2007. Proceedings of the Indiana Academy of Science (116):139–147

VEHICLE IMPACTS ON VEGETATION COVER AT CAMP ATTERBURY, INDIANA: PART 2. PREDICTING IMPACTS OF UNTESTED VEHICLES

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ABSTRACT. Vehicle tracking systems were installed on four military vehicles (M813 cargo truck, M998 utility vehicle, M548A cargo carrier, M1025 utility vehicle) at Camp Atterbury, Indiana to assess the impact of tracking by these vehicle types on vegetation loss. Study data were used to estimate parameters for models previously reported in the literature and to validate model results. Instrumented vehicles were driven through courses of varying velocities and turning radii. Vegetation loss was recorded immediately after tracking. The tracked M548A cargo carrier caused the most site damage. The wheeled M813 cargo truck caused more vegetation loss than either of the other wheeled vehicles (M998 utility vehicle or M1025 utility vehicle). Power equations using vehicle type and turning radius as the independent variables predicted vegetation loss with an R^2 value of 0.845. Using only straight-line tracking data from our study to estimate parameters of a model proposed in an earlier reported study, we were able to predict vegetation loss for a range of turning radii almost as effectively as using the complete data set (R^2 = 0.843). Using vehicle weights combined with impact models proposed in an earlier study, we were able to predict vegetation loss for untested vehicles almost as well as with field data (R^2 = 0.810). Results from our study indicate that vehicle impact data and models can be applied to untested vehicles and reasonably estimate vegetation loss at Camp Atterbury. The ability to estimate site impacts of untested vehicles allows installation natural resources personnel to more accurately assess proposed land management actions in a timely and economical manner.

Keywords: Vehicle impacts, off-road, vegetation impact, impact assessment

The Department of Defense is responsible for administering more than 10 million hectares of federally-owned land in the United States. Much of this land is used for vehicle-based training activities. Continued management of these lands requires assessing the impact of vehicles on installation natural resources. These assessments are often mandated by the National Environmental Policy Act of 1969 (NEPA) PL. 91-190, which requires analysis and documentation of potential environmental effects associated with all major federal decisions. The fielding of new weapon systems or the relocation of military units and their vehicles to new locations are activities that require assessments of potential vehicle impacts.

The impact of off-road vehicle use on soil and vegetation has been extensively studied (Anderson et al. 2005). However, the effective use of this information in environmental impact assessments has been limited by a number of factors (Morrison-Saunders & Bailey 2003). Factors that limit the utility of impact study data in assessments include vehicles having multiple configurations, assessments required before vehicles are available for testing, and assessments that involve multiple vehicle types.

Impact assessments may be required before vehicles are physically available for testing. In these situations, impact studies have been conducted using vehicles with similar static properties (Haugen et al. 2003). In these cases impact data must be inferred from substituted test vehicles to the vehicle being fielded. Static vehicle properties important in determining vegetation damage include contact area, surface pressure, total weight, and track design (Ayers et al. 1994).

The range of static vehicle properties that represents a vehicle type complicates the integration of vehicle impact study data into impact assessments. Individual weapons systems are often fielded in more than one configuration, each with unique static vehicle properties. Static vehicle properties like tire pressure can also be modified during use. As an example, the eight-wheeled Stryker armored combat vehicle comes in eight configurations. Depending on configuration and payload, individual vehicles can vary in weight from 12.7–18.6 metric tons. Tire pressure for the Stryker vehicle can also be varied during operation using the central tire inflation system. Field studies that quantify vehicle impacts typically use a single vehicle type configuration (Anderson et al. 2005).

A new weapon system is not fielded independently of other vehicles. Multiple vehicle types make up military units. Assessing new weapon systems or relocation of existing units requires comparison between different units, each made up of varying vehicle types. Insufficient funding, study area, and time limit the number of vehicles that can be studied. Typically, field studies quantify the impacts of a dominant vehicle where the dominant vehicle represents the most common or most potentially damaging vehicle (Anderson et al. 2005).

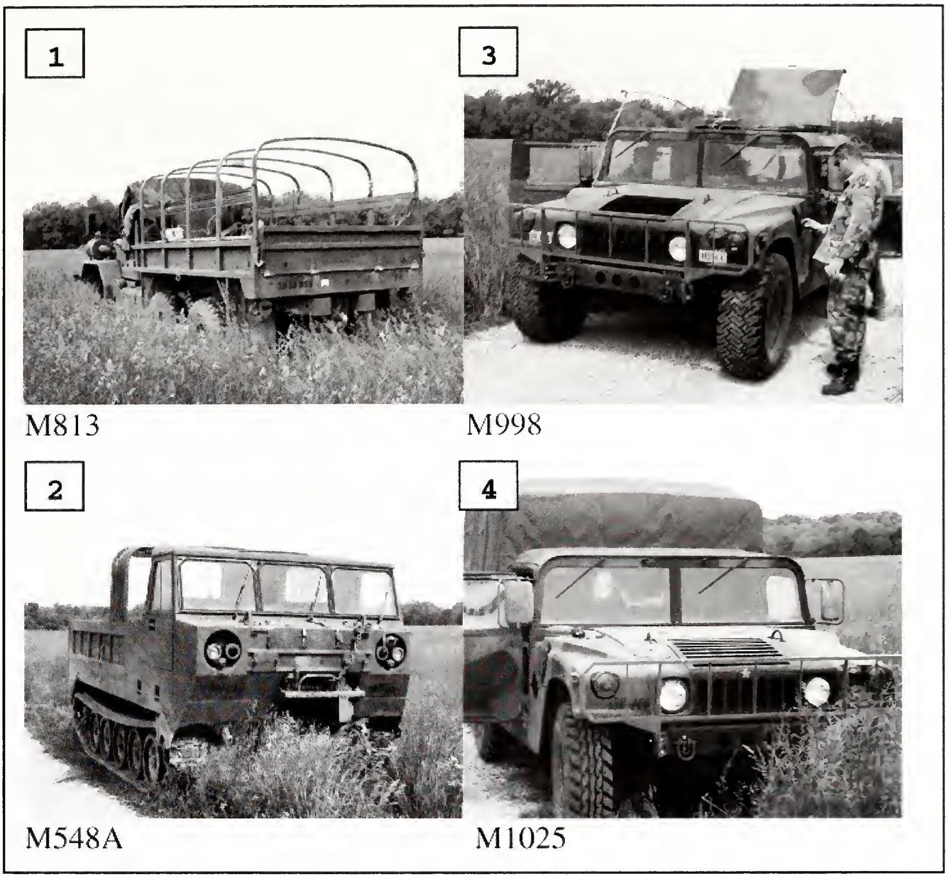
Current environmental impact assessments lack the ability to objectively predict impacts of untested vehicles (or alternative configurations) using vehicle static properties and data from existing vehicle impact studies. Predicting vehicle impacts based on static vehicle properties is important because static properties are known for currently-fielded vehicle types and are approximately known during design and development phases of fielding new vehicles.

Sullivan & Anderson (2000) proposed the use of vehicle static properties to estimate vegetation damage as a percentage of the damage caused by a baseline vehicle. Models used by the authors incorporated vehicle weight and properties used to estimate vehicle ground contact area. A preliminarily validation of the methodology was conducted using subject matter expert opinion. Results of the proposed methodology correlated reasonably well with predicted subject matter expert opinions (R^2 = 0.77) using 37 vehicles that varied widely in vehicle static properties. However, the authors were not able to validate their methodology more rigorously with field data because of the lack of data representing a range of vehicles tested under similar conditions.

Vehicle impact factors based on Sullivan & Anderson (2000) have been used to assess vehicle impacts on installation resources as part of environmental impact assessments of new weapon systems (Tetra Tech Inc. 2003; Colorado State University 2004; Tetra Tech Inc. 2004; Shoop et al. 2005). The vehicle impact factors also have been used to develop land repair funding requirements based on proposed training schedules (Anderson et al. 1996; Concepts Analysis Agency 1996). While these approaches for evaluating vehicle impacts are easily used in decision support processes, the relative impacts of vehicles have not been thoroughly validated using field data.

Anderson et al. (2007) quantified and modeled the impact of vehicles on vegetation loss using vehicle type and vehicle dynamic properties (speed and turning radius). The study indicated that a common model form was applicable for all vehicles tested at the study area and that turning radius was the critical vehicle dynamic property required to predict vegetation loss. While the authors were able to model vegetation loss using vehicle type, they did not directly use static vehicle properties that would have allowed the models to be applied to other vehicle types.

The overall objective of our study was to evaluate the use of vehicle static properties and existing vehicle impact study data to predict vegetation impacts of unstudied vehicles as a function of vehicle dynamic properties. The first objective was to validate that models proposed by Anderson et al. (2007) were generally applicable for similar sites and environmental conditions. The second objective was to predict vegetation impacts using only straight-line vehicle tracking data and equations that incorporate vehicle dynamic properties. In this objective, we used models developed by Anderson et al. (2007) as the foundation for extrapolating straight-line



Figures 1–4.—Four vehicle types used in the tracking study include the M813 cargo truck, M998 utility vehicle, M548A cargo carrier and M1025 utility vehicle. See Anderson et al. (2007) for pictures of the M88 base reference vehicle and additional vehicles used in model development.

tracking data. The third objective was to estimate vegetation damage using only vehicle static properties and models proposed by Anderson et al. (2007).

METHODS

Study site.—The study was conducted at Camp Atterbury, Indiana, an Army National Guard training facility. A more detailed description of terrain, soil and vegetation typical of the installation can be found in Anderson et al. (2007). The study site is located in training area 2A (39.70° N, 86.33° W). The study site was selected because it was representative of many vehicle use sites found on the installation. Study site soils were classified as a Stonelick (Wigginton & Marshall 2004). The Stonelick series is a coarse-loamy, mixed, superactive, calcareous, mesic Typic Udifluvent. Vegetation at the study site consisted primarily of introduced grasses with a smaller component of native and introduced forbs.

Study design.—A field study was conducted on 28 May 2003 using four vehicles: M548A cargo carrier, M813 cargo truck, M1025 utility vehicle and M998 utility vehicle (Figs. 1–4). The M548A cargo carrier is a tracked vehicle that is 4.86 m long, 2.69 m wide, 2.50 m high that weighs 12,832 kg. The M548A track width is 38.1 cm with pads that are 15.2 cm wide by 8.9 cm long. The M813 cargo truck is a three-axle ten-wheeled vehicle with a 5.23 m total wheelbase, 2.49 m width, and weight of 10,037 kg. The M813 tire height is 106.7 cm with a tread width of 190.5 cm front and 221.0 cm rear. Tire pressure at the time of tracking was 391 to 514 kPa during the study. The M1025 utility vehicle and M998 utility vehicle are the same vehicle type but represent different fielding configurations.

The M1025 is a four-wheeled vehicle with a 3.30 m wheelbase, 2.13 m width, and a weight of 3720 kg. The M1025 tire height is 93.3 cm with a tread width of 182.9 cm. Tire pressure at the time of tracking was 176 to 194 kPa during the study. The M998 is a four-wheeled vehicle with a 3.28 m wheelbase, 2.13 m width, and a weight of 3493 kg. The M998 tire height is 88.2 cm with a tread width of 182.9 cm. Tire pressure at the time of tracking was 95 to 132 kPa during the study.

The field study design is based on methods described in Anderson et al. (2007). Each vehicle drove a systematically planned course (spiral) within four randomly located treatment plots. Each spiral course within a treatment plot consisted of a section of straight-line travel followed by a section of constantly decreasing turning radius. Two spirals for each vehicle were traversed at a slower or faster velocity. The fast velocity spiral represents the fastest velocity the vehicle could safely be driven for the site conditions.

Each vehicle was equipped with a vehicle tracking system that allowed monitoring of vehicle velocity and turning radius. See Ayers et al. (2000) and Anderson et al. (2007) for details about the tracking systems.

Sampling methodologies.—Sample points were randomly located approximately every 5 m along the inner vehicle track of each spiral resulting in approximately 20 sample points per spiral per vehicle. Each sample point consisted of a paired subplot. One subplot was located within the track and the other subplot was 0.5 m adjacent to and on the inside of the track in undisturbed vegetation.

Immediately after tracking, vehicle impacts were assessed as disturbed width (DW), impact severity (IS) and cumulative impact (CI). Disturbed width was measured perpendicular to the vehicle track and encompassed the area where soil and/or vegetation were impacted by the vehicle tire or track. Vegetation cover was visually estimated within the disturbed vehicle track and control subplots. Impact severity was calculated as the percent cover in the undisturbed subplot minus the percent cover in the disturbed subplot. Cumulative impact was calculated as the product of disturbed width and impact severity.

Soil moisture was determined gravimetrically on the day of tracking for the 0–10.16 cm depth using methods of Gardner (1986). Soil samples were dried at 105° C for 48 h in a conventional oven. Water content was calculated on a mass basis as a percentage of dry soil. Air temperature was recorded one meter above the soil surface at the beginning and end of tracking treatments.

Statistical analysis.—Nonlinear regression analysis methods were used to determine best-fit model parameter values. Nonlinear regression analyses were conducted using raw dependent and independent variables. Cumulative impact was the dependent variable. Independent variables included in the model were variables found by Anderson et al. (2007) to be significant in quantifying vegetation loss by vehicles. Independent variables included in the model were turning radius and vehicle type. Vehicle type was included in the model as dummy variables such that $d_i = 0$ except for $d_1 = 1$ for the M813 cargo truck, $d_2 = 1$ for the M998 utility vehicle, $d_3 = 1$ for the M1025 utility vehicle and $d_4 = 1$ for the M548A cargo carrier. The a model term was set to 538.2323 to make the model parameter values directly comparable to results from Anderson et al. (2007). The b model term was first estimated directly from the data and then set to −0.5764 (obtained from Anderson et al. 2007) in two separate analyses. Estimating the b term from the data was to determine the best overall fit of the model. Setting the b term to a value obtained from Anderson et al. (2007) was to assess the utility of their proposed model to our site. Model parameters were estimated using the Proc Model of SAS® (SAS Institute Inc., Cary, North Carolina). The general form of the model employed is

$$CI = [a + (a_1 \cdot d_1) + (a_2 \cdot d_2) + (a_3 \cdot d_3) + (a_4 \cdot d_4)]TR^b$$

where CI is the dependent variable cumulative impact, TR is the independent variable turning radius, d_1 is the dummy variable to indicate the M813 cargo truck, d_2 is the dummy variable to indicate the M998 utility vehicle, d_3 is the dummy variable to indicate the M1025 utility vehicle, d_4 is the dummy variable to indicate the M548A cargo carrier, a is the intercept coefficient, a_1 is the intercept shift coefficient for the M813 cargo truck, a_2 is the intercept shift coefficient for the M998 utility vehicle, a_3 is the intercept shift coefficient for the M1025 utility vehicle, a_4 is the intercept shift coefficient for the M548A cargo carrier, b is the slope coefficient.

Most published studies quantify vehicle impacts using only straight-line tracking (Anderson et al. 2005). However, several studies have demonstrated that turning can cause more damage than straight-line tracking (Ayers 1994; Anderson et al. 2007). To determine if we can extrapolate straight-line tracking data for tested vehicles to vehicle tracking of any turning radius, we calculated the average cumulative impact value for turning radii greater than 40 m. This subset of the field data was used to estimate straight-line tracking because 40 m is well above the critical turning radius of 15–20 m reported by Anderson et al. (2007). Critical turning radii derived from other studies are also well below 40 m (Haugen et al. 2003). Equations obtained from Anderson et al. (2007) were then used to calculate vehicle specific a_n parameter values for a turning radius of 17.5 m. A turning radius of 17.5 m was used because this was the midpoint of the 15 to 20 m critical turning radius reported by Anderson et al. (2007). The resulting model was then used to estimate vegetation impact values for each measured point. Model R^2 values were calculated to quantify how well the model fit the complete data set that included straight-line tracking and turning at varying radii.

To determine if we can predict vegetation loss for untested vehicles, we estimated vehicle specific a_n parameter values for the equation obtained from Anderson et al. (2007). Parameter values were estimated using vehicle weight as a surrogate variable for vehicle type. For vehicles used in Anderson et al. (2007) we developed a linear regression model to describe the relationship between published a_n parameter values and vehicle weights. The resulting regression model was used along with the weights of vehicles used in our study to predict a_n parameter values for the vehicles. The resulting model was then used to estimate vegetation impact values for each measured data point. Model R^2 values were calculated to quantify how well the model fit the complete field data set.

RESULTS

Vehicle impacts.—At the time of tracking, soil water content, averaged 23.7%. This represents a soil condition typical for many maneuver activities at this site and is wetter than soil conditions tested by Anderson et al. (2007). Air temperature ranged from 12–26° C during tracking treatments. Vegetation cover for undisturbed sample points averaged 100 indicating a densely vegetated site.

The tracked M548A cargo carrier caused more damage than any of the wheeled vehicles. For wheeled vehicles the M813 cargo truck caused more damage than the M998 utility vehicle and M1025 utility vehicle.

Cumulative impact increased exponentially with decreasing turning radii (Fig. 5). Cumulative impact increased suddenly at turning radii less than approximately 15–20 m for all vehicle types. This critical turning radius where increase site damage occurred is similar to that reported by Anderson et al. (2007)

Modeling vehicle impact using all field data.—Nonlinear regression analyses indicated that a model of the form proposed by Anderson et al. (2007) reasonably describes the data in our study. The model using a and b parameter values from Anderson et al. (2007) had an R^2 value of 0.845. Figure 5 shows predicted values plotted against field observations. The model R^2 remained 0.845 when model parameter values were not restricted to values obtained from other studies.

Log transformations of the dependent and independent variables did not result in completely linear relationships between the data as found in Anderson et al. (2007). This was most apparent for the M548A cargo carrier. The lack of a linear relationship indicates that other model forms may better describe the data for this specific study site. In our study, the models tended to over estimate impacts for turning radii between 15–25 m. The dramatic increase in vegetation loss at turning radii less than 25 m may be due to the dense above and below-ground vegetation typical of this site. Foster et al. (2006) found similar results in their study of the impact of turning vehicles on vegetation loss.

Predicting vehicle impact using only straight-line tracking data.—Figure 6 shows measured and predicted cumulative impact as a function of turning radius for the M813 cargo truck, M998 utility vehicle, M548A cargo carrier and M1025 utility vehicle. Cumulative impact was predicted using straight-line tracking data from our study to estimate a_n param-

$$CI = (538.2323 - (451.441 * d_1) - (495.137 * d_2) - (500.829 * d_2) - (423.741 * d_2))TR^{-0.5764}$$

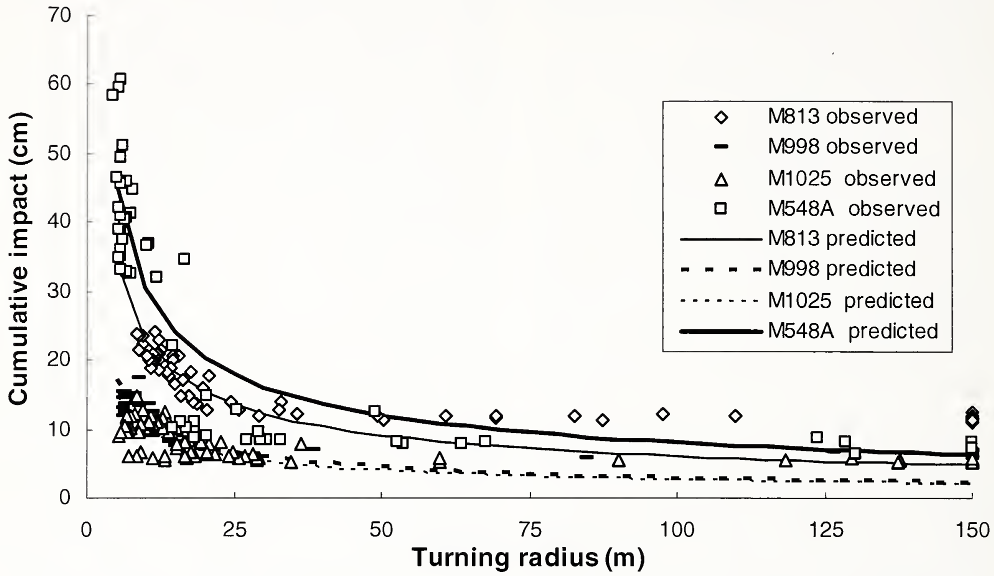


Figure 5.—Cumulative Impact (CI) as a function of turning radius (TR) for the M813 cargo truck, M998 utility vehicle, M548A cargo carrier and M1025 utility vehicle. The parameters of the power equation for fitted lines are provided at the top of the graph. Variables d_1, d_2, d_3 and d_4 are dummy variables that account for vehicle type. Dummy variables $d_i = 0$ except that $d_1 = 1$ for the M813, $d_2 = 1$ for the M998, $d_3 = 1$ for the M1025, and $d_4 = 1$ for the M548. Parameter values were estimated using all field data and the equation from Anderson et al. (2007). The R^2 fit for the equation is 0.845.

eter values for individual vehicle types for use in the equation from Anderson et al. (2007). The R^2 fit for the model containing all four vehicles is 0.843. The R^2 value for a model based only on straight-line tracking data is only slightly less than for a model using all the field data. R^2 values for individual vehicles ranged from 0.486 for the M1025 utility vehicle to 0.843 for the M813 cargo truck. Higher correlations were obtained for the heavier vehicles. The higher correlations for the heavier vehicles resulted from a larger range of vegetation loss across turning radii relative to the variation in vegetation loss at any specific turning radius.

Predicting vehicle impacts using static vehicle properties.—Figure 7 shows measured and predicted cumulative impact as a function of turning radius for the M813 cargo truck, M998 utility vehicle, M548A cargo carrier and M1025 utility vehicle. Cumulative impact was predicted using vehicle weight to estimate vehicle type specific a_n parameter values for inclusion into a model obtained from Anderson et al. (2007). The R^2 fit for the model containing all four vehicles is 0.810. The R^2 value for a model based only on vehicle weight is only slightly less than for a model using only straight-line tracking data or all the field data. R^2 values for individual vehicles range from 0.486 to 0.843. Higher correlations were obtained for the heavier vehicles.

DISCUSSION

GPS technology is currently being used to track vehicles during live training events (Haugen et al. 2003). This data is useful for characterizing how vehicles are used in live training exercises. These studies characterize vehicle locations, velocities, and turning radii. However, to quantify the overall impact of a training event, we must also be able to estimate vehicle impacts for the full range of vehicle operating conditions observed during these training events. Currently most impact studies have only documented the impact of straight-line tracking on vegetation loss, with straight-line tracking often being one of the least destructive vehicle operating conditions. In our study, we demonstrated the use of straight-line vehicle tracking data to calibrate

$$CI = (538.2323 - (451.764 * d_1) - (486.799 * d_2) - (496.482 * d_2) - (411.107 * d_2))TR^{-0.5764}$$

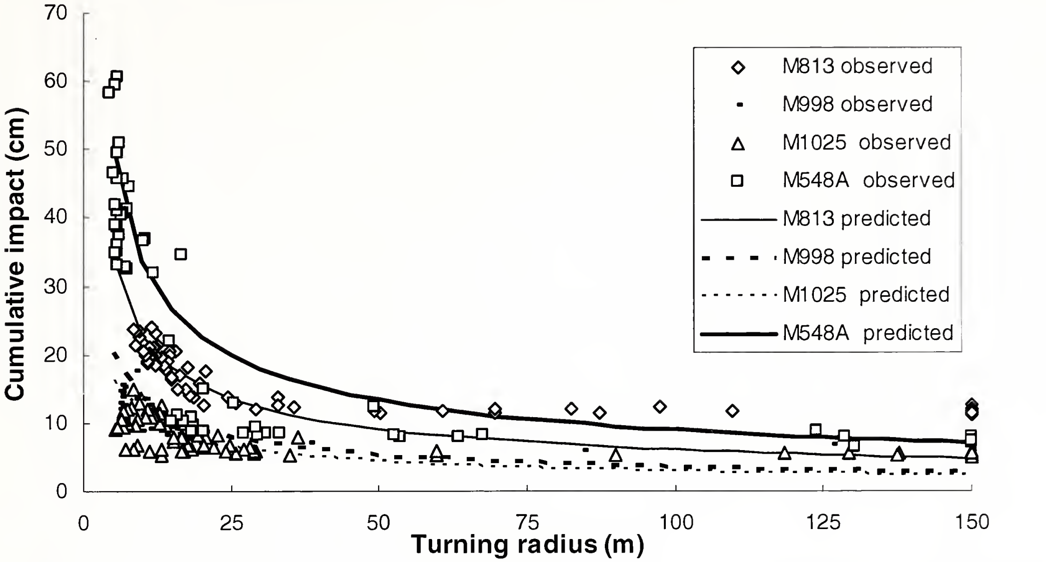


Figure 6.—Cumulative Impact (*CI*) as a function of turning radius (*TR*) for the M813 cargo truck, M998 utility vehicle, M548A cargo carrier and M1025 utility vehicle. The parameters of the power equation for fitted lines are provided at the top of the graph. Variables d_1, d_2, d_3 and d_4 are dummy variables that account for vehicle type. Dummy variables $d_i = 0$ except that $d_1 = 1$ for the M813, $d_2 = 1$ for the M998, $d_3 = 1$ for the M1025, and $d_4 = 1$ for the M548. Parameter values estimated using straight-line tracking field data only, equation from Anderson et al. (2007), and calculating a_n parameters using a critical turning radius of 17.5 meters. R^2 fit for the equation is 0.843.

models that predict vegetation impacts of existing vehicles for different turning radii. Our study also verified that models developed at one study site are applicable to other study sites with similar soil and vegetation conditions.

In environmental impact assessments we often need to predict the impact of vehicles that have not been tested. In our study we demonstrated that we could predict vegetation loss for untested vehicles by using simple vehicle static properties like weight and data from field tests of other vehicles.

Several issues are relevant when interpreting results from our study. First, our study results are site specific. While we validated our approach using a different study site from the original study (that varied in soil type, vegetation composition, and soil moisture), we do not have data from a wide range of sites or moisture conditions to quantify how far conclusions or models can be extrapolated. Althoff & Thein (2005) demonstrated that soil moisture can significantly affect vegetation loss due to vehicle traffic. Soil moisture or vegetation characteristics could explain differences in the shape of our response data between the two study sites. Models extrapolated from Anderson et al. (2007) tended to underestimate large turning radii impacts and over estimate small turning radii impacts for our study site.

A second issue is that all modeling approaches we proposed for predicting vehicle impacts require some existing site-specific impact data to estimate model parameters. The approaches differed only in the amount of site-specific data required. If the approach is to be repeated at another location, at least one vehicle must be tested for a range of turning radii and several vehicles must be tested to develop a relationship between static vehicle properties and vegetation impact.

Application of the models we evaluated may be limited by the empirical nature of the models as they are applied to more diverse sites. A more productive long-term approach may be to model vehicle static and dynamic properties in ways that relate more directly to assessed impacts. Li et al. (2007) used pro-

$$CI = (538.2323 - (463.876 * d_1) - (488.564 * d_2) - (494.268 * d_2) - (381.780 * d_2))TR^{-0.5764}$$

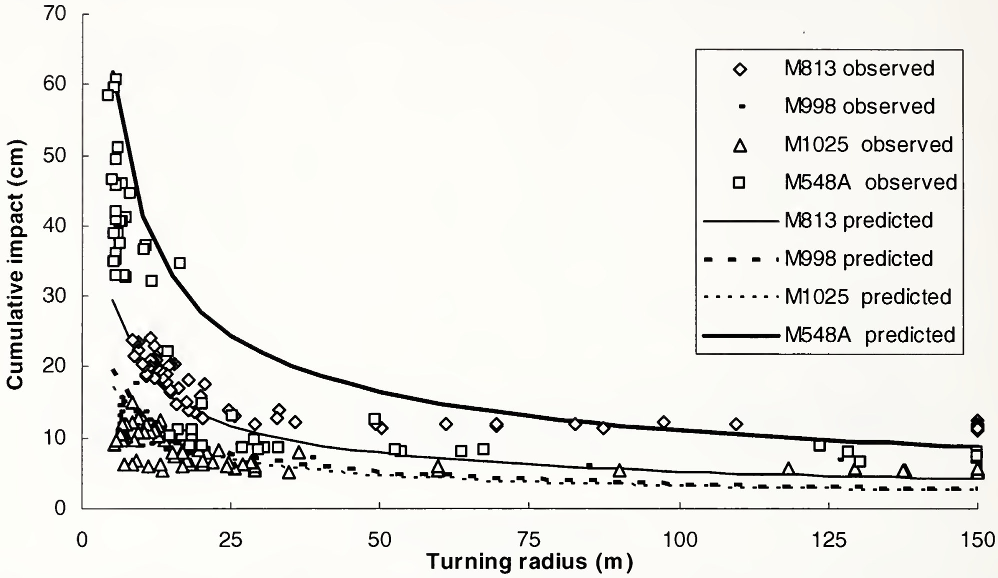


Figure 7.—Cumulative Impact (*CI*) as a function of turning radius (*TR*) for the M813 cargo truck, M998 utility vehicle, M548A cargo carrier and M1025 utility vehicle. The parameters of the power equation for fitted lines are provided at the top of the graph. Variables d_1, d_2, d_3 and d_4 are dummy variables that account for vehicle type. Dummy variables $d_i = 0$ except that $d_1 = 1$ for the M813, $d_2 = 1$ for the M998, $d_3 = 1$ for the M1025, and $d_4 = 1$ for the M548. Parameter values estimated using vehicle static properties and equation from Anderson et al. (2007). R^2 fit for the equation is 0.810.

cess-based models to predict vegetation impacts based on vehicle static and dynamic properties as well as soil strength. Including soil strength in their model allows site conditions like soil moisture to be directly incorporated into the model. The approach of Li et al. (2007) was demonstrated to work for a much more diverse range of study sites than evaluated in our study.

Despite potential limitations of the models we evaluated, we demonstrated that vehicle impact study data is representative of impacts measured for similar sites. We also demonstrated that relatively simple models that relate vehicle static properties to vegetation loss could be used to predict impacts of untested vehicles for a range of vehicle dynamic properties. These models will help resource managers evaluate the impact of current and proposed vehicle use at military installations. Most importantly, the ability to predict impacts from vehicles before available for testing allows land managers to proactively prepare for potential impacts.

ACKNOWLEDGMENTS

We acknowledge the Strategic Environmental Research and Development Program (SERDP) and the Army Environmental Quality Technology program for providing financial support for this study. We gratefully acknowledge Dr. George Z. Gertner, Dr. Guangxing Wang, and Dr. Shoufan Fang for their guidance on statistical analysis of the data.

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