JTLS-2017-13200 Improve Grid Movement Optimization

Harold Yamauchi, Ellen Roland, Rick Kalinyak

1.0 Summary of Model Change Request

JTLS-GO provides the capability to move entities either on a movement network or off network on a direct path. A JTLS-GO scenario may incorporate multiple road, rail, and river networks, as well as a single worldwide air network and a single worldwide sea lane network. Off network movement can be generalized to a direct route that follows the great circle from a starting location to a designated destination.

This change request addresses the need to improve entity off-network movement on the underlying terrain grids. The general problem involves an entity that encounters an impediment to movement that requires the entity to detour around the obstacle and continue to its destination.

2.0 Design Summary

The entities affected by this update include:

- Ground Aggregate Resolution Units (ARUs)
- High Resolution Units
- Naval Units
- Truck Convoys - Note that rail convoys and barge convoys are not part of this design because they cannot move off their respective networks.
- Air Missions

Entity movement in the context of this document means that the entity will move under its own power; it will not be transported. Only individual entity movement is addressed; entities moving as a group, such as a naval formation and Tactical Ground Formations (TGFs), are not addressed.

It is desired to replace the current direct route approach to off-network planning and movement with an approach similar to planning and movement on a movement network. The approach taken by this change request is based upon methods applied to the cross country movement (CCM) problem. Although planning for the CCM problem is a land navigation problem, the basic principles can be carried over to the sea and air realms, as well. Section 3.0 Detailed Design discusses how these changes can be achieved.

Note on terminology: the terms “off-network graph” and “off-network route” are used throughout this document. “Off-network graph” refers to a graph composed of a set of vertices (nodes) and a set of edges (arcs) where the nodes are arranged in a raster (grid) pattern. “Off-network route” refers to one of the following:

- a direct route that follows the great circle from a starting location to a designated destination
- the best route, or any feasible route, using an off-network graph

3.0 Detailed Design

This section is broken down into three main parts.

- Background, Section 3.1, discusses how route planning and obstacle avoidance are currently implemented by the JTLS model.
- Proposed Off-Network Graph, Section 3.2, covers the data structures needed by the model to improve off-network planning and movement.
- Implementation, Section 3.3, outlines how this off-network design can be integrated into the model.

3.1 Background

Concepts and methods currently used for route planning on movement networks are discussed because they can be applied to off-network planning. Current Path Finding Capabilities, Section 3.1.1, describes how routes are presently planned for ground units, naval units, truck convoys and air missions. Current Obstacle Avoidance Capabilities, Section 3.1.2, describes how these entities deal with obstructions to movement.

3.1.1 Current Path Finding Capabilities

Dijkstra's algorithm is implemented to find the best (fastest) routes on the movement networks. Off-network path finding is limited to finding the direct route from specified start and end locations. (A direct route simply follows the great circle arc from the start to end locations.) The following sections discuss how the model implements network and direct route planning.

3.1.1.1 Current ARU Ground Unit Movement

A Move order for an ARU requires it to move from its current location to a destination. The order has an option to direct the model to find either an “optimal' or “direct” route. If direct is specified, the direct route from the ARU's location to the destination is checked for feasibility. A direct route is not feasible if it intersects an uncross-able barrier segment, river segment, national boundary segment or passes through an “implicit” shoreline (for example, the direct route passes through an Open grid that is not dual use followed by an Ocean grid). If it is feasible, the ARU will follow the direct route. If it is not feasible, the ARU will follow the direct route as far as possible.

If the Move order specifies an optimal route, one or more feasible road networks are sought. A candidate road network is selected if it has at least one road node within a specified search distance of the ARU's location and at least one road node within the same search distance of the destination. These nodes are identified, respectively, as the start node(s) and the end node(s) used by the network routing algorithm. It is possible that multiple feasible start nodes and end nodes exist, but it may not be practical, from a model performance standpoint, to examine every start and end node combination to identify the pair of start and end nodes that produce the fastest route. In this case the methodology performs a trade-off that simply finds the first feasible route. The following constraints are applied during the search for the feasible route:

- If a road arc has an associated target, such as a bridge or tunnel, and that target is perceived to be destroyed, the arc is assessed to be unusable and is not selected.
- If the road arc crosses a national boundary that the ARU does not have permission to cross, the arc is not selected.
- Large road networks impact the performance of the model, therefore the search is restricted to a calculated rectangular search area. Nodes found outside the search area will not be selected.
- If a road node has an associated target, such as an interdiction point, and that target is perceived to be destroyed, the node is assessed to be unusable and is not selected.

Total travel time is the time for the ARU to take the direct route from its location to the start node of the network, plus the time to travel the route from the start node to the end node of the network, plus the time to take the direct route from the end node to the destination. When more than one network is found to be feasible, the one with the fastest total travel time is selected.

The fastest network travel time is compared to the travel time for a direct route. If the network is faster, the ARU is given the network route; otherwise, the direct route is assigned. If it turns out that there are no feasible road networks, the ARU will take the direct route. If the direct route is not feasible, the ARU will follow it as far as possible.

3.1.1.2 Current HRU Movement

An HRU Move task provides a choice to move on rivers: “Mandatory”, “Optional”, or “No Use”. The following sections describe how each choice affects the route planning.

- Mandatory River Option - Since the HRU must own a small boat to move on rivers, the movement is not done at all if the HRU doesn't own one. If the HRU owns a small boat, one or more feasible road and river networks are sought. A road or river network is selected in the same manner that a road network is selected for an ARU (Current ARU Ground Unit Movement, Section 3.1.1.1).

  Since the selected network may have multiple feasible start nodes and end nodes, the methodology finds the first feasible route. The constraints applied during the search for the feasible road network route are listed in Section 3.1.1.1. One constraint is applied during the search for the feasible river network route: if a river arc crosses a national boundary and the HRU does not have permission to cross it, the arc is not selected.

  Total travel time is the time for the HRU to take the direct route from its location to the start node of the network, plus the time to travel the route from the start node to the end node of the network, plus the time to take the direct route from the end node to the destination. When more than one network is found to be feasible, the one with the fastest total travel time is chosen to be the best network. If there are no feasible networks, the HRU is not allowed to move.

  If the fastest network is identified, the total travel time is compared to the travel time for a direct route from the HRU's location to the destination. If the network is faster, the HRU is given the network route; otherwise, the HRU is not allowed to move.

- Optional River Option - If the HRU owns a small boat, one or more feasible road and river networks are sought. If the HRU does not own a small boat, only feasible road networks are considered. A road or river network is selected in the same manner that a road network is selected for an ARU described in Section 3.1.1.1. Since the selected network may have multiple feasible start nodes and end nodes, the methodology finds the first feasible route. The constraints applied during the search for the feasible road network route were also listed in Section 3.1.1.1.

  The national boundary constraint is applied during the search for the feasible river network route.

  Total travel time is the time for the HRU to take the direct route from its location to the start node of the network, plus the time to travel the route from the start node to the end node of the network, plus the time to take the direct route from the end node to the destination. When more than one network is found to be feasible, the one with the fastest total travel time is chosen to be the best network.

  The fastest network travel time is compared to the travel time for a direct route from the HRU's location to the destination. If the network is faster, the HRU is given the network route; otherwise, the direct route is assigned. If it turns out that there are no feasible networks, the HRU will take the direct route.

- No Use River Option - Only feasible road networks are considered. Following the procedure discussed in Current ARU Ground Unit Movement, Section 3.1.1.1, the road network with the best total travel time is selected amongst all feasible road networks. This travel time is compared to the travel time for a direct route from the HRU's location to the destination. If the network is faster, the HRU is given the network route; otherwise, the direct route is assigned. If there are no feasible networks, the HRU will take the direct route.

3.1.1.3 Current Truck Convoy Movement

When an implicit convoy cannot be used, a truck convoy can be created by a supply unit if it is the appropriate mode of transportation to get supplies to the receiving unit. When a truck convoy is ready to be dispatched, the model attempts to find all feasible road networks for the convoy to use. The procedure as discussed in Current ARU Ground Unit Movement, Section 3.1.1.1 is used to find the networks and determine the fastest one. Total travel time in this case is the time for the convoy to take the direct route from the supply unit's location to the start node of the network, plus the time to travel the route from the start node to the end node of the network, plus the time to take the direct route from the end node to the destination.

The fastest network travel time is compared to the travel time for a direct route from the supply unit's location to the destination. If the network is faster, the convoy is given the network route; otherwise, the direct route is assigned. If there are no feasible road networks, the convoy will take the direct route.

3.1.1.4 Current Naval Unit Movement

When a Naval Move order is received by a naval unit, the model checks if a direct route from the unit's location to the specified destination is feasible: every terrain grid along the direct route must be Ocean, Small Island, or Dual Capable, every grid depth must be able to handle the unit's minimum depth requirement, and every grid must not contain a mandatory sea lane arc. The feasible and infeasible cases are discussed separately in the following sections.

- Direct Route Feasible - The model proceeds to find an alternate route through the sea lane network. The model checks that a sea lane node is accessible from the unit's location. Candidate nodes must fall within a calculated search area. If there are multiple nodes available, the one closest to the unit is chosen. This node will be the designated the start node for the network routing algorithm. Similarly, the node within the same search area that is closest to the specified destination is selected. This node will be the designated the end node for the routing algorithm. If neither the start node nor the end node can be determined, the unit will take the direct route.

If a start node and an end node can be identified, the model determines whether the direct route from the unit's location to the start node and the direct route from the end node to the destination are feasible. If either direct route is infeasible, the unit will take the direct route from its location to the destination.

If the direct routes from the unit's location to the start node and from the end node to the destination are both feasible, the travel times for these routes are obtained (respectively, TIME TO START and TIME TO END) and summed. If this sum exceeds a maximum allowable time, which is derived as a function of the time to travel the direct route from the unit's location to the destination, the unit will take the direct route from its location to the destination.

The model attempts to find the fastest route through the sea lane network from the start node to the end node. The routing algorithm enforces the following constraints:

a. If the sea lane arc's depth is shallower than the unit's minimum depth requirement, the arc is not selected.
b. If the sea lane arc crosses a national boundary that the unit does not have permission to cross, the arc is not selected.

If no feasible route is available through the network, the unit will use the direct route from its location to the destination.

Given that a feasible route from the start node to the end node was found, the total travel time is obtained. This is TIME TO START, plus the travel time from the start node to the end node on the sea lane network, plus TIME TO END. If the total travel time exceeds MAX TIME, the unit will use the direct route from its location to the destination. If the total time is faster than the direct route travel time from the unit to the destination, the unit will use the network; otherwise, the unit takes the direct route.

- Infeasible Direct Route - The model only considers the sea lane network. It attempts to find a path for the unit through the network using the same process presented by Direct Route Feasible. If there is no feasible solution, the unit will follow the direct route from its location to the destination as far as possible.

3.1.1.5 Current Air Mission Movement

An air mission, depending on the air control prototype and mission type, may be required to use the air network. If this is the case, the model attempts to find the closest air node to the mission's location and the closest air node to the destination. These nodes will be, respectively, the start node and end node used by the network routing algorithm. The search for these nodes is undertaken within a calculated search area. If the search cannot establish either the start node or the end node, the air mission will take the direct route from the mission's location to the destination.

If the start node and end node can be identified, the routing algorithm attempts to find the fastest route through the air network from start to end. The routing algorithm insures that the air mission will not be sent through an air arc that does not satisfy the following constraints:

- The air arc covers the altitude restriction of the mission: the minimum altitude of the arc is lower than the maximum altitude capability of the aircraft flying the mission.
- The air arc intersects a national boundary that the mission has permission to cross.

If no feasible route is available through the network, the mission will use the direct route.

3.1.2 Current Obstacle Avoidance Capabilities

Once an entity is given a route to follow, it begins movement. At each movement event, the entity plans its next move. During this time a check is made for obstructions that may block its movement. The following sections summarize how each type of entity currently handles obstructions.

3.1.2.1 Current Ground Unit Obstacle Avoidance

ARUs and HRUs moving on a road network cannot pass through a nonoperational node (for example, a destroyed interdiction point), cannot cross a nonoperational arc (for example, a destroyed bridge), and cannot cross a national boundary that it does not have permission to cross. In addition, HRUs moving on a river network cannot cross a national boundary that it does not have permission to cross. When an impediment is encountered on a network, the unit stops moving.

Units moving off road can be blocked by an uncross-able barrier segment, river segment, national boundary segment or an implicit shoreline. If there is an impediment, the model calls the routine FIND AUTOMATIC SOLUTION to find a way around the obstacle. Starting with the ROUTE POINT representing the unit's destination, and searching backwards through each preceding ROUTE POINT, the routine attempts to find the first ROUTE POINT that can be reached from the unit's current location via a road network. If FIND AUTOMATIC SOLUTION cannot find a solution, the unit must stop and wait; otherwise, the unit will detour to the ROUTE POINT found by the routine and follow the subsequent ROUTE POINTs to the destination.

3.1.2.2 Current Truck Convoy Obstacle Avoidance

Truck convoys are affected by the same obstructions that affect ground units both on and off network. If an obstruction is encountered on a road network, the convoy stops and waits. If off road, the model also calls FIND AUTOMATIC SOLUTION to detour the convoy around an obstacle.

If the routine cannot find a solution, the convoy must stop and wait; otherwise, the convoy will detour to the ROUTE POINT found by the routine and follow all the subsequent ROUTE POINTs to the destination.

3.1.2.3 Current Naval Unit Obstacle Avoidance

Naval units can be blocked by an implicit shoreline or a national boundary that it does not have permission to cross. The unit must stop and wait if either obstruction is encountered.

3.1.2.4 Current Air Mission Obstacle Avoidance

An air mission can be blocked by a national boundary it does not have permission to cross, terrain grid elevations that exceed the mission's altitude capability, and the weather condition. The mission must stop and hold if one of these obstructions is encountered.

3.2 Proposed Off-Network Graph

The solution for off-network planning begins with superimposing a regular rectangular grid over the terrain. The unit cost of traversing a given grid-cell is uniform within a cell, but may vary between cells based on the underlying terrain.

3.2.1 Graph Representation

The grid representation can be transformed into a graph by making the center point of each cell a node and implicitly extending arcs to the center points of adjacent cells. The cost to go from cell to cell can be measured in terms of travel time. The graph representation allows the same network algorithms used by the JTLS-GO movement networks to be utilized in the off-network space.

3.2.2 Cell Connectivity

Although an entity may move an infinite number of ways in two dimensions, the number of possible directions of movement on the graph is finite. There are multiple ways to approximate the connectivity between cells. A straight-forward connection pattern links a cell to its eight adjacent neighbors, as shown in Figure 1.

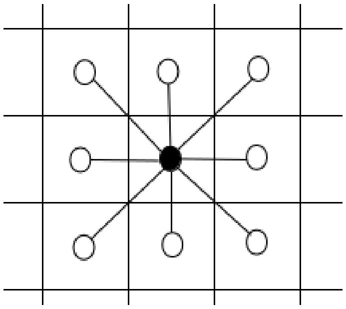

Figure 1. Cell Connected To Its Eight Neighbors

3.2.3 Cell Attributes

In order to apply the network path-finding algorithm (Dijkstra's algorithm), the NETWORK NODE structure currently used by the CEP will be used to represent a cell. The node attributes to be utilized are listed in Table 1.

Table 1. **Cell Attributes For Off-Network Graph**

ATTRIBUTE	TYPE	DESCRIPTION
NN LATITUDE	Real	Latitude of cell center
NN LONGITUDE	Real	Longitude of cell center
NN SCANNED	Integer	• NO = Cell has not been checked by Dijkstra's algorithm, yet • YES = Cell has been checked
NN OPTIMIZATION VALUE	Real	Best (minimum) time to reach this cell from source cell
NN SELECTED ARC	Pointer	The off-network arc from either this cell's NN SOURCE SET or NN SINK SET that forms part of the minimum time route from the source cell
NN TERRAIN LAYER	Integer	TERRAIN LAYER in which this cell resides
NN X GRID	Integer	Column index of NN TERRAIN LAYER's array of grids in which this cell resides
NN Y GRID	Integer	Row index of NN TERRAIN LAYER's array of grids in which this cell resides
NN SOURCE SET	Set	Set of off-network arcs whose source node is this node
NN SINK SET	Set	Set of off-network arcs whose sink node is this node

All attributes will be set by the model:

- NN LATITUDE and NN LONGITUDE will be calculated based on the graph's extents and cell size (see Generating the Off-Network Graph, Section 3.2.5).
- NN TERRAIN LAYER, NN X GRID and NN Y GRID will be determined by NN LATITUDE and NN LONGITUDE. The layer and grid indices can be obtained by calling routine LAT LONG TO GRID and passing NN LATITUDE and NN LONGITUDE to this routine.
- NN SCANNED, NN OPTIMIZATION VALUE and NN SELECTED ARC will be determined during the execution of Dijkstra’s algorithm.
- NN SOURCE SET and NN SINK SET will be filled when the off-network graph is constructed.

3.2.3 Arc Attributes

The connection between cells illustrated in Figure 1 will be represented by the CEP's NETWORK ARC structure. An off-network arc connects the center of a cell to the center of its adjacent neighbor. All arcs allow two-way travel. The arc attributes to be utilized are listed in Table 2.

Table 2. **Arc Attributes for Off-Network Graph**

ATTRIBUTE	TYPE	DESCRIPTION
NA SOURCE NODE	Pointer	The cell in the graph that this arc departs from
NA SINK NODE	Pointer	The cell in the graph that this arc enters
NA DISTANCE	Real	Great circle distance from source cell to sink cell
NA MAXIMUM SPEED	Real	Always RL ZERO = no speed limit exists (see Note)
NA DEPTH DISTANCE	Real	Equivalent distance that a naval unit on this arc travels because of speed restrictions caused by the depth
NA TERRAIN DISTANCE	Real	Equivalent distance that a ground unit or truck convoy on this arc travels because of speed restrictions caused by the terrain
NA MINIMUM ALTITUDE	Real	Minimum altitude that can be flown by an air mission while traversing this arc
NA DEPTH	Integer	Shallowest depth that a naval unit will encounter while traversing this arc
NA BOUNDARY SET	Set	Set of all NATIONAL BOUNDARY INDICATORs referencing the national boundaries crossed by this arc

All attributes will be set by the model:

- NA SOURCE NODE, NA SINK NODE, NA MAXIMUM SPEED, NA DEPTH DISTANCE and NA TERRAIN DISTANCE will be determined when the off-network graph is created. Also, NA BOUNDARY SET will be filled at this time.

  NA TERRAIN DISTANCE is a new arc attribute for JTLS-GO 5.1. Using the TT RDT MOVE TIME MULTIPLIER, an equivalent distance traveled due to the terrain type and road type will be calculated for the arc. Given the distance D traversed by the arc through a given terrain grid, and the terrain type tt and road type rdt of the terrain grid, the equivalent distance within the terrain grid is D * TT RDT MOVE TIME MULTIPLIER (tt, rdt).

- NA MINIMUM ALTITUDE will be determined by the maximum elevation of the terrain grid (held by TH MAX ELEVATION) that the arc passes through. If the arc passes through multiple terrain grids, NA MINIMUM ALTITUDE will be set to the highest TH MAX ELEVATION.

- NA DEPTH will be determined by the depth of the terrain grid (TH DEPTH) that the arc passes through. If the arc passes through multiple terrain grids, NA DEPTH will be set to the shallowest TH DEPTH.
- NA DISTANCE will be determined by the location of NA SOURCE NODE and NA SINK NODE

Note: The implementation of this design will attempt to use as many existing CEP optimization routines as possible. Although the attribute NA MAXIMUM SPEED is not necessary for off-network planning, there are existing optimization routines that reference this attribute.

3.2.4 Working Sets

The off-network graph will not use the CEP's NETWORK ENTITY structure to hold the cells and arcs of the graph. In lieu of this structure, two working sets will be added to the CEP called the OFFNET NODE SET and the OFFNET ARC SET. The former will be used to hold the cells of the off-network graph, and the latter will be used hold the arcs.

3.2.5 Generating the Off-Network Graph

From a computer resource standpoint, it may not be practical to permanently maintain a worldwide collection of off-network graphs in memory during the JTLS-GO exercise run. When needed, memory will be allocated to dynamically generate a graph. The generated cells and arcs will be added to the sets described in Working Sets, Section 3.2.4. The sets will be cleared and the allocated cells and arcs will be released when the path-finding task is completed.

3.2.5.1 Graph Extents

The region covered by the graph will need to be limited. This can be accomplished by using the existing global variables:

- END OVERLAP FACTOR
- HALF WIDTH FACTOR
- AIR END OVERLAP FACTOR
- AIR HALF WIDTH FACTOR
- MIN END OVERLAP
- MIN HALF WIDTH

These variables are defined in Appendix B of the Data Requirements Manual. They are used to create a rectangular region that is used, in turn, to search for a movement network that provides an optimal path between two locations. END OVERLAP FACTOR and HALF WIDTH FACTOR are applied to finding road and sea networks; AIR END OVERLAP FACTOR and AIR HALF WIDTH FACTOR are applied to finding the air network; MIN END OVERLAP and MIN HALF WIDTH apply to all network types. The END OVERLAP FACTOR is also used to compute a search radius for finding river networks.

For the purposes of generating an off-network graph, the global variables will also be used to create a rectangular region that will define the area covered by the graph. Given an entity attempting to move between two locations called Source and Destination, the extents of the rectangle will be defined by the end overlap extended beyond Source and Destination, and the half width extended perpendicular to the line running from Source to Destination.

Figure 2 illustrates a region created for Source and Destination.

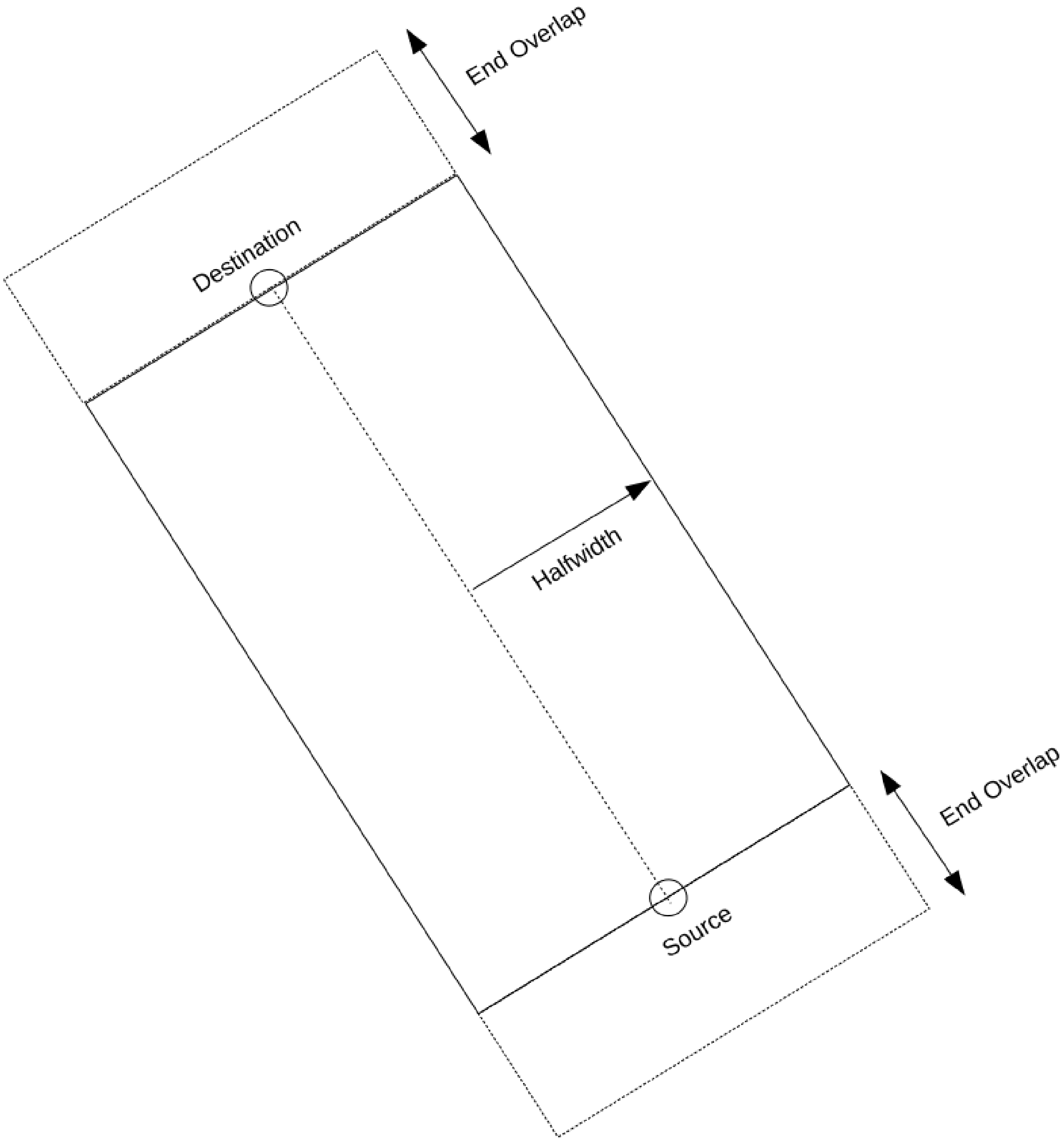

Figure 2. Extents Of Off-Network Graph

The End Overlap in Figure 2 is computed for Ground and Naval objects as follows:

$$\text{EndOverlap} = \text{Maximum}\ (\text{MinEndOverlap},\ \text{EndOverlapFactor} * \text{Distance})$$

where Distance is the great circle distance between Source and Destination.

Air Movement EndOverlap is computed in a similar manner only the database parameter AIR END OVERLAP FACTOR is used instead of the END OVERLAP FACTOR.

The Half Width shown in Figure 2 is computed for Ground and Naval objects using the following equation:

$$\text{HalfWidth} = \text{Maximum} \ (\text{MinHalfWidth}, \ \text{HalfWidthFactor} * \text{Distance})$$

Air movement HalfWidth is computed by substituting the database parameter AIR HALF WIDTH FACTOR for HALF WIDTH FACTOR.

3.2.5.2 Cell Size

The cells of the graph form squares of equal size from a latitude and longitude perspective, not a distance perspective. The cells will be arranged in rows of equal length and columns of equal length. The cell size will be measured in decimal degrees. By default, it will be 5 minutes. This is approximately 9 KM at the equator, close to the size of a standard JTLS 4.1 or earlier 7.5 KM hexagon. The cell size, however, should not be greater than the smallest terrain grid covered by the off-network graph. The smaller cell size will provide more flexibility to maneuver the moving entity around an impediment. There are nine terrain grid sizes:

- 10 degrees by 10 degrees
- 5 degrees by 5 degrees
- 1 degree by 1 degree
- 30 minutes by 30 minutes
- 15 minutes by 15 minutes
- 5 minutes by 5 minutes
- 1 minute by 1 minute
- 30 seconds by 30 seconds
- 15 seconds by 15 seconds

All terrain layers fully, or partially, within the boundaries of the off-network graph will be checked. Since the layers can be stacked on top of each other, only the top-most layers needs to be checked. The terrain grid sizes of these layers will be checked, and if the smallest grid size is greater than 5 minutes X 5 minutes, the graph's cell size will be set to 5 minutes. For smaller grid sizes, the corresponding off-network cell size will be half the size of the terrain grid as shown in Table 3.

Table 3. **Cell Size For Off-Network Graph**

SMALLEST TERRAIN GRID SIZE	TERRAIN GRID LENGTH	OFF-NETWORK GRAPH CELL SIZE
> 5 Minutes	> 9 KM	5 Minutes
5 Minutes	~ 9 KM	2.5 Minutes
1 Minute	~ 2 KM	30 Seconds
30 Seconds	~ 1 KM	15 Seconds
15 Seconds	~ 0.5 KM	7.5 Seconds

An off-network graph, restricted by the rectangular region described in Section 3.2.6.1 Graph Extents, is illustrated in Figure 3. Each node of the graph is located in the center of the imaginary cell and maintains the attributes listed in Table 1. An arc connects a node to its immediate neighbor node and maintains the attributes listed in Table 2. The arcs and nodes will be filed in the graph's OFFNET ARC SET and OFFNET NODE SET, respectively.

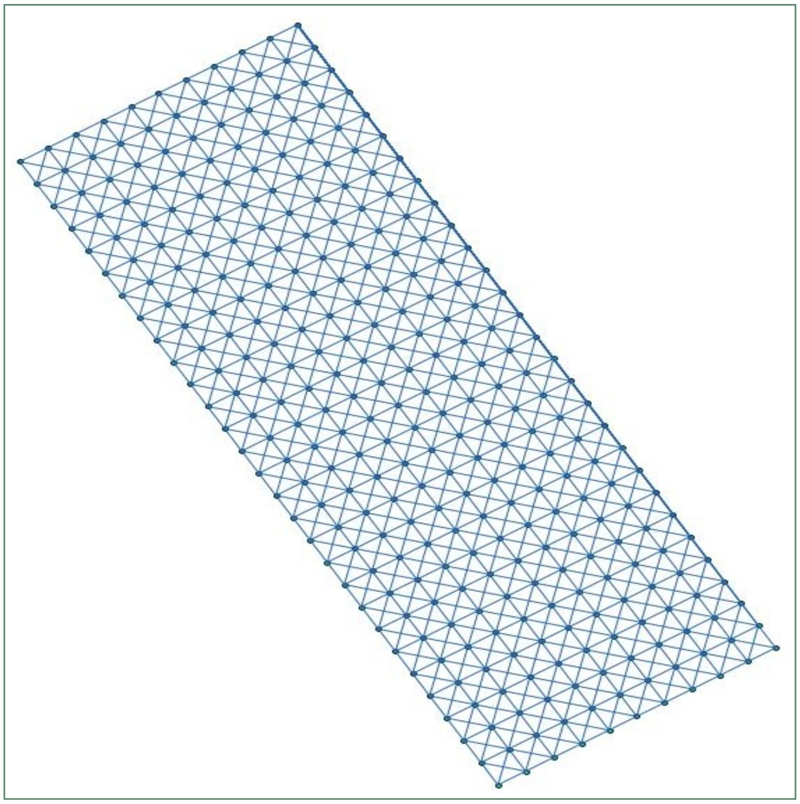

Figure 3. Example Off-Network Graph

Figure 3 shows a graph that fills the entire rectangular region. There may be cases, however, where the graph may not fill the rectangle entirely. For example, suppose the graph is created for ground movement and partially covers two terrain grids, one is a land grid and the other is a water grid. Only the nodes located on land need to be created. The nodes that would be on the water, and the arcs connected to them, should not be created. For this reason the following three general rules will be applied:

- Node Creation Rule 1 - If the off-network graph is created for ground movement, do not create a node if its coordinates are located in an Ocean or Small Island terrain grid. Create the node for any other terrain type including dual capable terrain.

- Node Creation Rule 2 – If the off-network graph is created for naval movement, create a node if its coordinates are located in an Ocean, Small Island, or dual capable terrain grid. Do not create the node for any other terrain type.

- Node Creation Rule 3 – If the off-network graph is created for air movement, create a node if air defense does not threaten the air mission at the node. Since the node represents the center of a cell in a gridded network, a sequence of eight checks will be performed to test whether the cell may be covered by air defense that threatens the mission. If it is perceived that air defense coverage over the cell threatens the mission, that cell will be ignored for route planning and a node will not be created. A node will be created if there is no perceived air defense threat over the cell. The checks are described below in order of execution:

    a. Check 1 - Does the mission care about air defense threats? The mission's AM IGNORE AIR DEFENSE attribute will be checked. If it indicates that air defense should be temporarily or permanently ignored, the cell will be considered for route planning. If the mission is told not to ignore air defense, continue to Check 2.

       All checks that follow will be based on the SO EFFECTS SET found for the air cell's location (the latitude and longitude of the cell's center). Each air defense site in the SO EFFECTS SET will be examined as follows:

    b. Check 2 - Examine the side-to-side relationship between the air defense site and the mission. If they are friendly or neutral, examine the next air defense site and start at Check 2. But if they are suspect or enemy, go to Check 3.

    c. Check 3 - Check the perceived detection level of the air defense site by the mission's side. If the detection level is localization or classification, there is not enough information about the site. In this case, examine the next air defense site and start at Check 2. But if the level is recognition or identification, treat the site as a possible threat and go to Check 4.

       Given recognition or identification, the mission now knows the type and characteristics of the air defense site. Checks 5, 7 and 8 look at these characteristics.

d. Check 4 - Check the perceived strength of the air defense site. If it is zero, the site will not be considered a threat. In this case examine the next air defense site and start at Check 2; otherwise go to Check 5.

e. Check 5 - Check if the air defense site is within range of the mission's current altitude zone. If the mission is outisde the site's range, the site will not be a threat. In this the case, examine the next air defense site and start at Check 2; otherwise we go to Check 6.

f. Check 6 - Check whether the terrain masks the mission at its current altitude. If the terrain can protect the mission, examine the next air defense site and start at Check 2; otherwise go to Check 7.

g. Check 7 - This check will be performed if the air defense site's fire control radar can be jammed. If it's not susceptible to jamming, skip to Check 7. Otherwise, check whether the mission has the capability to jam the radar. If it can be jammed, examine the next air defense site and start at Check 2; otherwise go to Check 8.

h. Check 8 - Get the air defense site's hit and kill probabilities against the mission's aircraft. If either the PH or PK are positive, the site will be considered a threat to the mission and the air cell will be ignored for route planning. In this case all testing will stop. On the other hand, if the PH and PK are both zero, examine the next air defense site and start at Check 2.

3.3 Implementation

The off-network graph will be implemented during route planning to supplant direct routes.Although more realistic entity movement may be achieved using the off-network graph as opposed to the direct route method, it may not be practical to construct and use the graph for route planning if an entity's location (source) is “close” to the specified destination. If this is the case, the conventional direct route will be sought.

On the other hand, if the distance between the source and destination exceeds a minimum limit, an off-network graph will be created and an attempt will be made to find the fastest route on this graph. It is proposed that the cell size be used as the minimum limit using the following equation:

$$\text{Minimum Limit} = \text{Cell Size} \times \text{NM Per Degree} \times \text{Kilometers Per NM}$$

Where Cell Size is the cell size determined for the off-network graph in decimal degrees, based on Table 3.

If the great circle distance between the source and destination is greater than Minimum Limit, the search for the fastest route on the off-network graph from the source to the destination will be attempted; otherwise, the direct route between source and destination will be sought.

3.3.1 Proposed Algorithm ARU Ground Unit

The initial implementation of the off-network graph will be applied to administrative moves. Other orders that require the ground unit to move (for example. the Withdraw order) will be handled in future ECPs.

The Move order has DIRECT and OPTIMIZED options specifying how the model should find a path for the ARU. The implementation of each option is described as follows:

- Direct Option - If the Move order specifies a direct route, the ARU will follow the great circle from its location to the specified definition. The rules for determining the feasibility of the direct route will remain unchanged (see Current ARU Ground Unit Movement, Section 3.1.1.1). If the direct route is feasible, the ARU will follow the direct route. If the direct route is not feasible, the great circle distance from the ARU's location (source) to the specified destination will be compared to the previously defined Minimum Limit. If the distance exceeds this limit, an off-network graph will be constructed and the fastest route from the source to the destination will be determined; otherwise the ARU will be assigned the direct route and the model will move the ARU as far as possible. The basic process flow is shown in Figure 4.

  If an off-network graph is constructed, the rectangular region that defines the extent of the graph will be created according to Graph Extents, Section 3.2.5.1; the ARU's location will serve as the source location and the destination specified in the order will serve as the destination location illustrated in Figure 2. The off-network node closest to the ARU's location and the off-network node closest to the destination will be, respectively, the start node and end node to be used by Dijkstra's algorithm. The algorithm will be applied to find the fastest route on the graph from the source node to the end node.

  The following constraints will be applied during the search:

  a. If the off-network arc intersects an uncrossable barrier segment, the arc will not be selected.

  b. If the off-network arc intersects an uncrossable river segment, the arc will not be selected.

  c. If the off-network arc crosses a national boundary that the ARU does not have permission to cross, the arc will not be selected.

  d. If the off-network arc crosses an implicit shoreline, the arc will not be selected.

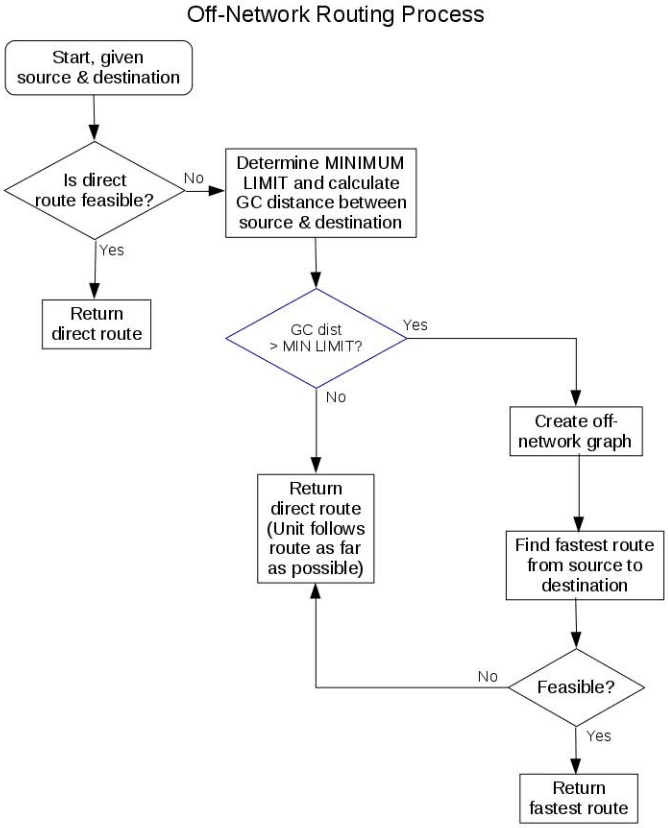

Figure 4. Direct Route Process

- Optimized Option - If the move order specifies an optimized route, the process described in Section 3.1.1.1 will be followed to obtain the fastest route amongst one or more feasible road networks will be obtained. If a route is found, the ARU will be given this route. If no feasible route can be found, an off-road route will be sought. The great circle distance from the ARU’s location to the specified destination will be compared to the previously defined Minimum Limit. If the distance exceeds this limit, an off-network graph will be constructed and the fastest route on the graph will be determined. The construction of the graph and the constraints applied during Dijkstra's search will follow the constraints described previously for Direct Option.

If either the Minimum Limit criterion is not met, or there is no feasible route on the off-network graph, the ARU will be assigned the direct route and the model will move the ARU as far as possible. The basic process flow is shown in Figure 5.

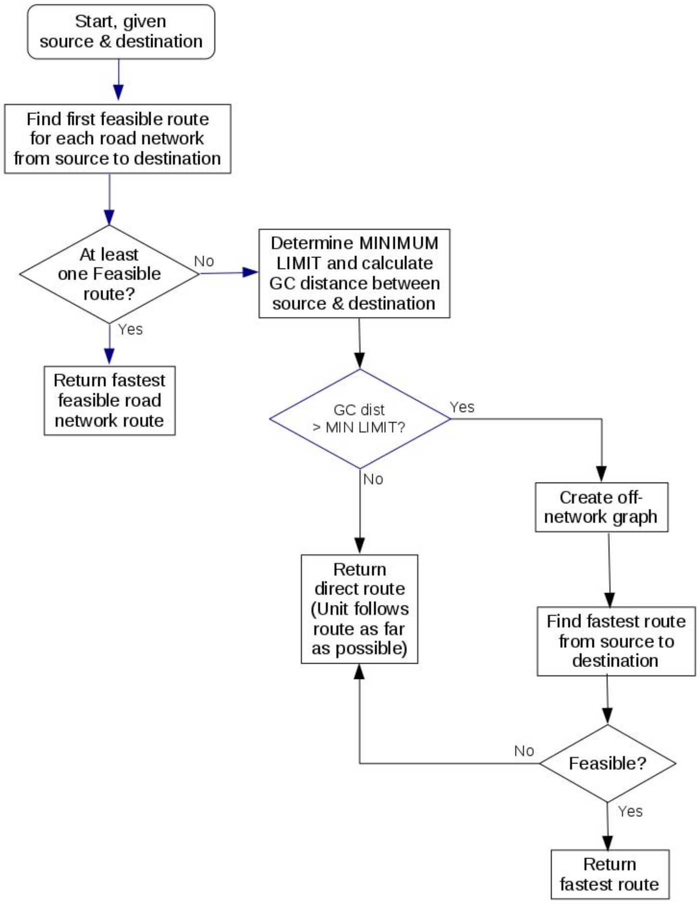

Figure 5. Finding Optimal Route Process

3.3.2 HRU

The HRU Move task has MANDATORY, OPTIONAL, and DO_NOT_USE options specifying how the route planning should include rivers. The implementation of each option is described in the following sections.

- Mandatory Option - If the HRU does not have a Small Boat, the Move task will be canceled. The rest of this option implementation assumes that the HRU has a Small Boat:

  If the HRU does not have a Small Boat, the Move task will be canceled. The rest of this option implementation assumes that the HRU has a Small Boat:

Attempt to find all feasible road and river networks that the HRU can use to get to the destination. The steps that are already in place to find the networks, determine the fastest one, and calculate the total travel time over the designated network will continued to be used (see Current HRU Movement, Section 3.1.1.2). If there are no feasible networks, the Move will be canceled.

At this point, one or more feasible networks will have been identified and the fastest network will have been chosen to be the best network for the HRU to use. The total travel time over this network will be compared to the time it will take the HRU to follow the direct route from its current location to the destination. The rules for determining the feasibility of the direct route will follow the same rules applied to ARUs (see Current ARU Ground Unit Movement, Section 3.1.1.1) with one exception: the direct route implicit shore line restriction will not be applied. If the direct route is feasible, the best network travel time will be compared to the direct route travel time. If the network is faster, the HRU will be given the network route.

If the direct route is not feasible, the off-network graph will be considered if the previously discussed MINIMUM LIMIT criterion is met. If the great circle distance from the HRU’s location to the destination does not exceed the MINIMUM LIMIT, implying that a direct route should be used, the Move task will be canceled.

If the MINIMUM LIMIT criterion is met, however, the off-network graph will be constructed and Dijktra's search will be applied in the same manner as they are for ARUs (see Proposed Algorithm ARU Ground Unit, Section 3.3.1). If an optimal cross country route is found, the travel time for this route will be compared to the travel time from the best road/river network. If the road/river network is faster, the HRU will be given the network route; otherwise, the Move task will be canceled.

The basic process flow is shown in Figure 6.

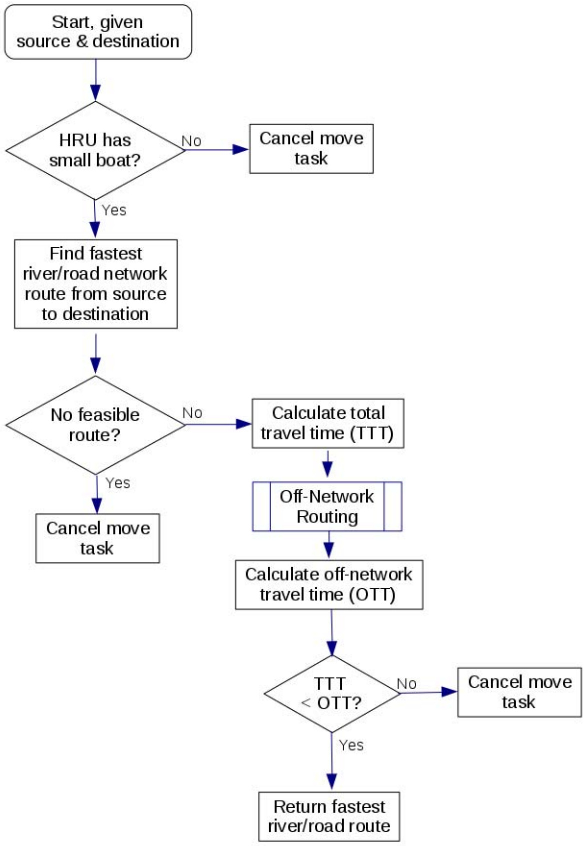

Figure 6. Finding HRU Route Process – Mandatory Option

- Optional River Travel Option - Attempt to find all feasible road networks for the HRU to use. In addition, if the HRU has a Small Boat, find all feasible river networks for the HRU to use. The steps that are already in place to find the networks, determine the fastest one, and calculate the total travel time over the designated network will continued to be used (see Current HRU Movement, Section 3.1.1.2)

  The total travel time over the fastest road/river network will be compared to the time it will take the HRU to follow the direct route from its current location to the destination. The rules for determining the feasibility of the direct route for an HRU without a Small Boat will follow the same rules applied to ARUs (see Current ARU Ground Unit Movement, Section 3.1.1.1). If the HRU has a Small Boat, the direct route implicit shore line restriction will not be applied. If the direct route is feasible, there are two possibilities:

  a. If there is an optimal route on the road/river network, the HRU will follow the faster of the road/river network route and the direct route.

b. If no feasible road/river network route exists, the HRU will follow the direct route.

If the direct route is not feasible, the off-network graph will be considered if the previously discussed MINIMUM LIMIT criterion is met. If the great circle distance from the HRU's location to the destination does not exceed the MINIMUM LIMIT, there are two possibilities:

a. If there is an optimal route on the road/river network, the HRU will follow the road/river network route since it is known at this point the direct route is infeasible.
b. If no feasible road/river network route exists, the HRU will follow the direct route and the HRU will go as far as possible on this route.

If the MINIMUM LIMIT criterion is met, however, the off-network graph will be constructed and Dijktra's search will be applied in the same manner as they are for ARUs (see Proposed Algorithm ARU Ground Unit, 3.3.1). If an optimal cross country route is found, there are two possibilities:

a. If there is an optimal route on the road/river network, the HRU will follow the faster of the road/river network route and the cross country route.
b. If no feasible road/river network route exists, the HRU will follow the cross country route.

Finally, if no feasible cross country route exists, the HRU will be given the direct route and the HRU will go as far as possible on this route.

The basic process flow is shown in Figure 7.

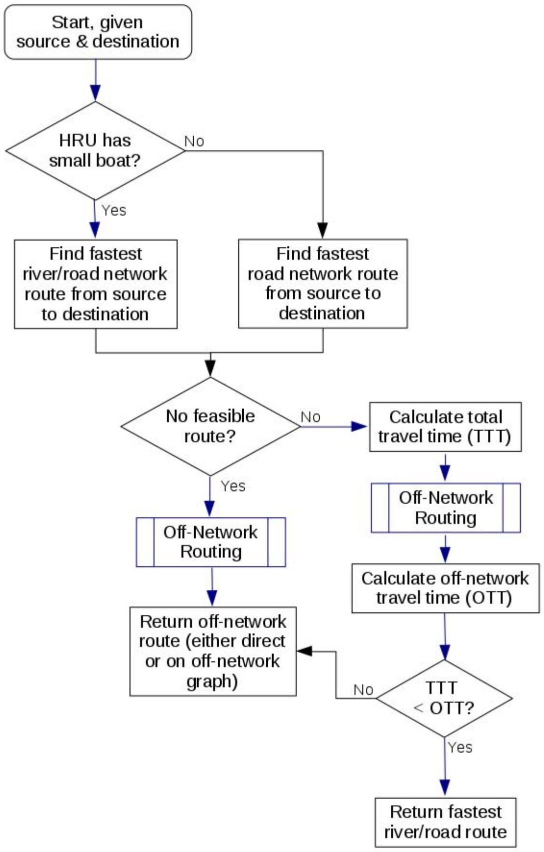

Figure 7. Finding HRU Route Process – River Optional

- Do Not Use River Travel Option - The implementation of this is option will be similar to the implementation of the Optional River Travel Option with one difference: only the road networks will be considered and the river networks will be ignored.

3.3.3 Truck Convoy

When a truck convoy is ready to be dispatched, an attempt will be made to find all feasible road networks for the convoy to use. The steps that are already in place to find the networks, determine the fastest one, and calculate the total travel time over the designated network will continued to be used (see Current Truck Convoy Movement, Section 3.1.1.3).

The total travel time over the road network will be compared with the time it will take the convoy to follow the direct route from its current location to the destination. The rules for determining the feasibility of the direct route will follow the same rules applied to ARUs (see Current ARU Ground Unit Movement, Section 3.1.1.1). If the direct route is feasible, there are two possibilities:

- If there is an optimal route on the road network, the convoy will follow the faster of the road network route and the direct route.
- If no feasible road network route exists, the convoy will follow the direct route.

If the direct route is not feasible, the off-network graph will be considered if the previously discussed MINIMUM LIMIT criterion is met. If the great circle distance from the convoy's location to the destination does not exceed the MINIMUM LIMIT, there are two possibilities:

- If there is an optimal route on the road network, the convoy will follow the road network route since it is known at this point the the direct route is infeasible.
- If no feasible road network route exists, the convoy will follow the direct route and the convoy will go as far as possible on this route.

If the MINIMUM LIMIT criterion is met, however, the off-network graph will be constructed and Dijktra's search will be applied in the same manner as they are for ARUs (see Proposed Algorithm ARU Ground Unit, Section 3.3.1). If an optimal off-road route is found, there are two possibilities:

- If there is an optimal route on the road network, the convoy will follow the faster of the road network route and the off-road route.
- If no feasible road network route exists, the convoy will follow the off-road route.

Finally, if no feasible off-road route exists, the convoy will be given the direct route and the convoy will go as far as possible on this route.

3.3.4 Naval Unit

The initial implementation of the off-network graph will be applied to Naval Move orders directed at naval units. Naval Move orders directed at naval formations and other orders that require the naval unit to move will be handled in future ECPs.

When a naval unit receives a Naval Move order, no more than three attempts will be made to create a route from the unit's location to the destination as follows:

- Feasible Direct Route - The first attempt will determine whether a direct route to the destination is possible. A check will be made of the terrain grids that the naval unit will pass through. The direct route will be considered feasible if all of these terrain grids meet the following constraints:

  a. The terrain type of the grid is either Ocean or Small Island, or the grid is dual-capable.
  b. The depth of the grid can accommodate the unit's depth requirement.
  c. There are no national boundary restrictions on any boundary that the unit will cross.

- Sea Lane Network - If a direct route is not possible, the second attempt will use the sea lane network to try to find the fastest route to the destination. This process will remain unchanged from JTLS-GO 5.0, therefore, no CEP coding changes will be required.

- Off-Network Graph - If it is not possible to find a route through the sea lane network, the third attempt will construct the gridded graph described in Proposed Off-Network Graph, Section 3.2, and find the fastest route therein. The rectangular region that defines the extent of the graph will be created according to Graph Extents, Section 3.2.5.1. The off-network node closest to the unit's location and the off-network node closest to the destination will be, respectively, the start node and end node to be used by Dijkstra's algorithm. The algorithm will be applied to find the fastest route on the graph from the source node to the end node. The following constraints will be applied during the search:

  a. If the off-network arc's depth is shallower than the unit's minimum depth requirement, the arc is not selected.
  b. If the off-network arc crosses a national boundary that the unit does not have permission to cross, the arc is not selected.

  Travel time on the off-network arc will depend upon the unit's PET SPEED and the arc's NA DEPTH DISTANCE. Total travel time using the graph will be the direct route travel time from the unit's location to the start node, plus the time to travel the route from the start node to the end node of the graph, plus the direct route travel time from the end node to the destination.

If the third attempt fails to find a route, the naval unit will be assigned the direct route and the model will move the unit as far as possible. The basic process flow is shown in Figure 8.

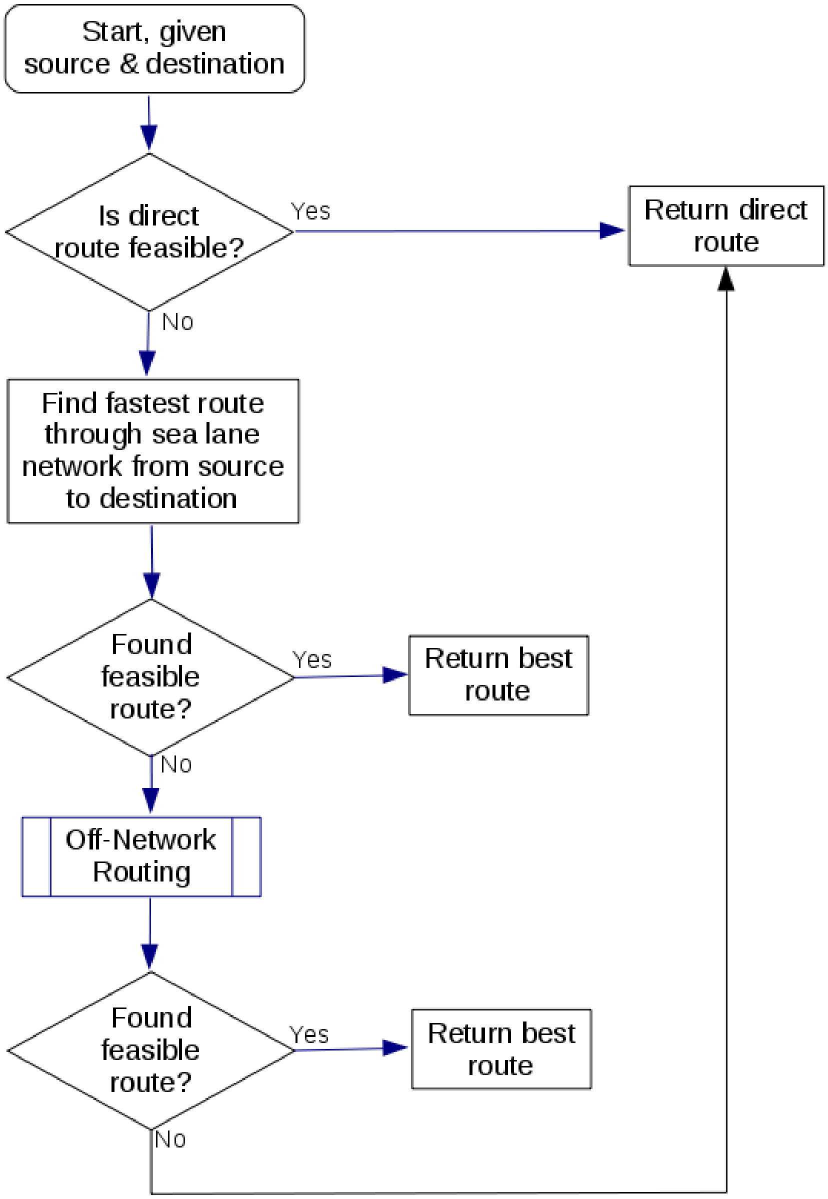

Figure 8. Finding Naval Route Process

3.3.5 Air Mission

The air mission's AM USE NETWORK flag will be checked. If the flag is NO, three attempts will be made to create a route from the mission's location to the destination, but if it is YES, two attempts will be attempted. The process for handling each situation is described, below.

- AM USE NETWORK is NO - Three attempts to find a route will be made as follows:

  a. Feasible Direct Route - The first attempt will determine whether a direct route to the destination is possible. A check will be made of the terrain grids that the mission will fly over. The direct route will be considered feasible if all of these terrain grids meet the following constraints:

     1. The maximum elevation of the grid is less than the mission's maximum altitude limit.

     2. There are no national boundary restrictions on any boundary that the mission will cross.

  b. Air Network - If a direct route is not possible, the second attempt will use the air network to try to find the shortest route to the destination. (Route planning over the air network assumes constant speed over every arc in the network, so the problem simply becomes a shortest route problem.) This process will remain unchanged from JTLS-GO 5.0, therefore, no CEP coding changes will be required.

  c. Off-Network Graph - If it is not possible to find a route through the air network, the third attempt will construct the gridded graph described in Proposed Off-Network Graph, Section 3.2, and find the shortest route therein. Constant speed will also be assumed over all edges in the graph. The rectangular region that defines the extent of the graph will be created according to Graph Extents, Section 3.2.5.1. The off-network node closest to the air mission's location and the off-network node closest to the destination will be, respectively, the start node and end node to be used by Dijkstra's algorithm. The algorithm will be applied to find the fastest route on the graph from the source node to the end node.

     The following constraints will be applied during the search:

     1. If the minimum altitude of the off-network arc is higher than the maximum altitude capability of the aircraft flying the mission, the arc will not be selected.

     2. If the off-network arc crosses a national boundary that the mission does not have permission to cross, the arc will not be selected.

  If the third attempt fails to find a route, the mission will be assigned the direct route and the model will move the mission as far as possible. The basic process flow is shown in Figure 9.

- AM USE NETWORK is YES - Two attempts to find a route will be made as follows:

  a. Air Network - The first attempt will use the air network to try to find the shortest route to the destination.

b. Off-Network Graph - If it is not possible to find a route through the air network, the second attempt will construct the gridded graph described previously, and find the shortest route therein.

If the second attempt fails to find a route, the mission will be assigned the direct route and the model will move the mission as far as possible. The basic process flow is shown in Figure 9.

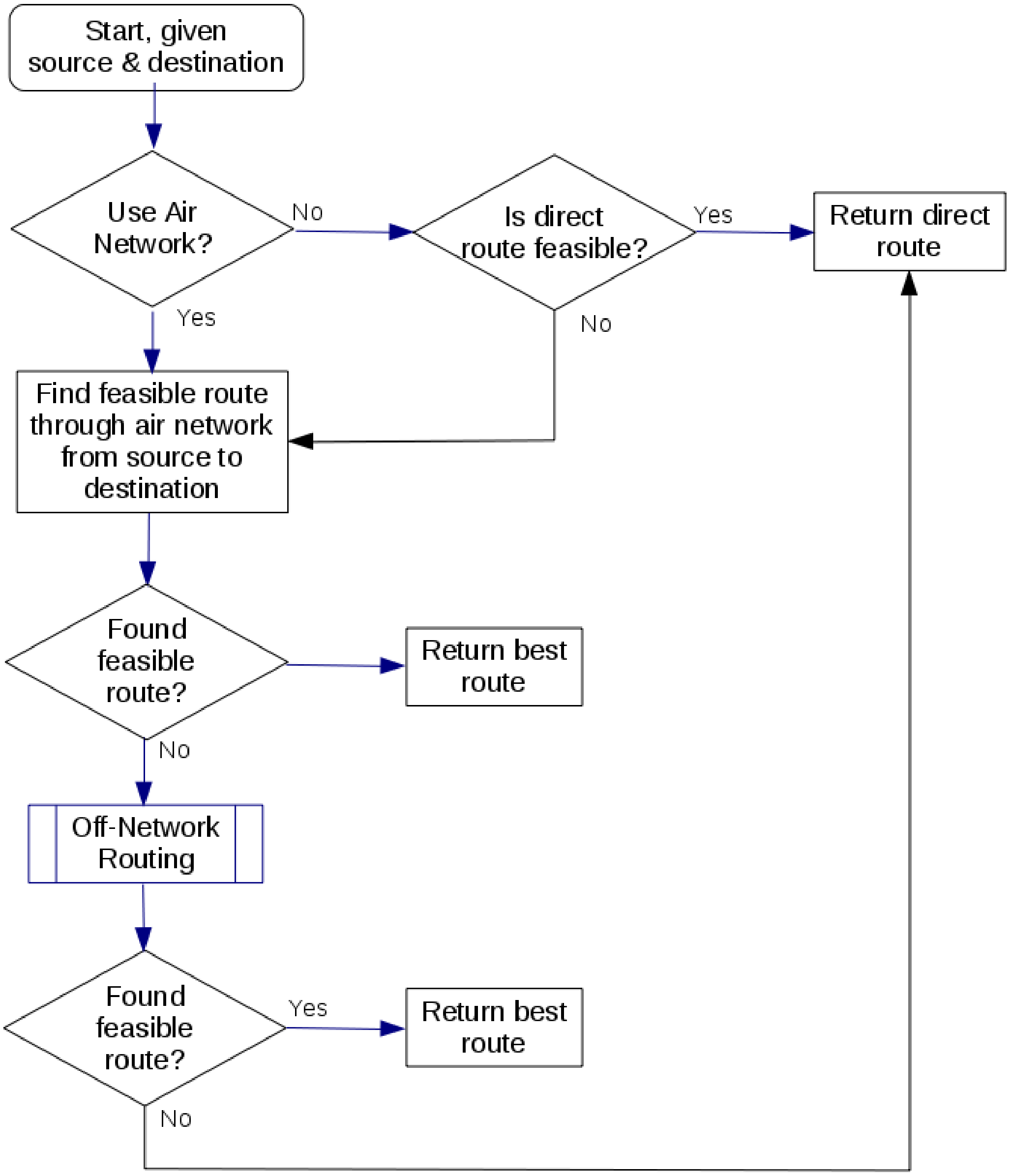

Figure 9. Finding Air Route Process

4.0 Data Changes

No data changes are required for this ECP.

5.0 Order Changes

No order changes are required for this ECP.

6.0 JODA Changes

No JODA Data System parameter, structure, or protocol changes are required to implement this design.

7.0 Test Plan

Text [*Describe the basic test objectives and procedures. This Test Plan section may be published as a separate document.*]

7.1 Test 1 Title

Purpose: [*Describe the specific feature, function, or behavior to be tested or measured.*]

Step 1: Text

Step 2: Text

Expected Results: [*Describe the specific model behavior to be observed.*]

7.2 Test 2 Title

Purpose: [*Describe the specific feature, function, or behavior to be tested or measured.*]

Step 1: Text

Step 2: Text

[*Describe the specific model behavior to be observed.*]