

# GIS APPLICATION TO DEVELOPMENT OF MILITARY CROSS-COUNTRY MOVEMENT MAPS AT MAE SOT DISTRICT, WESTERN THAILAND

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## Abstract

To demonstrate the merit of the geographic information system (GIS) in military work to the public, this paper reports the GIS-based derivation of cross-country movement (CCM) maps for 4 major types of military vehicles (M35 truck, M113 carrier, Stingray tank, and Scorpion tank) in Mae Sot District, a renowned strategic location in western Thailand. The constructing process was carried out based on guidelines adopted by the US Army and the Royal Thai Army. Each map was made from the direct product of 5 crucial terrain factors: slope, slope-intercept-frequency, vegetation, soil, and surface roughness, in which 3 categories of trafficability were identified: Go, Slow Go, No Go. The resulting maps indicated that the most trafficable areas for all the listed vehicles were located on the large flat plain in the western part of the district as the middle and eastern parts were predominately high mountains and relatively rough terrain. The average land trafficability for most vehicles (except the M113) significantly decreased from the dry to the wet season due to softer soil conditions. In terms of the performance score, both tank vehicles did comparably well during the dry season followed by the M113, but for the wet season, the Scorpion did best followed by the M113 and the Stingray, respectively. In both cases, the M35 truck was found to perform worst. These results which were obtained are useful as primary information for the future preparation and operation by the Royal Thai Army of the effective CCM activity for the vehicles which were included in this study.

**Keywords:** Military terrain analysis, land trafficability, cross-country movement, CCM map, GIS

## Introduction

Knowledge of terrain characteristics has been recognized since ancient times as a key element in the decisive planning and operation of warfare strategy which can define the ultimate fate of a war's outcome. Therefore, the accumulation, preparation,

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and analysis of terrain information for warfare operations have become vital tasks of terrain analysts throughout the known history of military warfare (Bayles, 1993; Kiersch and Underwood, 1998; Guth, 1998; Doyle and Bennet, 2002; Halsall, 2006). The ultimate goal is to prepare essential terrain and weather databases of an area and analyse their effects on the contemplated military operation (Whitmore, 1960; Lane, 1986; Bruzese, 1989; US Army, 1990). At present, military terrain analysis has become a crucial part of the intelligence preparation of the battlefield process because its results can contribute critical information to assist the intelligence preparation, decisions, and operations of the preferred military activities (US Army, 1994; 2000). The analysis typically focuses on 5 main aspects of the terrain's effect on the military operation including; observation and fields of fire, cover and concealment, obstacles, key terrain, and avenues of approach. These processes are formally known collectively as "OCOKA" (US Army, 1990, 2000).

One of the main tasks of the military analysts is the construction of a guide map for the off-road movement of military personnel and vehicles called the cross-country movement (CCM) map. This map is usually referred to as an avenue of approach map because it can indicate the appropriate routes by which vehicles or troops can move to an objective when the prepared roads cannot be used as normal (US Army, 1985, 1990). Traditionally, the entire CCM mapping process is operated by military experts based on their prior knowledge of key terrain and environmental characteristics of the area, e.g., topography, soil properties, vegetation characteristics, water resources, land use, and surface configuration (Messmore *et al.*, 1979; Kastella *et al.*, 2000). To produce the CCM map, the individual maps of all the terrain factors that are used will be systematically combined (or overlaid) manually to classify trafficable zones for the concerned vehicles based on some predefined decision rules. The resulting CCM map for a particular vehicle provides its approximate speeds for

movement over the entire studied area (US Army, 1990).

In the past, most of the work required in a conventional military terrain analysis, as well as its subsequent applications, had to be processed manually by well-trained staff. This practice makes them laborious and time-consuming tasks, especially in the accumulation and preparation of terrain intelligence from the primary terrain data (Bruzese, 1989; Kiersch and Underwood, 1998). However, due to the tremendous advance of the geographic information system (GIS) technology in recent decades (Berry, 1993; Burrough and McDonnell, 1998; Chrisman, 2001; Bernhardsen, 2002; Longley *et al.*, 2005; Bolstad, 2012), the terrain analysis process as a whole can be done much more conveniently, efficiently, and productively, through the high capability of GIS operating tools in the collection, manipulation, analysis, presentation, and distribution of the relevant spatial data required in a specific working process. These capacities make the GIS an excellent platform for the construction and implementation of a developed terrain database (Bruzese, 1989; Wilson and Gallon, 2000; Goodchild and Longley, 2005; Harvey, 2008). Conclusive information of the GIS applications in military affairs in general is provided in, for example, Bruzese (1989); Swann (1999); Gumos (2005); ESRI (2013a); Singhal (2000); Satyanarayana and Yogandron (2002).

Although the merit of GIS technology in the management of military affairs is now well acknowledged, detailed reports of this kind are still fairly rare in public literature. For CCM mapping in particular, little work can be found from the reviewed literature. For example, Khotcharit (2004) applied GIS tools to create a CCM map in Kanchanaburi Province in western Thailand, using the weight-linear-combination method. The considered data were surface slope, soil, vegetation, transportation, obstacle, rainfall, and built-up area. Recently, Talhofer *et al.* (2011) have developed a GIS-based model for the production of a simple CCM map

for the Czech Army based on the direct product of 7 terrain parameters including terrain relief, vegetation, soil, climate, hydrology, built-up area, and road network.

To demonstrate the capability of advanced GIS technology in the established field of military CCM analysis, this paper reports the construction and implementation of a GIS-based model to formulate effective CCM maps for 4 selected military vehicles in Mae Sot District, western Thailand. The construction phase was based on the standard procedure described in the US Army-Field Manual: FM 5-33 (US Army, 1990) and in the Royal Thai Survey Department (RTSD) Reference Manual of the Royal Thai Army (RTSD, 1997) for military terrain analysis. This method was chosen due to its realistic structure and a straightforward interpretation of the obtained results for intended military operation. It is hoped that this report will emphasize to the public the merit of GIS utilization for CCM mapping in particular, and to military analysis work as a whole.

### Study Area

The study area is Mae Sot District in Tak

Province, western Thailand (Figure 1). This area has long been a strategic location on the western border under the supervision of the 3<sup>rd</sup> Army due to territory conflicts with Myanmar and the military activities of some ethnic minorities residing within Myanmar. Mae Sot is also notable as a major Thai-Myanmar trade hub and as home for a large number of Burmese migrants and refugees (Boonyarattanasoontorn, 2012). As a principal Thai-Myanmar gateway, the area has gained a notorious reputation as a center of black market activities such as illegal labor and drug trafficking which have become problems of great concern both locally and internationally (McGeown, 2007; Jacobsen and Nichols, 2011; Zwartz and Mort, 2013).

Mae Sot District comprises 10 sub-districts (or Tambons) as detailed in Figure 1 with a total area of 1986.12 km<sup>2</sup> and an official population of 70272 in 2012 (DOPA, 2012). The climate is monsoonal where heavy rainfall usually occurs during the monsoon season (May-October) while the rest of year is relatively dry. The highest amounts of average rainfall are 353.5 mm in August and 305.2 mm in July (for the period 1961-1990)

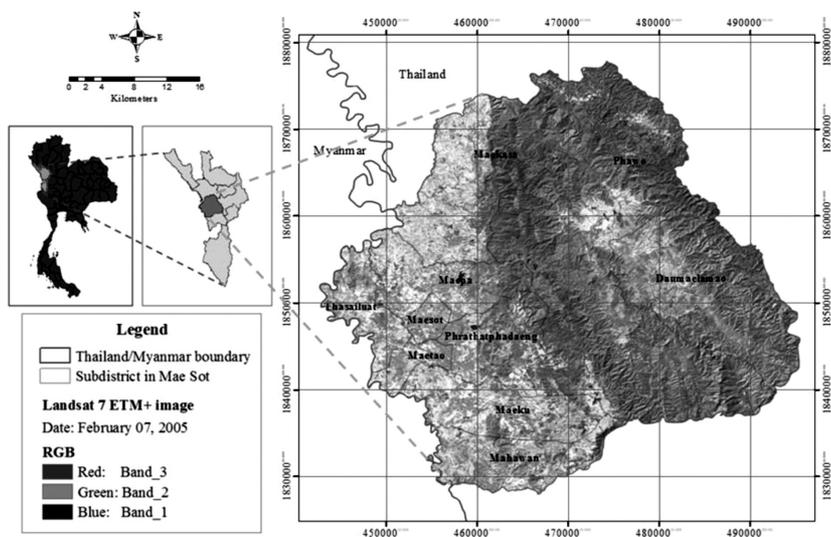


Figure 1. Satellite-based location map of the Mae Sot District in Tak Province, western Thailand

(TMD, 2012). The predominant topography is a network of high mountains in the middle and eastern portions and a large lowland plain on the western side, as depicted in Figures 1 and 2(a-b). The satellite-based land use/land cover (LULC) classification in 2005 indicates that the 2 prominent LULC groups are forest

(about 59%) and agricultural land (about 39%) with a small portion (1.34%) being identified as urban and built-up land (Table 5). The most abundant geological structures are rock outcrops in the middle and the east and a mixed dominance of clay, silt, and sand in the western lowland area (Figure 2(d)).

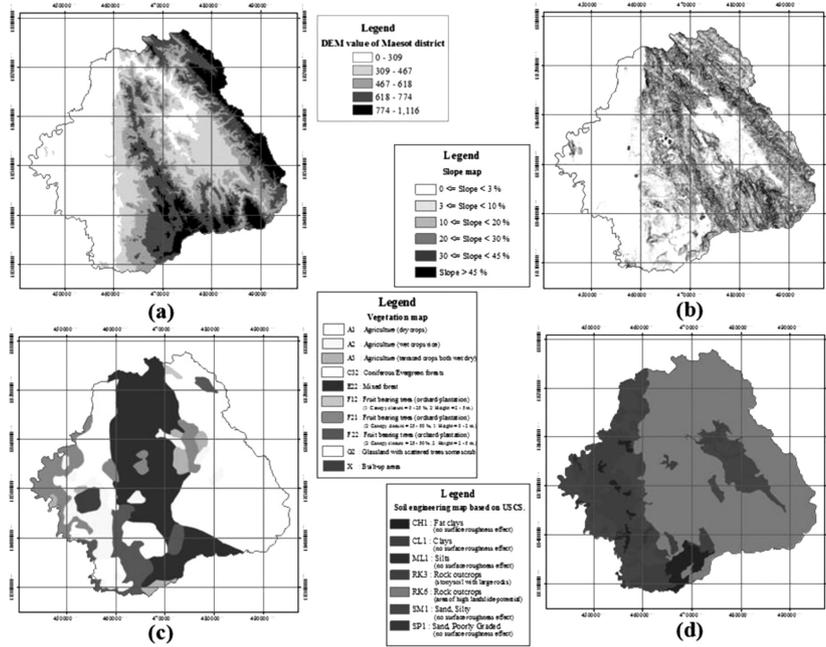


Figure 2. (a) Topographic map, (b) Slope map, (c) Classified LULC map in 2005, and (d) Classified soil map (based on USCS). Details of the used LULC and soil codes are described in Tables 5 and 6, respectively. Numbers attached to the soil code are the associated surface roughness category ( $F_s$  factor) detailed in Table 7

Table 1. Information of the vehicle characteristics (US Army, 1990; RTSD, 1997)

Characteristics	M35 truck (wheeled)	M113 carrier (tracked)	Stingray tank (tracked)	Scorpion tank (tracked)	Note (for)
Vehicle width: W (m)	2.43	2.69	2.70	2.23	F3
Vehicle factor: $V_F$	0.20	0.20	0.20	0.20	F3
Override diameter: OD (m)	0.06	0.10	-	-	F3
Maximum road speed (km/h)	56.00	48.00	69.00	72.40	F1
Maximum on-road gradability (%)	64.00	60.00	60.00	60.00	F1
Maximum off-road gradability (%)	30.00	45.00	40.00	45.00	F1
Vehicle cone index 1 pass: $VCI_1$	30.00	17.00	23.60	13.50	F4
Vehicle cone index 50 passes: $VCI_{50}$	48.00	40.00	54.40	32.30	F4

### Research Methodology

This work comprises 2 main parts which are, (1) the preparation of the necessary input data for the construction of the CCM maps, and (2) the production of the CCM maps for 4 prominent types of military vehicle employed in various divisions of the Royal Thai Army detailed in Table 1. Among these, only the M35 truck is a wheeled vehicle while the rest are all tracked vehicles (Figure 3). The preparation and processing of all relevant spatial data were principally carried out using the ArcGIS software (ESRI, 2013b). The input data were divided into 2 main categories:

- (1) Vehicle characteristics (Table 1); and
- (2) Terrain/LULC characteristics. These include surface slope, vegetation, soil property, road network, and water body (Table 2).

These data were acquired from original sources (Tables 1 and 2) and then prepared as

a GIS dataset for further use in the formulation of the CCM maps (Figures 2(a-d)).

### Derivation of the CCM Maps

The derivation process for each CCM map was carried out following the descriptive guidelines for military terrain analysis described in the US Field Manual: FM 5-33 (US Army, 1990) and the RTSD Reference Manual of the Royal Thai Army (RTSD, 1997). According to these sources, the CCM velocity (V) for a specified vehicle over a particular location was determined directly from the following equation:

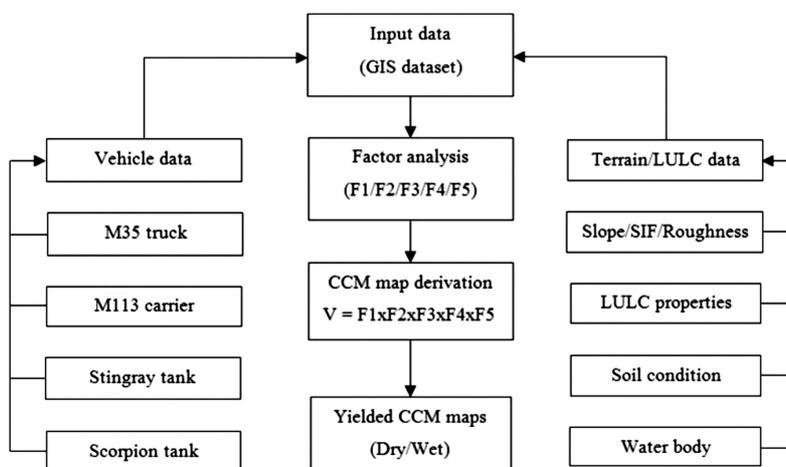
$$V = F_1 \times F_2 \times F_3 \times F_{4D/W} \times F_5. \tag{1}$$

Terms  $F_1$  to  $F_5$  seen above represent the key terrain and environmental characteristics of the area that can influence the apparent speed of the vehicle as detailed below. The  $F_1$  factor is often given in a unit of km/h while

**Table 2. Category of land trafficability in terms of the CCM speed (adapted from US Army, 1990)**

Category	Speed (km/h)	Description
1	> 30.0	Go
2	> 1.5 - 30.0	Slow Go
3	≤ 1.5	No Go

Note: Water body was marked as No GO area.



**Figure 3. Work flowchart of the study**

the  $F_2$  to  $F_5$  factors are designed to have values between 0-1 only, where higher values mean higher adverse impact on the vehicle's mobility. The velocity gained from equation 1 indicates the level of land trafficability for each listed vehicle while traveling over an area from which 3 broad categories of land trafficability were identified (Go, Slow Go, No Go) based on the original classifying scheme described by the US Army (1990) as described in Table 3.

### Determination of the Speed/Slope Factor ( $F_1$ ) and Slope/Intercept/Frequency Factor ( $F_2$ )

$F_1$  is a speed/slope factor. It determines the individual influence of a specific slope on the vehicle's speed. A higher slope value means a greater resistance to the movement.

The  $F_1$  values for each vehicle type were computed from the following equation:

$$F_1 (\text{kph}) = \frac{\text{Max off- road gradability } (\%) - \text{Surface slope } (\%)}{\times \text{Max on- road gradability } (\%)} \times \text{Max road speed (kph)}, \quad (2)$$

where Max = Maximum. Reference values for all the listed parameters required in equation 2 are given in Table 1 and, if the derived  $F_1 < 0$ , then  $F_1 = 0$ .

$F_2$  is a slope-intercept-frequency (SIF) factor. It quantifies the impact of the surface configuration on the CCM activity. By definition, SIF is the number of times the ground surface changes between positive and negative slopes over a 1-km distance. However, determination of the SIF values on a topographic map, or in the field, is often an extremely time-consuming task. Therefore, applied values for this factor were approximated from the reference values suggested by the RTSD (Table 4).

### Determination of the Vegetation Factor ( $F_3$ )

$F_3$  is the vegetation factor. It represents the impact of the vegetation aspects (e.g., type, density, or distribution) on the vehicle's mobility. This effect was assessed from the following formula (using the larger value of  $V_1$  or  $V_2$ ):

**Table 3. Information of the terrain-related input data**

Category	Factor characteristics	Data type	Scale	Year	Source
Road	Road network	Polyline	1:50000	2004	DOH
Water body	Water area	Polygon/ polyline	1:50000	2004	MNRE
Surface	Slope	Raster	30 m × 30 m	2007	CU
	Topography	Polygon	1:50000	2004	RTSD, MNRE
Vegetation cover	Vegetation type Stem spacing/ diameter	Polygon	1:50000	2004	
Soil	Soil type/strength	Polygon	1:50000	1999	RTSD

Note: DOH = Department of Highways, MNRE = Ministry of Natural Resources and Environment, CU = Chulalongkorn University, RTSD = Royal Thai Survey Department.

**Table 4. Reference  $F_2$  values at different slope values (RTSD, 1997)**

Slope (%)	0-3	3-10	10-20	20-30	30-45	≥ 45
$F_2$ value	1.00	0.99	0.98	0.97	0.96	–
Area (%)	37.61	19.64	17.52	13.40	7.31	4.52

$$F_3 = V_R \times \max(V_1, V_2), \tag{3a}$$

$$V_1 = V_F \times V_C; V_C = \frac{SS - SD}{W}, \tag{3b}$$

$$V_2 = 1 - \left[ V_T \times \frac{SD^2}{OD^2} \right]; V_T = \frac{(W + SD)}{SS}, \tag{3c}$$

where  $V_R$  is the vegetation roughness factor,  $V_F$  is the vehicle factor,  $SS$  and  $SD$  are the average stem spacing and stem diameter, respectively (Table 5),  $W$  is the vehicle width, and  $OD$  is the override diameter of the vehicle. It should be noted that stem spacing is the distance from the center of a tree to the center of the nearest adjacent tree and the tree stem diameter is a measured diameter at a height of about 1.4 m (4.5 feet) above ground. This is also normally referred to as the diameter at breast height.

In practice, if values for the  $SS$  or  $SD$  are not available (for non-forest types), then  $F_3$  is approximated from the equation:  $F_3 = V_R$  (where terms  $V_1$  or  $V_2$  are ignored). The  $V_1$  factor is the product of 2 terms: the vehicle factor ( $V_F$ ) and the vehicle clearance factor ( $V_C$ ). The first one accounts for the response of drivers when approaching wooded areas while the second accounts for the physical ability of a vehicle to maneuver between the

tree stems in a wooded area. In addition, the  $V_2$  factor is used if it would be easier for the vehicle to override the trees rather than maneuver between them (as accounted for by the  $V_1$  factor). In this case, the  $V_T$  portion is used to calculate the minimum number of trees a vehicle can hit at one time where, if  $V_T \leq 1$ , then  $V_T = 1$  and, if  $SD > OD$  or  $OD$  is not available, then  $V_2 = 0$  (there is no need to calculate the  $V_2$  factor). For practical use, if the returned value of  $V_1$  (or  $V_2$ )  $\leq 0$ , then  $V_1$  (or  $V_2$ ) = 0, and if  $V_1 \leq 1$ , then  $V_1 = 1$ , just to maintain the final  $F_3$  values to be in the range of 0-1.

#### Determination of the Soil Factor ( $F_4$ )

$F_4$  is a soil factor that informs about the impact of soil properties on a vehicle's traffic ability over an area. The analysis usually concentrates on determining the capability of the soil strength to support a specific vehicle's movement under 2 common conditions, dry and wet. The corresponding dry-soil factor ( $F_{4D}$ ) and wet-soil factor ( $F_{4W}$ ) mentioned above were determined as follows:

$$F_{4D/W} = \frac{RCI_{D/W} - VCI_1}{VCI_{30} - VCI_1}, \tag{5}$$

**Table 5. Vegetation-related information for the calculation of  $F_3$  data (RTSD, 1997)**

ID	LULC class	SD (m)	SS (m)	VR	Area (%)
A1	Agriculture (dry crops)	Null	Null	0.85	13.32
A2	Agriculture (wet crops/rice)	Null	Null	0.90	7.45
A3	Agriculture (terraced crops both wet/dry)	Null	Null	0.90	2.61
C32	Coniferous/Evergreen forests	0.06	1.50	1.00	31.29
E22	Mixed forest	0.05	2.00	0.90	28.12
F12	Fruit bearing trees (orchard/plantation) (1: Canopy closure = 0-25 %, 2: Height = 2-5 m.)	0.05	5.50	0.70	0.32
F21	Fruit bearing trees (orchard/plantation) (1: Canopy closure = 25-50 %, 2: Height = 0-2 m.)	0.04	5.00	1.00	8.36
F22	Fruit bearing trees (orchard/plantation) (1: Canopy closure = 25-50 %, 2: Height = 2-5 m.)	0.08	3.00	0.80	6.93
G2	Grassland with scattered trees/some scrub	Null	Null	0.85	0.26
X	Built-up areas	Null	Null	0.30	1.34

Note:  $SD$  = Stem diameter,  $SS$  = Stem spacing,  $V_R$  = Vegetation roughness, Null = No data.

where *RCI* is the rating cone index widely used to represent the proportion of the original soil strength being retained after a specific vehicle has passed over and *VCI* (vehicle cone index) is a value given to a vehicle for a specific number of its passes. The values of *RCI* depend principally on the types of the soil and their humidity; in general, the larger the *RCI*, the stronger the soil (Ciobotaru, 2009). The *VCI* is used as the minimum soil strength necessary for the free vehicle to consistently conduct a specific number of passes without becoming immobilized. Often-used values are for 1 and 50 passes called *VCI*<sub>1</sub> and *VCI*<sub>50</sub>, respectively (US Army, 1994; Priddy and Willoughby, 2006). The *VCI* has been employed by the US Army as a simple performance indicator for vehicles to traverse on soft-soil terrain for a long time (US Army, 1947; Paul, 1985). In general, if the *VCI* exceeds its corresponding *RCI*, that soil is not trafficable for the specified number of passes for the vehicle. Also, if it is found that the value of  $F_4 \leq 0$ , then  $F_4 = 0$ , and if  $F_4 \geq 1$ , then  $F_4 = 1$ . The reference values of the *RCI* and

*VCI* factors for the calculation of  $F_4$  data are given in Tables 6 and 1, respectively. It should be noted that only 6 types of identified soil unit, based on the Unified Soil Classification System (USCS), were found in the study area as depicted in Figure 2(d).

**Determination of the Surface Roughness Factor ( $F_5$ )**

The surface roughness factor ( $F_5$ ) is used to find the effect of surface characteristics

(like surface roughness or slope stability) on the vehicle movement. Possible values of the  $F_5$  factor range from 0 to 1 with a 0.05 increment where the value of 1.00 indicates no degradation to the vehicle speed while a factor of 0.80, for example, would degrade vehicle speed by 20% (US Army, 1990). To estimate the magnitude of this factor, all physical characteristics of the land surface as well as the vehicle characteristics, such as ground clearance and wheel size, must be evaluated. The  $F_5$  factor is typically classified for 5 categories of military movements: medium or large tanks, large wheeled vehicles,

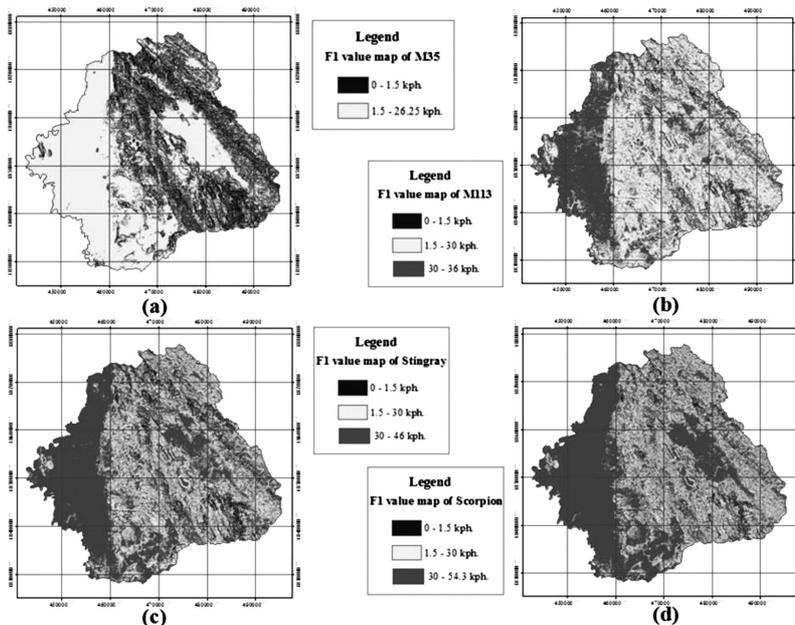


Figure 4. The  $F_1$  maps for (a) M35 truck, (b) M113 carrier, (c) Stingray tank, and (d) Scorpion tank

small wheeled vehicles, small tracked vehicles, and troops (Table 7). It should be noted that only 3 categories (1, 3, and 6) were used for the study area as expressed by the associated soil types described in Figure 2(d).

## Results and Discussion

### Evaluation of the Yielded $F_1$ - $F_5$ Maps

As described earlier, to produce the preferred CCM maps for an area of interest, the associated maps of 5 key terrain and environmental characteristics of the area, called  $F_1$  to  $F_5$ , must be formulated first for the concerned vehicles which, in this case, are the M35 truck, the M113 carrier, the Stingray tank, and the Scorpion tank. Figures 4(a-d)

present the  $F_1$  maps for all vehicle types mentioned above. The  $F_1$  values were derived from equation 2 using the slope information shown in Figure 2(b) and the vehicle properties addressed in Table 1. From the relationship given in equation 2, it is obvious that a vehicle's velocities in this case ( $F_1$ ) vary significantly according to the surface slope in a linear fashion, i.e.,  $F_1 = 26.25 - 0.875 \cdot \text{slope}$  (for M35),  $F_1 = 36 - 0.8 \cdot \text{slope}$  (for M113),  $F_1 = 46 - 1.15 \cdot \text{slope}$  (for Stingray), and  $F_1 = 54.3 - 1.207 \cdot \text{slope}$  (for Scorpion). These relationships indicate that the Scorpion tank is the most sensitive to the slope change followed by the Stingray and the M35 while the M113 is least sensitive. In addition, the critical values of the surface slope that will terminate the vehicle movement (i.e., having  $F_1 \leq 0$ ) vary from 30%

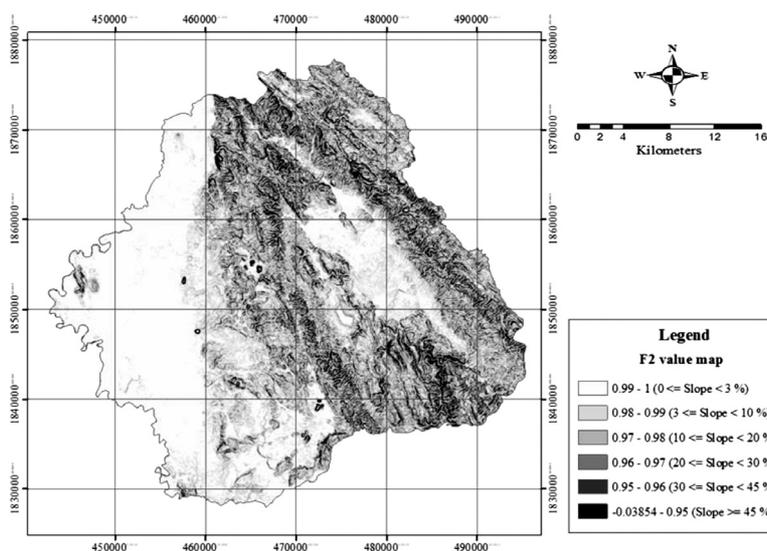


Figure 5. The SIF (or  $F_2$ ) map for all the vehicles

Table 6. RCI data for 6 different soil units found in the study area (US Army, 1990)

Soil unit	Type	RCI		Soil unit	Type	RCI	
		Dry	Wet			Dry	Wet
CH	Fat clays	136	62	RK	Rock outcrops	165	165
CL	Clays	123	40	SM	Sand, Silty	119	25
ML	Silts	118	20	SP	Sand, Poorly Graded	145	73

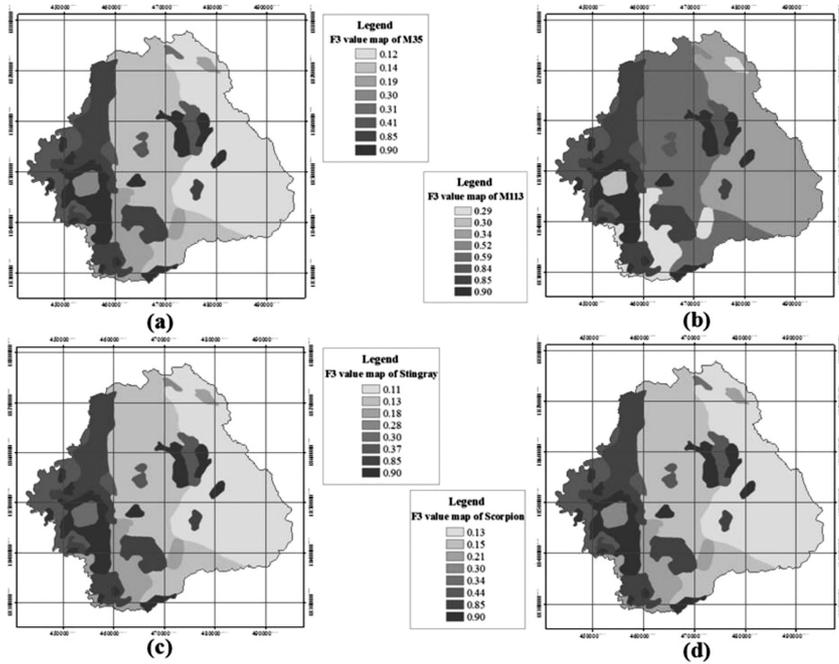


Figure 6. The  $F_3$  maps for (a) M35 truck, (b) M113 carrier, (c) Stingray tank, and (d) Scorpion tank

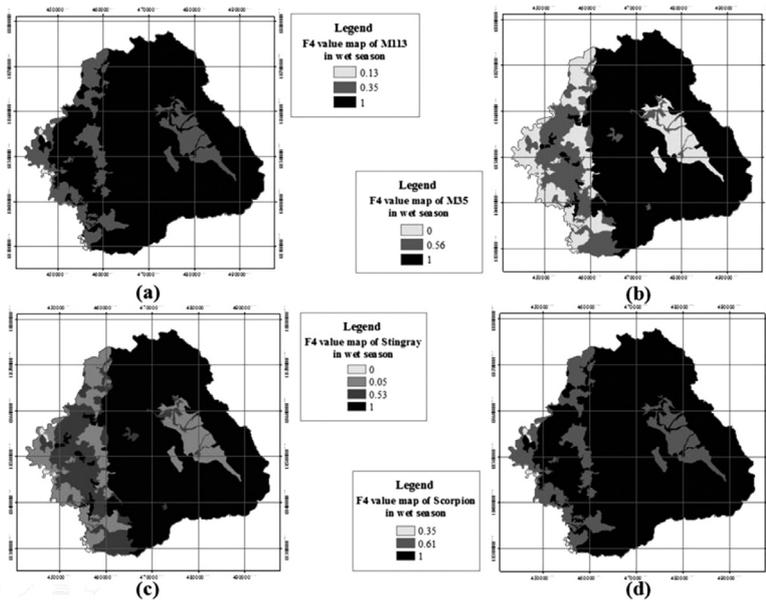


Figure 7. The  $F_4$  maps for (a) M35 truck, (b) M113 carrier, (c) Stingray tank, and (d) Scorpion tank, in the wet season

(for the M35) to 40% (for the Stingray) and 45% (for the M113 and Scorpion).

Examples of the derived  $F_1$  values at surface slopes of 0 to 45% are presented in Table 8 which demonstrate that the Scorpion tank can achieve the highest speed possible on flat terrain of 54.3 km/h while the M113 does worst (at 26.25 km/h). No vehicle can move over a terrain with a slope  $\geq 45\%$ . Figure 4 shows the strong influence of a slope on the vehicle mobility as all the examined vehicles can move best on the relatively flat terrain in the western part of the district and in the middle portion of the eastern side. This capability notably decreases within the mountain-dominated areas situated in the middle and the eastern parts (as identified by the “No Go” and “Slow Go” areas). Figure 5 presents the map of the SIF factor ( $F_2$ ) derived

from knowledge of the slope data (Table 4). It is clearly seen that the general appearance of the  $F_2$  map highly resembles that of the  $F_1$  maps (Figure 4) due to the strong linear dependency of both factors on the surface slope of the area.

The determination of the impact of the vegetation factor ( $F_3$ ) on the capacity of the vehicle movement over the area is probably the most difficult task for the CCM analysis done here, as both the vegetation properties (Table 5) and the vehicle characteristics (Table 1) must be considered together through the relationships expressed in equations 3a-c. The results are presented in Table 9 and Figures 6(a-d) which indicate that all vehicles can travel over the agricultural land (A1-A3) and the grass land (G2) well (with  $F_3$  values of 0.85-0.9), while movement over land filled

**Table 7. Information of the estimated surface roughness factor ( $F_s$ ) (US Army, 1990)**

Category	Description	Estimated surface roughness factors ( $F_s$ )			
		Medium/ large tanks	Large wheeled vehicles	Small wheeled vehicles	Small tracked vehicles
0	No data	null	null	null	null
1	No surface roughness effect	1.00	1.00	1.00	1.00
2	Stony soil with scattered surface rock	0.90	0.90	0.80	0.85
3	Stony soil with large rocks	0.70	0.70	0.70	0.70
4	Area with a variety of soils and landscapes	0.50	0.50	0.50	0.50
5	Disturbed areas (quarry, mining, and excavations)	0.20	0.20	0.20	0.20
6	Area of high landslide potential	0.00	0.00	0.00	0.00

**Table 8. Examples of the derived  $F_1$  values (from equation 2) at surface slope of 0 to 45%**

Slope (%)	$F_1$ (km/h)			
	M35	M113	Stingray	Scorpion
0	26.25	36.00	46.00	54.30
10	17.50	28.00	34.50	42.23
20	8.75	20.00	23.00	30.17
30	0.00	12.00	11.50	18.10
40	0.00	4.00	0.00	6.03
45	0.00	0.00	0.00	0.00

with tall and fertile trees like the coniferous/evergreen forest (C32), mixed forest (E22), and fruit bearing trees with a height of 2-5 m (F22) was found rather ineffective (with  $F_3$  values of mostly 0.1-0.3). As the agricultural land is most abundant on the western flat plain region while the forest is mostly concentrated in the middle and eastern parts (the mountainous zone), this makes the apparent pattern of the  $F_3$  maps somewhat similar to those found in the cases of the  $F_1$  (slope) and  $F_2$  (SIF) factors illustrated in Figures 4 and 5. In this study, the performance of the M113 carrier was found to be the most impressive on average when compared with the other vehicles, especially for the movement over forest (C32/E22) and fruit-tree lands (F12/F21/F22) in which all the other vehicles did fairly poorly (with  $F_3$  values

of mostly 0.1-0.2). In addition, the capability of all the vehicles for off-road travelling over the built-up land was also relatively poor (with the  $F_3$  value of 0.3).

The soil factor ( $F_4$ ) indicates the impact of the soil characteristics on vehicle mobility which was evaluated for both the dry and wet seasons based on the formula given in equation 5 and the  $RCI$  data (Table 6) and  $VCI$  data (Table 1). The results which were obtained are shown in Table 10 and Figures 7(a-d) (for the wet season). Maps for the dry season are not displayed here due to the homogenous output of the  $F_4$  data of 1 for all the vehicles (Table 10) which means that the soil condition during the dry season over the entire study area is capable of supporting the movement of all vehicles well (no degradation was encountered). In the wet season, the soil

**Table 9.**  $F_3$  data for each vehicle regarding different vegetation types (see Table 5 for details of the listed vegetation types)

Vehicle	$F_3$ values									
	A1	A2	A3	C32	E22	F12	F21	F22	G2	X
M35	0.85	0.90	0.90	0.12	0.14	0.31	0.41	0.19	0.85	0.30
M113	0.85	0.90	0.90	0.34	0.59	0.52	0.84	0.29	0.85	0.30
Stingray	0.85	0.90	0.90	0.11	0.13	0.28	0.37	0.18	0.85	0.30
Scorpion	0.85	0.90	0.90	0.13	0.15	0.34	0.44	0.21	0.85	0.30

**Table 10.**  $F_4$  data for each vehicle regarding different soil types (see Table 6 for details of the listed soil types). The attached numbers (1, 3, 6) are the associated surface roughness category for each soil type as explained in Table 7

Vehicle	Season	$F_4$ alues							
		CH1	CL1	ML1	RK3	RK6	SM1	SP1	
M35	Dry	1	1	1	1	1	1	1	
	Wet	1	0.56	0	1	1	0	1	
M113	Dry	1	1	1	1	1	1	1	
	Wet	1	1	0.13	1	1	0.35	1	
Stingray	Dry	1	1	1	1	1	1	1	
	Wet	1	0.53	0	1	1	0.05	1	
Scorpion	Dry	1	1	1	1	1	1	1	
	Wet	1	1	0.35	1	1	0.61	1	

strength substantially dropped from that of the dry season regarding the reference *RCI* data displayed in Table 6, e.g., from 123 to 40 (for clays) and from 118 to 20 (for silts). This makes some parts of the area much less efficient in accommodating effective movement of the vehicles during the wet season. For example, clay (CL) can dramatically reduce the CCM speed of the M35 and the Stingray by nearly 50% (with  $F_4$  values of 0.56 and 0.53, respectively) while it has no effect on the movement of the M113 and Scorpion (with the  $F_4$  value of 1).

Similarly, the silt (ML) can tremendously reduce the mobility of all vehicles during the wet season with the  $F_4$  values of 0 (for the M35 truck and the Stingray tank), 0.13 (for the M113 carrier), and 0.35 (for the Scorpion tank), respectively. This means the M35 and Stingray should be immobile over the silt-dominated land during wet season. A similar impact was also observed for movements over the mixed sand and silt soil (SM) where the M35 should be immovable and the Stingray should be barely movable. On the contrary, 3 other soil types, i.e., fat clay (CH), rock

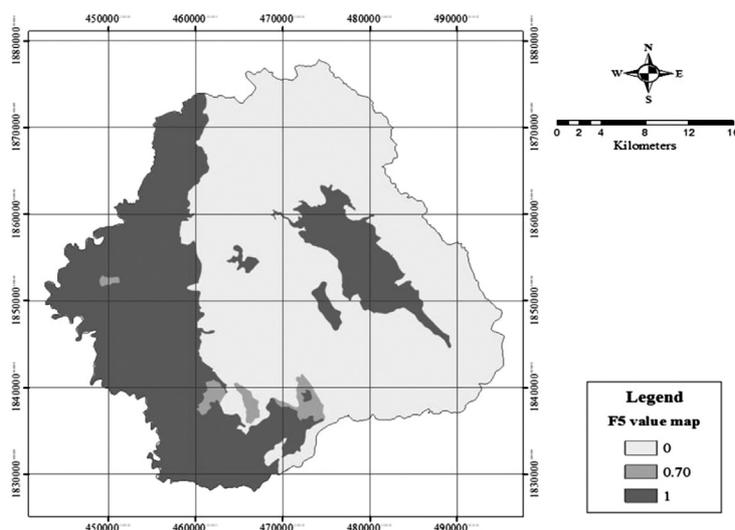


Figure 8. The  $F_5$  map for all the vehicles regarding different surface roughness scales of 0 (for land with a high landslide potential), 0.7 (for the stony soil with large rocks), and 1.0 (mostly for flat terrain in the west and in the middle portion of the east)

Table 11. Proportion of classified area extracted from the developed land trafficability maps for each vehicle type (in Figure 9) and their performance scores

Trafficability category	Assumed weight	Area proportion (%)							
		M35		M113		Stingray		Scorpion	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Go	1	-	-	4.30	3.10	15.26	1.24	17.05	9.52
Slow Go	0.5	35.12	17.63	33.71	33.20	22.12	23.70	20.85	26.97
No Go	0	64.88	82.37	61.99	63.70	62.62	75.06	62.10	63.51
Performance score (out of 100)		17.56	8.82	21.16	19.70	26.32	13.09	27.48	23.01
		13.19		20.43		19.71		25.25	

outcrop (RK), and poorly-graded sand (SP), were found to maintain the moving capability of all the vehicles during the wet season well when compared with that capability experienced in the dry season (with the  $F_4$  value of 1), due to their relatively high  $RCI$  values in this season (with  $RCI_w > VCI_{50}$ ).

In conclusion at this stage, silt-dominated land was found to be the most vulnerable area for the off-road movements of all vehicles of interest during the wet season followed by the mixed sand/silt and the clay-dominated lands, respectively. But no degradation in the moving capacity of all the vehicles (in terms of the  $F_4$  value) was found for land dominated by the fat clay, rock outcrop, and poorly-graded sand. On average, the mobility of the M35 and the Stingray were most affected during the wet season followed by the M113 and the Scorpion, respectively (Table 10).

The surface roughness factor ( $F_5$ ) represents the influence of the surface material on the vehicle mobility. The result is reported in Figure 8 (for all vehicles). Only 3 types of the surface roughness aspect were identified in this study, which are:

(1) Surface with no roughness effect ( $F_5 = 1$ ); this comprises all land parcels in the area except those located in the rock outcrop zone (RK) and are most abundant over the flat plain terrain in the west and in middle portion of the east.

(2) Stony soil with large rocks ( $F_5 = 0.7$ ) which includes all the land in the defined RK zone without a high landslide potential (or RK3 in Table 10); only a small portion of the area in this category was identified, as shown in Figure 8.

(3) Areas with a high landslide potential ( $F_5 = 0$ ) which includes most of the land found in the RK zones (or RK6 in Table 10) which are automatically classified as being a "No Go" area in the production of the CCM maps for each vehicle type.

### Evaluation of the CCM Maps

All the  $F_1$  to  $F_5$  maps which were produced for each listed vehicle type discussed earlier were integrated using the

standard GIS overlay technique to produce their respective CCM velocity maps for the entire area based on the relationship presented in equation 1 in both the dry and wet seasons. The results are reported in Table 11 and Figures 9(a-d), respectively. The land traffic ability data (inferred from the CCM velocities) for all the vehicles was separated into 3 broad categories: No Go (0-1.5 km/h), Slow Go (1.5-30 km/h), and Go (> 30 km/h), as detailed in Table 3.

In general, the No Go areas were found to be most abundant with a proportion of about 62-65% in the dry season and 63-82% in the wet season. Most of these areas are situated in the middle and eastern parts of the district due to the existence of high mountains with rough and high slope terrains and a high landslide potential. The marked increase in the No Go areas during the wet season was clearly evident for the M35 truck (from 64.88 to 82.37%) and the Stingray tank (from 62.62 to 75.06%) but only a slight increase was observed for the M113 carrier (1.71%) and the Scorpion tank (1.41%). A notable expansion of the No Go areas in the wet season is due to softer soil conditions (as indicated by the  $RCI$  values) which makes vehicle movement more difficult, especially on land dominated by clay, silt, and mixed sand/silt (as discussed earlier). Usually, wheeled vehicles, like the M35, have been found to be inferior to their tracked counterparts in terms of off-road mobility due to their smaller surface area which results in a higher ground pressure (as indicated by the  $VCI$  values). This makes them less mobile on soft soil and also on the sloped terrain (Hornback, 1998; Wang and Huang, 2006).

On the contrary, the Go areas, which are most preferable for CCM activity, were mostly found to be concentrated in the agricultural zone on the western side of the district surrounded by the large Slow Go areas. In the dry season, the Go areas for the Scorpion and Stingray tanks were found to be more abundant (at 17.05% and 15.26%, respectively) than those of the M113 carrier and the M35 truck (at 4.30% and 0%,

respectively). This difference is due mostly to the fairly higher maximum road speeds of the tank vehicles (about 70 km/h) to those of the M113 and M35 (about 50 km/h), as stated in Table 1. This enables them to attain a higher CCM velocity under similar terrain conditions (see data in Table 8 for example). However, the number of the Go areas considerably dropped in the wet season for both tank vehicles, i.e., to 1.24% for the Stingray and 9.52% for the Scorpion. Similarly, the Slow Go areas were mostly identified on the western side of the district and the central portion of the eastern side where terrain properties (e.g., LULC and soil strength) are less favorable for vehicle movement than those of the Go areas. In the dry season, the proportion of these areas for the tank vehicles is about 20 % while for the M113 and M35 it is about 35%. However, a sharp drop in the Slow Go areas was found in the wet season for the M35 (from 35.12% to 17.63%) in favor of the No Go areas while a noticeable rise was found for the Scorpion tank (from 20.85% to 26.97%) due to a transition from the Go areas; but for the M113 and Stingray they are rather constant.

When considering the general performance of each vehicle type in terms of the weighted trafficable areas (Table 11), it was found that the performance of all the listed vehicles significantly decreased from the dry to the wet season, (especially for the M35 and Stingray), except for the M113 for which the performance is comparable in both seasons. In the dry season, both tank vehicles did comparatively well followed by the M115, but in the wet season, the Scorpion did best followed by the M113 and the Stingray, respectively. In this study, the M35 truck was found to perform worst in both seasons. In addition, if comparing the average performance score from both seasons (out of 100), the Scorpion tank comes first (25.25) followed by the M113 carrier (20.43), the Stingray tank (19.71), and the M35 truck (13.19), respectively. The results support the general belief that the tracked vehicles are critically superior to the wheeled vehicle ones in terms

of off-road mobility, especially on relatively rough and sloped terrain as encountered in Mae Sot District. Interestingly, similar conclusions were reported by the US Army (1973) from a modelled analysis of the CCM performance for 4 types of military vehicles: the M35 truck (wheeled), M151 truck (wheeled), M60 tank (tracked), and M113 carrier (tracked) based on the so-called AMC'71 Mobility Model. It was found from the study that the tracked vehicles performed significantly better than the wheeled ones in all examined cases (using the extracted Puerto Rican terrain as a reference). Their results indicate that the M60 tank did best in both the dry and wet seasons in terms of average mobility followed by the M113, while the M35 and M151 did comparatively badly. In addition, the seasonal effect was clearly exhibited for the M60 tank and M35 truck but it was much less obvious for the M113 carrier and M151 truck.

## Conclusions

In general, suitable areas for the CCM activity of all the studied vehicles (Go and Slow-Go areas) were found to be situated mostly in the western part of the district due to the favorable topography (a relatively large flat plain) while the unsuitable ones (No-Go areas) were found to be abundant in the middle and eastern parts as a result of fairly rough and sloped terrain over the area. The proportion of the No-Go areas notably dropped from about 62-65% in the dry season to 63-82% in the wet season due to the effect of softer soil conditions. All the tracked vehicles, especially the tanks, were found to perform significantly better than the wheeled counterpart in both seasons. The average performance scores for both seasons (out of 100) indicated that the Scorpion tank was on top (25.25) followed by the M113 carrier (20.43) and Stingray tank (19.71), while the M35 truck was ranked bottom (13.19). These findings support the general conclusion that military tracked vehicles are significantly superior to their wheeled counterparts in

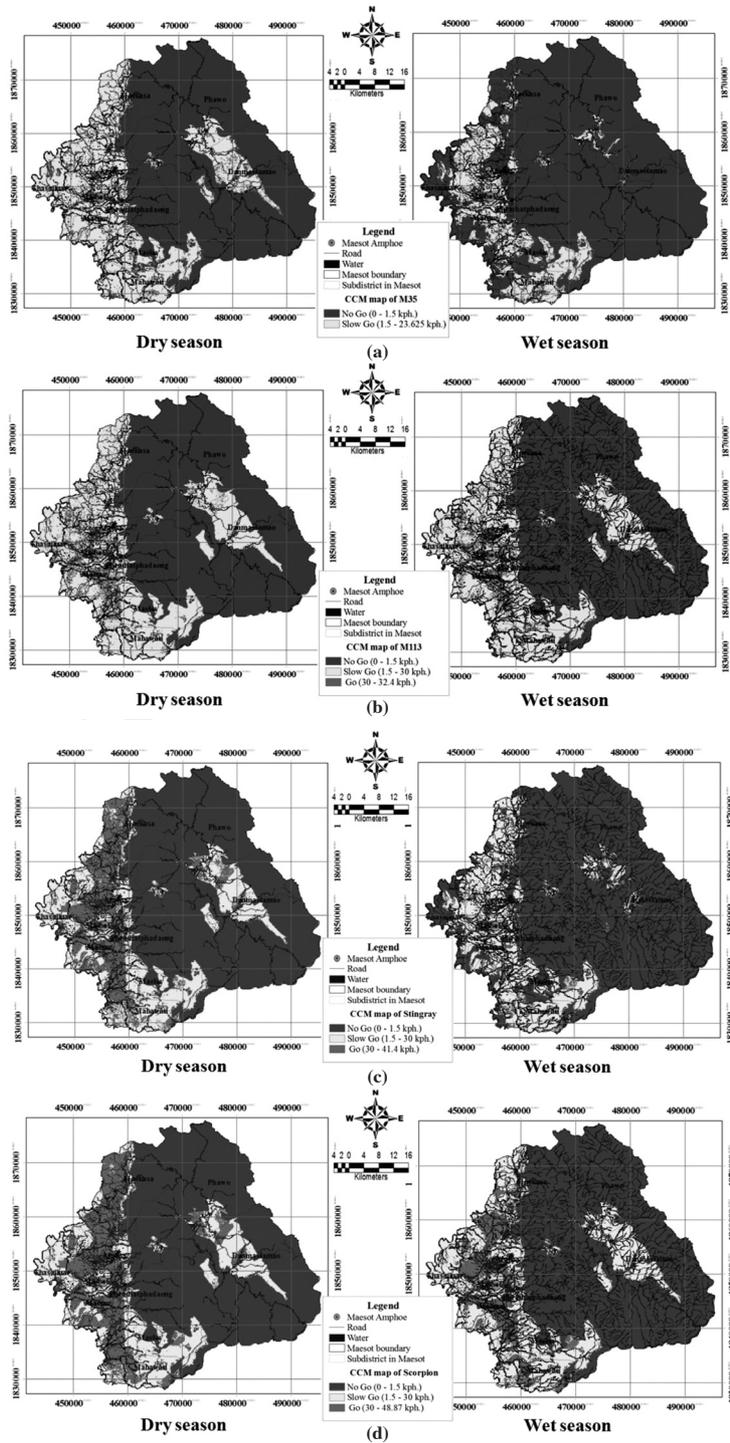


Figure 9. The CCM maps for (a) M35 truck, (b) M113 carrier, (c) Stingray tank, and (d) Scorpion tank, in both the dry and wet seasons

terms of off-road operation.

The results yielded from this work are useful as primary information for the preparation and operation of the effective CCM activity for each vehicle type used over the area by the Royal Thai Army in the future, e.g., in the identification of the shortest path, or the fastest path, for the relevant vehicle. This work is just an example of how to productively apply GIS tools to support military CCM activity and more applications can be investigated in further works, e.g., the production of detailed OCOKA maps for this area. In addition, similar maps for other strategic areas in Thailand should also be established for possible use, using the approach demonstrated in this paper as a guideline.

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