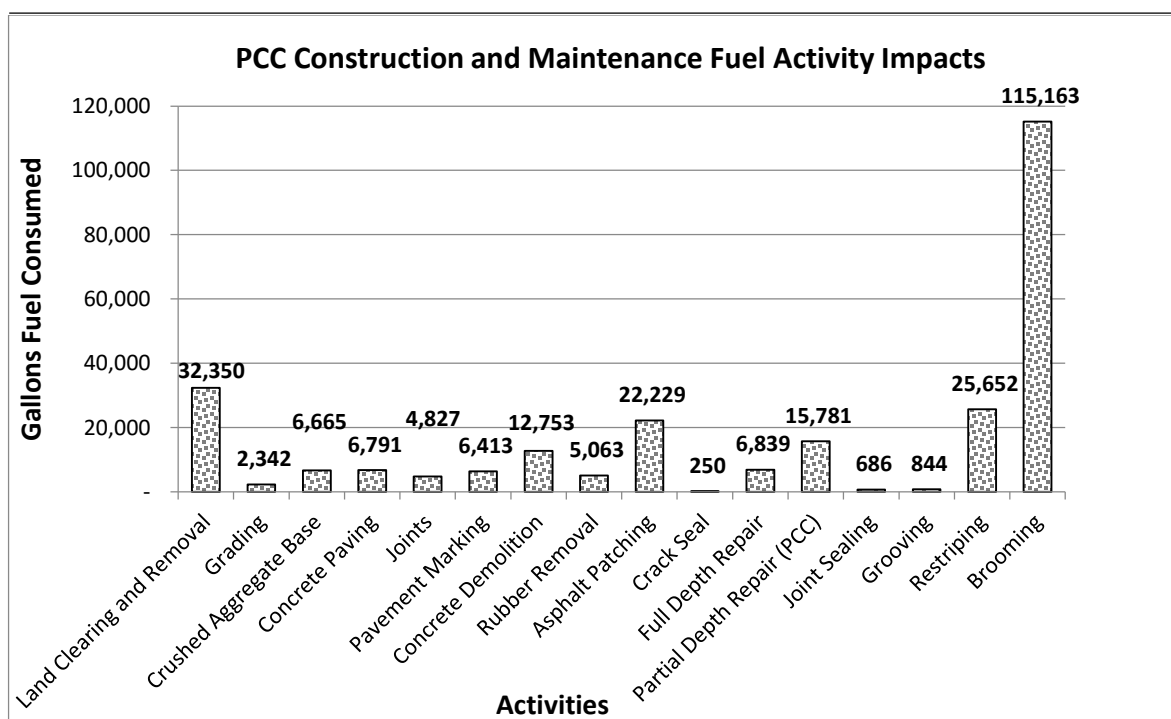
$$\text{Total Impact}_{\text{construction}} = \frac{V_{\text{material}} \times \gamma_{\text{material}} \times \Gamma_{\text{equipment}} \times \varphi_{\text{diesel}}}{P_{\text{equipment}}}$$

where, V_{material} is the volume (ft³) of raw materials, γ_{material} is the average material density (ton/ft³), $P_{\text{equipment}}$ is the equipment productivity (tons/hr or ft²/hour), $\Gamma_{\text{equipment}}$ is the fuel efficiency (gallons/hour) and φ_{diesel} is the Ecoinvent environmental impact value per gallon of diesel combusted.

Though material type and construction processes are similar to roadways, the material quantities and size of equipment per square yard differ for airports. Additionally, maintenance type and frequency differ on an airfield. Figure 6 shows the construction and maintenance activity contributions to environmental impacts. For PCC, the largest contribution for fuel consumption was brooming (115,163 gals) followed by land clearing (32,350 gals), and restriping (25,652 gals). Constant brooming of the airfield is one of the significant difference compared to roadway maintenance. Unlike highway vehicles, small, foreign object debris (FOD) pose a significant risk to aircraft and passenger safety. Therefore, maintenance crews must be vigilant in ensuring FOD is removed from pavement surfaces. Further evaluation of equipment used in land clearing for AC pavement, showed bulldozing and dump truck hauling accounted for 21% and 16% of initial construction impacts. This is similar to AC findings (24% and 18%, respectively) by Yang (2014). Specific impact analysis of paving equipment showed placement of crushed

aggregate base course contributes as much or more than the actual paving itself (Guistozzi et al. 2012; Ferrebee 2014).

AC construction and maintenance activities differed from PCC. Brooming was the largest contributor (115,163 gals) followed by crack sealing (108,317 gals) and asphalt patching (78,998 gals). Brooming and FOD removal do not change significantly with pavement type. The fuel consumption for AC maintenance is higher than PCC as expected because of more inlays and patching. Crack sealing, a time intensive activity, is required to minimize water infiltration into the flexible pavement structure and limit spalling. An additional difference with AC is the increase in restriping because of milling and inlay operations occurring two times (13 and 26 years) over the 40-year life.



(a) PCC

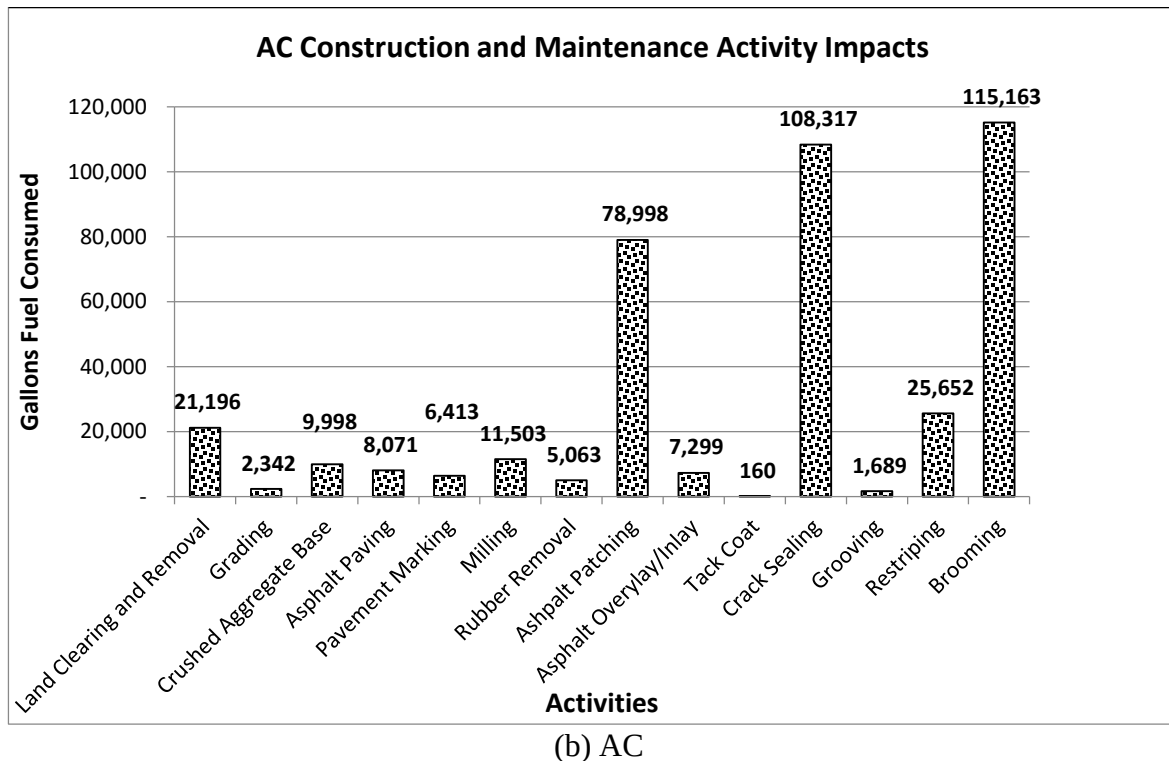


Figure 6: CMR activity impacts based on fuel consumption

Use Phase Impacts

The use phase is broken into the following three categories: aircraft fuel consumption, snow removal operation (fuel consumption), and lighting (electricity usage). Lighting and snow removal showed small contribution to overall impacts. Lighting only showed a significant contribution (46.3%) in ozone depletion stemming from power plant generation. Snow removal impacts were the fuel consumption from operating a plow, rollover plow and a broom for 20 snowfalls per year. Aircraft fuel consumption dominates the use phase and subsequently the LCA impacts.

Figure 7 shows the taking off stage is the largest consumer of fuel followed by cruising. This study used 1,100 miles as the flight distance (approximately 2 hours). LCA-AIR attributes one-half of the time in flight to the departure and arrival airport. Taxi-out time is 20 minutes, taxi-in time is seven minutes and landing descent is five minutes. These times are similar to the times used by Wasiuk et al. (2015) in accordance with the International Civil Aviation Organization (ICAO) guidelines. Take off (leaving pavement to cruising altitude of 25,000 ft.) accounts for 20 - 25% of fuel consumption per flight (Worldwatch Institute 2005; Lewis 2013) with LCA-AIR attributing 25% to take off. Cruising fuel consumption is based on the manufacturer's fuel efficiency of each aircraft. For this analysis and flight plan, the impact contribution from taking off is 25%, while cruising is 49%. As the length of flight increases, the cruising fuel consumption percentage will increase. For example, when the flight distance is increased to

5,500 miles (approximately 10 hours), LCA-AIR shows a contribution of 68% for cruising. The intensity of fuel consuming activities is critical for shorter flights.

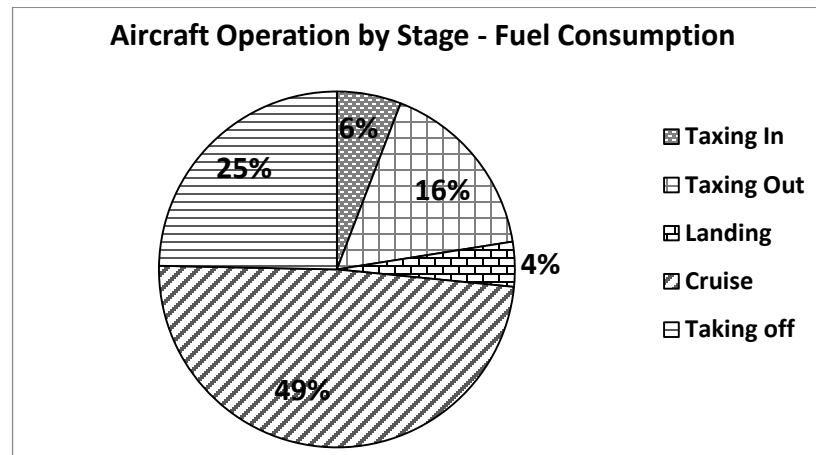


Figure 7: Aircraft operation by stage – fuel consumption of specific flight pattern

Roadway LCAs attribute fuel consumption to the pavement facility for each vehicle because of constant pavement-vehicle interaction. However, this pavement-vehicle interaction is negligible for airport pavement facilities with the aircraft traversing the pavement surface approximately 20 minutes before taking off. The IRI was calculated based on a regression curve adapted from highways (Wu, Revision of Pavement Condition Calculation Models for IDOT Interstate Highways and Development of Pavement Condition Prediction Models for Illinois Tollway 2015):

$$IRI_t = (IRI_{t-1}) \times (a) \times (h^b) \times (Total\ operations^c)$$

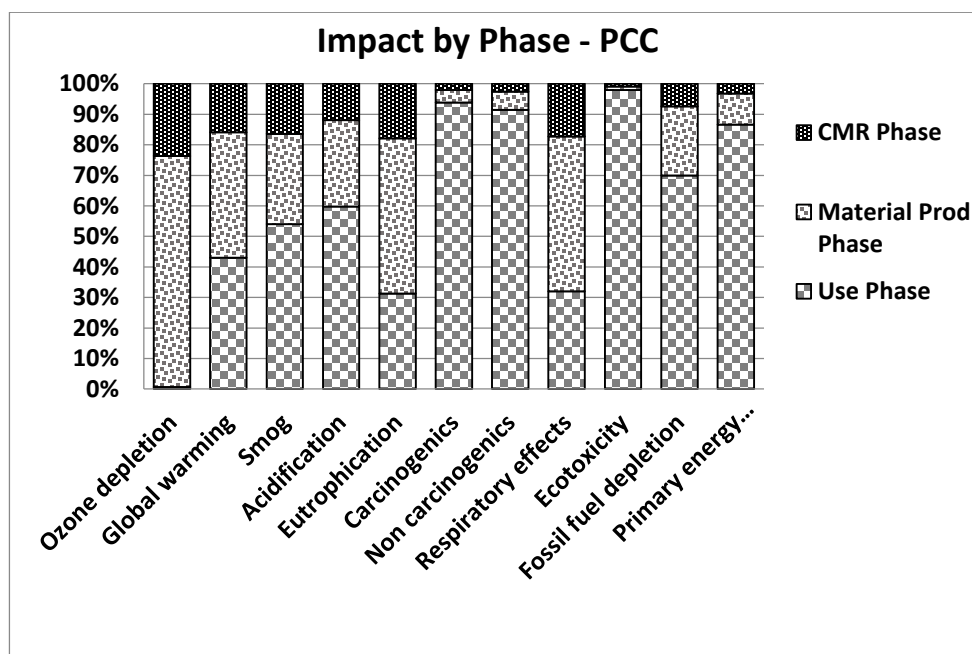
where, regression coefficients a , b and c are: a is 21.9054 [PCC], 36,4843 [AC], b is -1.0612 [PCC], -1.3612 [AC], c is 0.13183 for both PCC and AC), h is the pavement thickness and $Total\ Operations$ is the number of aircraft passes. LCA-AIR showed a 0.6% increase in fuel consumption because of a change in International Roughness Index (IRI) over time. The change in pavement roughness over time and rolling resistance has a minimal increasing effect on fuel consumption. Greater resistance and increased fuel consumption for airplanes is experienced from aerodynamic drag (Goldhammer & Plendl 2014).

Phases Contribution to Total Impact

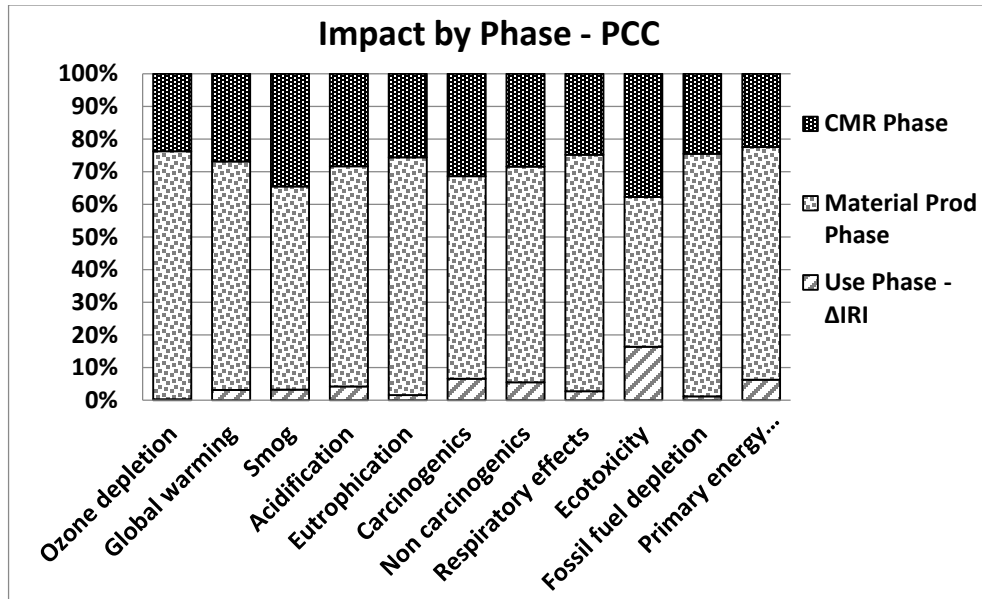
Figure 8 shows the impact percentages for the MP, CMR and U phase. For each pavement structure the U phase dominates, followed by MP, and finally CMR phase. Considering primary energy consumption, the U phase for PCC accounts for 85% and for AC it is 79%. Yang (2014) found the U phase accounted for 91%. This dominance over the other two phases is attributed to the aircraft operation over a 40-year period. MP for PCC accounts for 10% and AC accounts for 16%. The CMR for PCC accounts for 4% and for AC it is 6%.

Considering GWP, the U phase for PCC accounts for 40% and for AC it is 62%. The percentages for airfield pavements significantly differ from the roadway LCA by approximately 40% (Yang 2014). Materials production for PCC accounts for 42% and for AC, it accounts for 27% of the GWP. The higher percentage for PCC compared to AC is attributed to the carbonation of limestone in the cement production. The CMR for PCC accounts for 19% while AC is 11%.

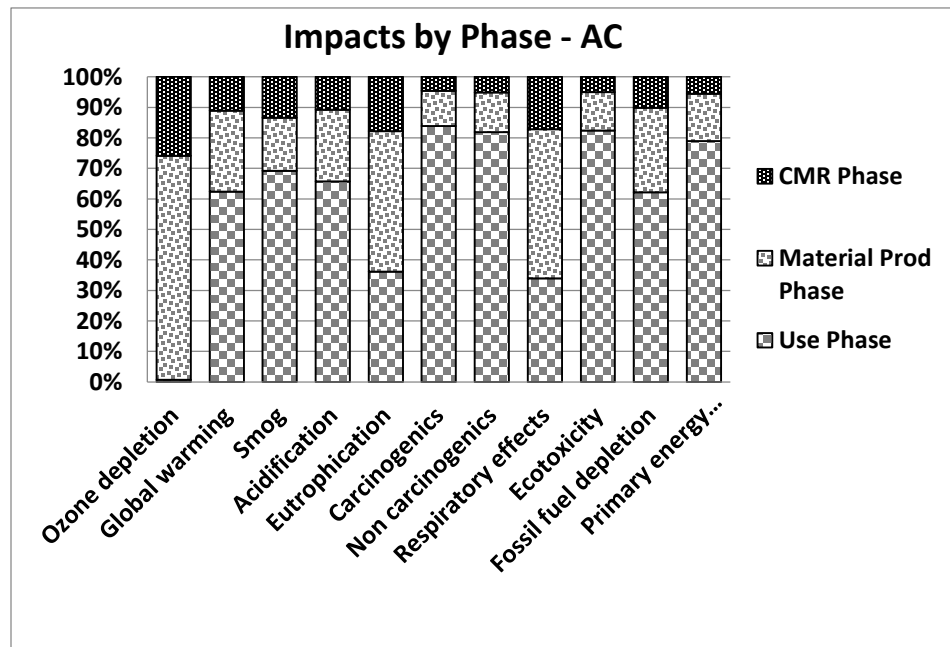
When only considering the additional fuel consumed because of a change in IRI in the use phase, the MP (~70%) and CMR (~28%) phases dominate as seen in Figure 8b and 8d. The change in pavement IRI associated use phase has a limited impact, which is significantly different than for roadways (Wang et al. 2012; Yu & Lu 2012). From a pavement sustainability standpoint, future improvements should focus on the MP and CMR phase.



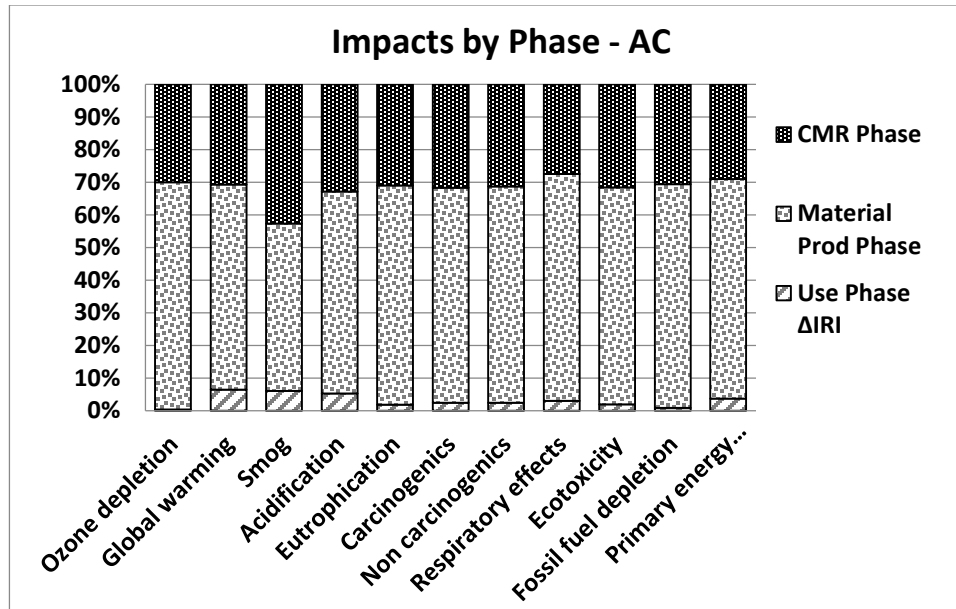
(a) PCC – considering total aircraft fuel in use phase



(b) PCC – considering only additional fuel consumed for Δ IRI in use phase



(c) AC – considering total aircraft fuel in use phase



(d) AC – considering only additional fuel consumed for Δ IRI in use phase

Figure 8: Impacts by phase

Impacts Per Functional Unit

Table 3 below, shows the impacts per functional unit for two sets of mixes for PCC and AC. One set used virgin material [no fly-ash (FA) and no recycled asphalt pavement (RAP), respectively]. The other set used fly ash and RAP, respectively. This table is for total impacts including half of the fuel consumed by the aircraft which dominates the values. These specific impacts are for a hypothetical case study used to demonstrate the capability of LCA-AIR. These numbers are for specific pavement mix designs with associated maintenance and rehabilitation schedules mentioned previously. It is not meant to be a comparison of PCC and AC because of the differences in mix designs and their relative impacts. For example, the AC mix with recycled material used 28% RAP in the base course layer, where the concrete did not use recycled aggregates. However, PCC used 25% FA as supplementary cementitious material. For each impact category a reduction with the use of recycled material is seen. The replacement of cement with FA and subsequent reduction in limestone calcination reduced the GWP and fossil fuel impacts for PCC.

Table 3: Total impacts per functional units for hypothetical case studies

a) virgin mixes

Pavement Type		PCC		AC	
Impact category	Unit	Total Impact Per yd ²	Total Impact Per lbs-mile	Total Impact Per yd ²	Total Impact Per lbs-mile
Ozone depletion	kg CFC-11 eq	7.102E-05	4.709E-15	6.786E-05	4.499E-15
Global warming	kg CO2 eq	3.548E+02	2.353E-08	1.884E+02	1.249E-08
Smog	kg O3 eq	3.031E+01	2.009E-09	1.967E+01	1.304E-09
Acidification	kg SO2 eq	2.298E+00	1.524E-10	1.931E+00	1.280E-10
Eutrophication	kg N eq	2.967E-01	1.967E-11	2.459E-01	1.630E-11
Carcinogenics	CTUh	7.254E-06	4.810E-16	1.004E-05	6.657E-16
Non carcinogenics	CTUh	7.387E-05	4.897E-15	1.013E-04	6.717E-15
Respiratory effects	kg PM2.5 eq	1.261E-01	8.364E-12	1.202E-01	7.970E-12
Ecotoxicity	CTUe	1.174E+03	7.781E-08	1.933E+03	1.282E-07
Fossil fuel depletion	MJ surplus	1.624E+03	1.077E-07	2.139E+03	1.418E-07
Primary energy consumption (renewable + non-renewable)	TJ	8.248E-03	5.469E-07	1.078E-02	7.151E-07

b) recycled material

Pavement Type		PCC		AC	
Impact category	Unit	Total Impact Per yd ²	Total Impact Per lbs-mile	Total Impact Per yd ²	Total Impact Per lbs-mile
Ozone depletion	kg CFC-11 eq	6.790E-05	4.502E-15	6.776E-05	4.493E-15
Global warming	kg CO2 eq	2.959E+02	1.962E-08	1.874E+02	1.243E-08
Smog	kg O3 eq	2.685E+01	1.780E-09	1.948E+01	1.291E-09
Acidification	kg SO2 eq	2.088E+00	1.384E-10	1.923E+00	1.275E-10
Eutrophication	kg N eq	2.743E-01	1.819E-11	2.452E-01	1.626E-11
Carcinogenics	CTUh	6.971E-06	4.622E-16	1.004E-05	6.655E-16
Non carcinogenics	CTUh	7.058E-05	4.680E-15	1.013E-04	6.713E-15
Respiratory effects	kg PM2.5 eq	1.183E-01	7.847E-12	1.168E-01	7.744E-12
Ecotoxicity	CTUe	1.171E+03	7.767E-08	1.932E+03	1.281E-07
Fossil fuel depletion	MJ surplus	1.590E+03	1.054E-07	2.138E+03	1.417E-07
Primary energy consumption (renewable + non-renewable)	TJ	7.872E-03	5.219E-07	1.077E-02	7.141E-07

Conclusion

LCA-AIR was developed to provide a sustainability LCA tool for airport owners, operators and engineers to quickly determine the environmental impacts related primarily to airfield pavement and maintenance activities. LCA-AIR requires inputs on the following: airfield geometry, materials and equipment required for construction, maintenance and rehabilitation, as well as airfield use and aircraft operation. It does not consider the end of life phase for pavement or life cycle impact of aircraft manufacturing, maintenance, and disposal. Terminal activities and associated impacts are also excluded. LCA-AIR calculates the environmental impacts for each phase and total impacts per functional unit (square yard and pound-mile traveled) using TRACI indicator categories.

Like roadway pavement LCAs, LCA-AIR showed the use phase dominates the impacts followed by material production and CMR when total fuel consumption is considered. This finding is attributed to the aircraft operation over the design life. Binding agent had the greatest contribution to the materials production phase followed by plant operations. Brooming the pavement surface, to remove FOD, regardless of pavement type, showed the largest contribution over the design life in CMR. For the use phase the aircraft fuel consumption plays a significant role in energy and emissions. Cruising has the largest contribution and take off has the greatest fuel consumption intensity. Unlike highway LCAs, IRI contributes minimally to fuel consumption because of the short period of pavement-aircraft tire interaction.

Acknowledgments

The authors would like to acknowledge Dr. Hasan Ozer, Ms. Di Wu and Matthew Brynick for their assistance. The contents of this paper reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. This paper does not constitute a standard, specification, or regulation.

References

- Al-Qadi, I. Y., Kang, S., Ozer, H., Ferrebee, Roesler, J. R., Salinas, A., et al. (2015). Development of Present and Baseline Scenarios to Assess Sustainability Improvements of Illinois Tollway Pavements Using a Life Cycle Assessment Approach. *Transportation Research Record: Journal of the Transportation Research Board* .
- Athena Sustainable Materials Institute. (2013). Retrieved August 15, 2015 from Athena Impact Estimator for Highways: <http://www.athenasmi.org/our-software-data/pavement-lca/>
- Chicago Department of Aviation. (2013, November 12). Sustainable Airport Manual. (3.1). Chicago, IL, United States of America: City of Chicago.
- Federal Aviation Administration. (2010, September 30). FAARFIELD 1.305. Washington D.C., MA, United States.
- Federal Aviation Administration. (2015). *National Plan of Integrated Airport Systems (NPIAS)*. Washington D.C.: U.S. Department of Transportation.
- Federal Aviation Administration. (2015a). *National Plan of Integrated Airport Systems (NPIAS)*. Washington D.C.: U.S. Department of Transportation.
- Federal Highway Administration. (2015b, January). Towards Sustainable Pavement Systems: A Reference Document. Washington D.C., MD, United States of America.
- Ferrebee, E. C. (2014). *Development Of The Materials, Construction, And Maintenance Phases Of A Life Cycle Assessment Tool For Pavements*. M.S. Thesis, University of Illinois, Department of Civil Engineering, Urbana, IL.
- Fowler, K., & Rauch, E. (2006). *Sustainable Building Rating Systems Summary*. Pacific Northwest National Laboratory. U.S. Department of Energy.

Goldhammer, M. I., & Plendl, B. R. (2014). Surface Coatings and Drag Reduction. *Aero* (49), pp. 14-20.

Guistoizzi, F., Crispino, M., & Flintsch, G. (2012). Recycling Practices for Achieving Environmental Sustainability in Airport Pavements. *Sustainability of Road Infrastructures*. Rome: Società Italiana Infrastrutture Viarie.

Horvath, A. (2004). *A Life-Cycle Analysis Model and Decision-Support Tool for Selecting Recycled Versus Virgin Materials for Highway Applications*. Research Report, University of California at Berkeley, Berkeley, CA.

Huang, Y., Bird, R., & Heidrich, O. (2009). Development Of A Life Cycle Assessment Tool For Construction And Maintenance Of Asphalt Pavements . *Journal of Cleaner Production* (17), 283-296.

Institute for Sustainable Infrastructure & Zofnass Program for Sustainable Infrastructure. (2015). *ENVISION - Rating System For Sustainable Infrastructure*. Washington D.C.: Institute For Sustainable Infrastructure.

International Civil Aviation Organization. (2014). Annual Report of the Council. Montréal, Quebec, Canada.

International Organization for Standardization. (2012). *Environmental management - Life cycle assessment - Illustrative examples on how to apply ISO 14044 to impact assessment situations*. International Standards Organization.

International Organization for Standardization. (2006). *Environmental Management - Life Cycle Assessment - Principles and Framework*. International Standards Organization.

Lewis, T. (2013). *A Life Cycle Assessment of the Passenger Air Transport System Using Three Flight Scenarios*. Norwegian University of Science and Technology, Department of Energy and Process Engineering.

Mukherjee, A., & Cass, D. (2011, May 1). PE-2: Project Emmission Estimator.

Institute For Sustainable Infrastructure; Zofnass Program for Sustainable Infrastructure. (2015). *ENVISION - Rating System For Sustainable Infrastructure*. Washington D.C.: Institute For Sustainable Infrastructure.

Reed, R., Bilos, A., Wilkinson, S., & Schulte, K.-W. (2009). International Comparison of Sustainable Rating Tools . (N. Miller, Ed.) *The Journal of Sustainable Real Estate* , 1 (1), 1-22.

Santero, N. J. (2009). *Pavements and the Environment: A Life-Cycle Assessment Approach*. Ph.D. Thesis, University of California, Berkeley, Department of Civil and Environmental Engineering.

Santero, N. J., Harvey, J., & Horvath, A. (2011). Environmental Policy for Long-Life Pavements. *Transportation Research Part D* , 129-136.

- Santero, N. J., Masanet, E., & Horvath, A. (2011). Life-Cycle Assessment Of Pavements Part II: Filling The Research Gaps. *Resources, Conservation and Recycling* (55), 810-818.
- Santos, J., Ferreira, A., & Flintsch, G. (2014, August 11). A Life Cycle Assessment Model for Pavement Management: Methodology and Computational Framework. *International Journal of Pavement Engineering* , 268-286.
- Senguttuvan, P. (2011). Global Trends in Air Transport: Traffic, Market Access & Challenges. *World Route Development Strategy Summit*. Berlin: International Civil Aviation Organization.
- SimaPro (Version 7.3.3). (2012). Amersfoort, Netherlands: PRé Consultants.
- U.S. Environmental Protection Agency. (2008a). NONROAD Emmission Model.
- U.S. Environmental Protection Agency. (2012). *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)*. User Manual, Cincinnati, OH.
- University of California Pavement Research Center. (2010). *Pavement Life Cycle Assessment Workshop: Discussion Summary and Guidelines*. Research Report - UCD-ITS-RR-10-37, University of California, Davis , Davis, CA.
- Wang, T., Lee, I.-S., Harvey, J. T., Kendall, A., Lee, E.-B., & Kim, C. (2012). *UCPRC Life Cycle Assessment Methodology and Initial Case Studies on Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance* . University of California, Davis. Davis, CA: Institute of Transportation Studies.
- Wasiuk, D., Lowenberg, M., & Shallcross, D. (2015). An Aircraft Performance Model Implementation For The Estimation Of Global And Regional Commercial Aviation Fuel Burn And Emissions . *Transportation Research Part D* , 35, 142-159.
- Worldwatch Institute. (2005). *Vital Signs 2005 - The Trends That Are Shaping Our Future*. Washington D.C.: W.W. Norton & Company, Inc.
- Wu, D. (2015). *Revision of Pavement Condition Calculation Models for IDOT Interstate Highways and Development of Pavement Condition Prediction Models for Illinois Tollway*. MS Thesis, University of Illinois at Urbana-Champaign, Urbana.
- Yang, R. (2014). *Development of a Pavement Life-Cycle Assessment Tool Utilizing Regional Data and Introducing An Asphalt Binder Model*. M.S. Thesis, University of Illinois, Department of Civil Engineering, Urbana, IL.
- Yu, B., & Lu, Q. (2012). Life Cycle Assessment of Pavement: Methodology and Case Study. *Transportation Research Part D* , 17, 380-388.