GPS-aided Walking Experiments and Data-driven Travel Cost Modeling on the Historical Road of Nakasendō-Kisoji (Central Highland Japan)

Yasuhisa Kondo[1] and Yoichi Seino[2]

[1] Department of Archaeology, University of Tokyo. Japan.
[2] Department of Cultural Coexistence, Kyoto University. Japan.

Abstract

The authors' first walking experiment on a remote island south to Tokyo in 2007 revealed that it was not only the slope of the terrain but also the field of view and roadbed conditions that could affect walking speed. Further, it was realized that it was appropriate to conduct experiments under conditions that were as close as possible to the historical context. The second experimentation was therefore carried out on the preserved and reconstructed pre-modern roads of Nakasendō-Kisoji in autumn 2008. In the experiment, the field of view and roadbed conditions were assessed, and the heart rate and energetic expenditure of the examinees were measured, in addition to the geodetic location that was recorded with a GPS receiver. The results indicate that (1) walking is slightly faster on gravel roads than that on flagstone although the difference is statistically insignificant, and (2) the slope of the terrain strongly affects the walking speed and heart rate. Based on these facts, the authors build a new travel cost model that predicts energetic expenditure based on the slope of the terrain as the primary parameter.

Keywords: *travel cost simulation, energetic expenditure, historical context, GPS, field experiments*

1 INTRODUCTION

In 2007, the authors carried out the first walking experiment on Kōzushima, a small island located 180 kilometers offshore from Tokyo, for the purpose of evaluating the validity of certain present travel cost algorithms including Tobler's Hiking Function,[1] the GRASS r.walk module,[2] and the metabolic energy expenditure model.[3] The results indicated that, in general, walking speed decreases on steeper slopes, as is expected by these models. It was also observed that the field of view and roadbed conditions may significantly affect walking speed.[4]

In addition to these findings, the authors noted three issues on archaeological travel cost modeling in the sectional meeting titled "GIS and Raster DEM Based Research in Landscape Archaeology" at CAA Budapest 2008.[5] First, the GIS models that simulate human travel in the past should reflect the reality of the past as closely as possible. Most models that have been broadly applied to archaeological research, however, have been designed with empirical data drawn from modern European contexts.[6] It is necessary, therefore, to construct a new travel cost model that can be customized to fit specific cultural and environmental contexts. In order to configure the model, we should collect kinesiological data of pedestrian travel in a part of the study area where the historical context is well preserved. Second, human travel in the past should be evaluated in energy-related units (calories) rather than in time-related ones (speed and hours), because time can be perceived differently in different societies and in different time periods. We must therefore create a new model that outputs the energetic expenditure as travel cost. Third, such customized models should be crosschecked with the original data for further improvement.

[1]Larry J. Gorenflo and Nathan Gale, "Mapping Regional Settlement in Information Space," *Journal of Anthropological Archaeology* 9 (1990): 240–73; Waldo Tobler, "Three Presentations on Geographical Analysis and Modeling," Technical Report 93-1 (Santa Barbara: National Center for Geographic Information and Analysis, University of California, 1993). www.ncgia.ucsb.edu/Publications/Tech_ Reports/93/93-1.PDF.

[2]Markus Neteler and Helena Mitasowa, *Open Source GIS: A GRASS GIS Approach,* 3rd ed. (New York: Springer, 2008) 381.

[3]Pieter Martijn van Leusen, *Pattern to Process: Methodological Investigations into the Formation and Interpretation of Spatial Patterns in Archaeological Landscapes* (Ph.D. diss., University of Groningen, 2002) chapters 6–7. http://dissertations.ub.rug.nl/faculties/arts/2002/p.m.van.leusen/.

[4]Yasuhisa Kondo et al., "FIELDWALK@KOZU: A Preliminary Report of the GPS/GIS-aided Walking Experiments for Re-modeling Prehistoric Pathways at Kozushima Island (East Japan)," paper presented at CAA 2008, Budapest, Hungary, April 2–6, 2008; also in *On the Road to Reconstructing the Past*, edited by Erzsébet Jerem et al. (Budapest: Archaeolingua, 2008) 151 (see next note).

[5]Erzsébet Jerem et al., *On the Road to Reconstructing the Past: CAA 2008 Program and Abstracts: 36th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Budapest, 2–6 April 2008* (Budapest: Archaeolingua, 2008) 141–151, www.caa2008.org/documents /caa_2008_book.pdf.

[6]See p. 158nn1, 2, and 3.

Motivated by these aims and concepts, the authors selected the pre-modern road of Nakasendō-Kisoji as the location for their second experiment because of the authentic historical contexts it offers, as discussed below. This paper presents the preliminary results of this experiment and suggests a new data-driven and energy-based travel cost model.

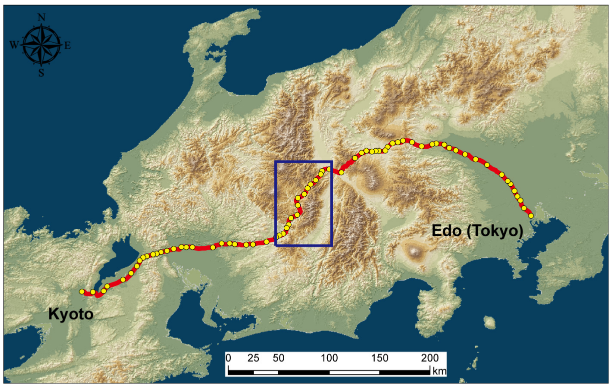

Figure 1. *Nakasendō and its post-station towns in the Tokugawa period. The dashed boundary indicates the study area.*

2 HISTORICAL CONTEXTS OF NAKASENDŌ-KISOJI

Kisoji is an eighty-kilometer-long road along the Kiso valley that connects the highland region to the southern coastal plain of central Japan (Gifu and Nagano prefectures). According to the ancient historiography *Shoku Nihongi*, Kisoji was officially opened to traffic in 702 AD (Taihō 2). However, the settlements and ceramics of Jōmon hunter-gatherers and of the subsequent Yayoi rice farmers in the Kiso valley indicate that since prehistoric times this region has served as a traffic and trade corridor for the cultural interaction between the eastern and western parts of the Japanese archipelago. The geopolitical importance of the Kiso valley also attracted the warring lords (the Takedas in the central highland, for instance) of the late medieval period. Then, at the beginning of the seventeenth century, the Tokugawa feudal government reorganized Kisoji as a part of Nakasendō, one of the five major roads to Edo—the capital in the Tokugawa period in eastern Japan (which today is Tokyo; see fig. 1). At that time, one *sekisho* checkpoint was placed at Fukushima and another ten *shukuba* post-station towns were settled at four-to-thirteen kilometer intervals, in order to secure and control traffic (see fig. 2). Among the travelers in the Tokugawa period were *daimyō* lords, who had to go to Edo and return to their own lands with their liegemen every other year in accordance with the Laws for the Military Houses (*Buke Shohatto*), bureaucrats, express messengers (*hikyaku*), porters, merchants, and pilgrims. According to the diaries of travelers, tourist guides, and the guest books of each post-station, it would take three or four days for a typical traveler to pass through all of Kisoji. Nakasendō, an inland route, and Tōkaidō, a southern coastal route, served as "highways" that bridged Edo and Kyoto—another urban center of politics and culture in western Japan—until their abandonment following the advent of modern railways along Tōkaidō in the last three decades of the nineteenth century.

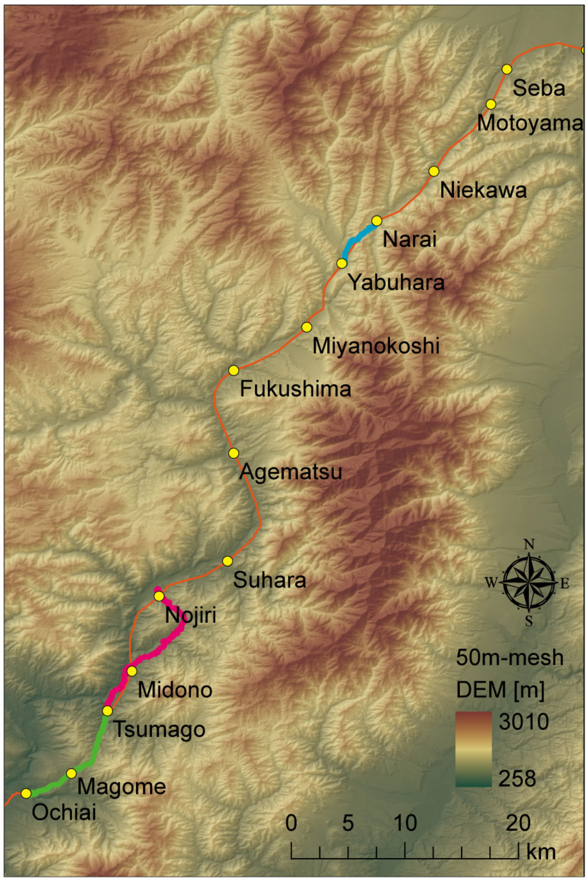

Figure 2. *Kisoji and its post-station towns in the Tokugawa period. The dark lines indicate the paths of the experiment.*

3 METHODOLOGY OF THE EXPERIMENT

In autumn 2008, the experiment team walked for four days on the following preserved and reconstructed trails in the Kiso valley: (1) Nakasendō, between Ochiai and Midono, (2) Yogawa-michi, a bypass of Nakasendō between Midono and Nojiri, and (3) Nakasendō, between Yabuhara and Narai over the Torii path (see fig. 2), a distance of 43 kilometers in total. The aim of the experiment in this season was to collect the data for walking speed and elapsed time on different slopes, which were related to field of view, roadbed conditions, and energetic expenditure, to create a new travel cost model. In order to document all of the required data as accurately and safely as possible, the experiment team comprised three persons—one examinee and two assistants.

The examinee carried a handheld GPS receiver (Garmin GPSMAP 60CSx) while walking and wore a wristwatch-type GPS receiver with an embedded heart rate sensor (Garmin ForeAthlete 305), in order to collect spatio-temporal data including the latitude, longitude, date, time, and horizontal distance traveled. The examinee's position was monitored every other second by 60CSx and every second by ForeAthlete. The examinee's heart rate was taken as an indicator of energetic expenditure. Walking speed in a given segment was determined by calculating the elapsed time and walking distance. The altitude was estimated by the air-pressure sensor embedded in those receivers. The slope of a given segment was calculated by dividing the vertical distance by the horizontal distance. In addition to this, energetic expenditure was occasionally estimated by means of a digital pedometer with an accelerated velocity sensor (Suzuken Kenz Lifecorder Plus). Furthermore, the walking environment, including the landscape, landmarks, and road conditions was documented by Geo Photo-logging System (a customized cellular phone with built-in digital camera, GPS, electronic compass, and tilt sensor, which is able to send a photograph and the attached geospatial information and description to a Web server that immediately publishes the information as Weblog entries).[1]

One of the assistants indicated the correct route to the examinee, and traced and timed the examinee's movement using another 60CSx receiver as backup. He also documented the field of view and roadbed conditions in a paper-based format (see fig. 3, a). Field of view was classified as "high" and "low" according to a subjective criterion—if we could see more than approximately fifty meters ahead, the assessment was "high visibility," and if not, it was "low visibility" (see fig. 3, b and c). Roadbed conditions were largely classified into three categories—flagstone, gravel, and wooden piers—excluding asphalt pavement (see fig. 3, d, e, and f). The other assistant operated a pair of GPS receivers (Magellan ProMark 3) for the stand-alone and post-processual kinematic positioning, and photographed the mission using a digital SLR camera. He was also in charge of oral documentation, for which he used an IC recorder. These data were mutually synchronized and matched to each other by using the time information as a unique identifier.

After the experiment, the GPS tracks of the examinees were imported into Microsoft Excel and split into approximately fifty-meter segments with homogeneous visibility and roadbed conditions. In total, 199 segments, excluding those of the asphalt pavement, were extracted from the GPS logs. For each segment, the average slope and walking speed were calculated, then their statistical correlation with visibility, roadbed, and heart rate were examined (see figs. 4 and 5).

Figure 3. *Example of the worksheet and classification of field-of-view and roadbed.*

4 RESULTS OF THE EXPERIMENT

Figures 4 and 5 show the walking data of the female examinee, who was in her thirties and was a relatively inexperienced hiker. The longitudinal axis of these dot charts represents the average slope, or the ratio of elevation divided by horizontal distance, per fifty-meter segment. On the other hand, the transverse indicates the average walking speed [km/hr] per segment. There was a great variability in the examinee's average speed. It is true that the data points largely fit Tobler's curve[2] in the slope range between –0.20 and +0.20, but they do not otherwise seem to fit that curve. It is also noted that the maximum speed expected by Tobler's model, six kilometers per hour at –0.05 (or approximately 2.86 degrees) downhill, was hardly ever the case.

In figure 4, the dots are classified into two categories, "high" and "low", with reference to visibility. The mean value of the walking speed per segment is 4.37 kilometers per hour for the "high visibility" group (n = 17) and 3.98 kilometers per hour for the "low visibility" group (n = 159). Although the walking speed in the higher visibility environment was faster than that in the lower visibility zone, Student's *t*-test indicates that the difference between these two groups is insignificant.

[1]Rieko Kadobayashi, "Public Involvement in Multiple Interpretation of Cultural Heritage Through 3D Blog and Photo-logging," paper presented at CAA 2009, Williamsburg, VA, USA, March 22–26, 2009); also in *Program and Abstracts, 37th CAA 2009*, edited by Lisa Fischer et al. (Williamsburg, VA: The Colonial Williamsburg Foundation, 2009) 39–40.

[2] See Tobler (p. 158n1). For the expression, see also equation (3) below.

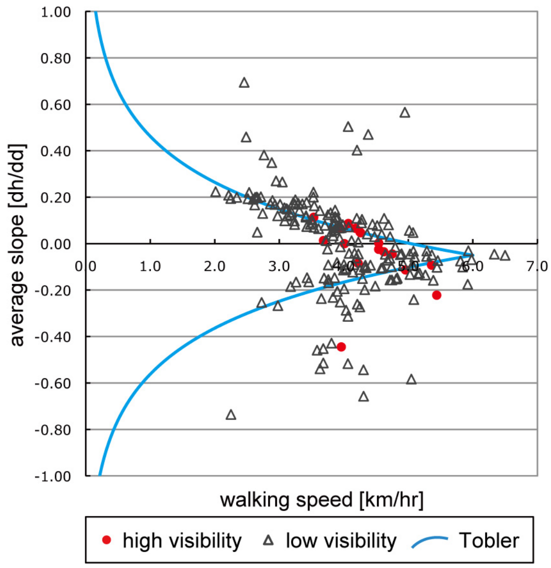

Figure 4. *Correlation between average slope and walking speed per fifty-meter segment, represented in terms of visibility.*

On the other hand, the dots symbolize the roadbed conditions (flagstone, gravel, or wooden piers) in figure 5. The mean value of the walking speed per segment is 3.85 kilometers per hour for flagstone (n = 40) and 4.05 kilometers per hour for gravel (n = 156). Once again, however, the difference in walking speeds on these two types of roadbed is insignificant as a result of Student's *t*-test. These results are probably due to the great variability among a large number of samples that might contain considerable noise and errors.

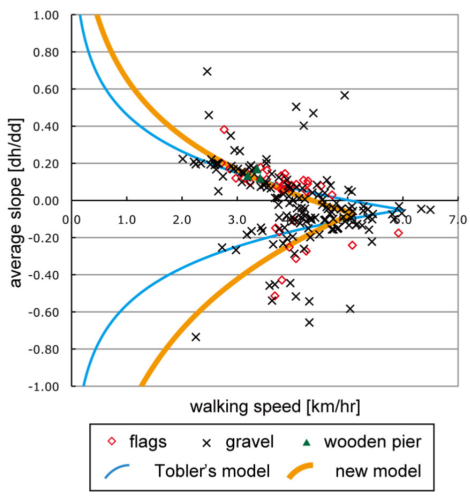

Figure 5. *Correlation between average slope and walking speed per fifty-meter segment, represented in terms of roadbed conditions.*

The spectrum of the heart rate of a male examinee (a relatively inexperienced hiker in his late twenties) while he walked from Narai to Yabuhara via the Torii path indicates that the heart rate increased at the beginning of movement and during a continuous uphill climb, and was rather calm and constant during a continuous downhill descent (see fig. 6). The digital pedometer estimated 443 kilocalories for this walk.

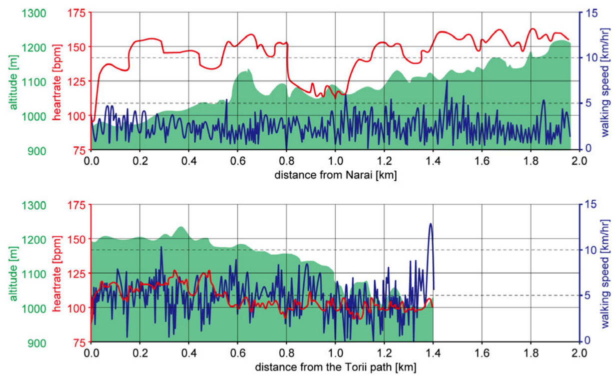

Figure 6. *Heart rate of male examinee in his twenties, walking from Narai to Yabuhara via the Torii path.*

5 BUILDING A NEW MODEL

The results of the field experiment have revealed that the slope of the terrain affects the walking speed and heart rate more significantly than the field of view or roadbed condition. Based on this observation, the authors have built a new energy-based travel cost model.

According to the official guidelines for good health issued by the Ministry of Health, Labour and Welfare, Japan, energetic expenditure is estimated by means of the following expression:[1]

$$E = 1.05 \cdot W \cdot METS \cdot T \qquad \textbf{(1)}$$

where E is energetic expenditure in kilocalories; $METS$ is an index of exercise intensity; T is movement time in hours; and W is body weight in kilograms.

Body weight (W) is so different from person to person that it should ideally be configured for individual cases. Since it is impossible to do this when dealing with past human behavior, we needed to set an arbitrary value as a constant. In this paper, the authors used 50 kilograms as the constant, assuming that an average male adult in pre-modern Japan would be distinctly smaller than the average modern Japanese male.
METS stands for Metabolic Equivalent, a relative value representing exercise intensity. The standard values for

[1]Undō Shoyōryō Undō Shishin no Sakutei Kentōkai [The Investigation Committee for Exercise Needs and Guideline], *Kenkō Dukuri no tameno Undō Shishin 2006 [Exercise Guide for Fine Health 2006]* (Tokyo: Ministry of Health, Labour and Welfare, 2006), www-bm.mhlw.go.jp/bunya/kenkou/undou01/pdf/data.pdf.

this are defined by the American College of Sports Medicine (ACSM).[1] Table 1 lists the selected MET values associated with walking activities. These values are empirically defined for modern Americans; it is therefore problematic to apply them to past human activities in different cultural and environmental contexts. That said, the authors refer to the MET values in order to calculate energetic expenditure because they are the sole source that is currently available and because there is no way to measure the energetic expenditure of people in the past.

CODE	METS	EXAMPLES
17010	7.0	Backpacking
17035	7.0	Climbing hills with 0 to 9 pound load
17040	7.5	Climbing hills with 10 to 20 pound load
17050	8.0	Climbing hills with 21 to 42 pound load
17060	9.0	Climbing hills with 42+ pound load
17080	6.0	Hiking, cross country
17090	6.5	Marching, rapidly, military
17120	8.0	Rock or mountain climbing
17151	2.0	Walking, less than 2.0 mph, level ground, strolling, very slow
17152	2.5	Walking, 2.0 mph, level, slow pace, firm surface
17170	3.0	Walking, 2.5 mph, firm surface
17180	2.8	Walking, 2.5 mph, downhill
17190	3.3	Walking, 3.0 mph, level, moderate pace, firm surface
17200	3.8	Walking, 3.5 mph, level, brisk, firm surface, walking for exercise
17210	6.0	Walking, 3.5 mph, uphill
17220	5.0	Walking, 4.0 mph, level, firm surface, very brisk pace
17230	6.3	Walking, 4.5 mph, level, firm surface, very, very brisk
17231	8.0	Walking, 5.0 mph
17260	5.0	Walking, grass track

Table 1. *MET values associated with outdoor walking (after Ainsworth et al., 2000, fig. 1). Note: 1 pound ≈ 0.45 kg, and 1 mph ≈ 1.6 km/hr.*

As shown in table 1, a different MET value was assigned to different loads borne (codes 17035 to 17060) and different walking speed and slope (codes 17151 to 17231). These discontinuous values are not very suitable for the travel cost algorithm because it treats the slope of the terrain as a continuous variable, and thus it is expected to return a continuous output. In addition, at least in the case of our experiment in Kisoji, we do not have to consider different friction values in conjunction with visibility and roadbed conditions because these will have an insignificant effect, if any. The authors therefore applied the MET value for hiking and cross-country (6.0) as a constant, because these activities most closely resemble the off-road travel that we were striving to simulate.

Movement time (T) can be calculated by trip distance and speed:

$$T = D / V \quad (2)$$

where D is trip distance in kilometers and V is walking speed in kilometers per hour. In the raster-based analysis of GIS, the D value corresponds to the cell size, and thus can also be treated as a constant. Here, D is substituted by 0.001 kilometers, or one meter, as the basic analytical unit.

As mentioned above, the results of the field experiment suggest that the walking speed we recorded basically fit Tobler's slope-dependent exponent function. Thus, the authors attempted to modify Tobler's parameters to build a new travel cost model that is optimized for the study area. The Tobler's function is given by the following expression:

$$V = 6e^{-3.5|S+0.05|} \quad (3)$$

where e is the base of natural logarithms (or Napier's number; approximately 2.718) and S is the slope of the terrain, the ratio of elevation divided by horizontal distance. As mentioned above, this expression yields six kilometers per hour as the maximum speed at –0.05 downhill. Next, the constant terms of expression (3) are converted to variables:

$$V = a \cdot e^{-b|S-c|} \quad (4)$$

where a is the maximum value of the average walking speed per statistical class of slope, b is the friction coefficient used to determine the curve of the exponent function, and c is the median of the class of slope in which the maximum speed (a) was recorded. The friction (b) is determined so as to minimize the residual sum of the individual data points.

In the case of the walking experiment in Kisoji, the maximum value of the average walking speed, 5.1 kilometers per hour, was recorded on the class of slope between –0.06 and –0.08. Therefore, 5.1 was given for parameter a, and –0.07, the median of the class of slope, was allocated for c. In the case of Kisoji, it was better to assign different values for the uphill and downhill travels because it was rather difficult to assign a singular b value in order to minimize the residual sum of both uphill and downhill. Considering then that the maximum speed was recorded at slope –0.07, 2.25 was assigned for the slope range over –0.07, while 1.5 was assigned for the rest (see fig. 5):

If $S \geq -0.07$, then $V = 5.1e^{-2.25|S+0.07|}$ **(5)**

[1]Barbara E. Ainsworth et al., "Compendium of Physical Activities: An Update of Activity Codes and MET Intensities," *Medicine and Science in Sports and Exercise* 32 (2000): S498–504, http://people.uncc.edu/jtlightf/classmats/assessment/ainsworth_MSSE_32_2000.pdf.

Or if $S < -0.07$, then $V = 5.1e^{-1.5|S+0.07|}$ **(6)**

In GIS, a raster cell of slope is basically able to contain only one isotropic value, and when needed, the aspect of slope is contained in another raster file. In order to distinguish uphill, downhill, and traverse (movement that is parallel to contours), it is necessary to estimate the effective slope in order to assign different values for different directions of movement on a case-by-case basis.[1] Effective slope is calculated by the following formula:

$$S = -\tan|\theta|\cos\chi \qquad (7)$$

where S is converted to the effective slope with θ, slope angle [degree], and χ, the cross angle [degree] of the aspect of the slope and the vector of movement. In this study, the slope and aspect of the terrain is based on the 50-meter resolution DEM published by Geographical Survey Institute of Japan (GSI). The aspect of the slope and the direction of movement are limited to the eight major azimuths because the three-by-three cells are fundamental to the raster-based GIS analyses. For this reason, the effective slope is simplified into five azimuths: uphill ($\tan|\theta|$), angled uphill ($0.7\tan|\theta|$), traverse ($0.4\tan|\theta|$), angled downhill ($-0.7\tan|\theta|$), and downhill ($-\tan|\theta|$).

In summary, energetic expenditure per meter of movement in Kisoji was calculated as follows:

If $S \geq -0.07$, then

$$E = \frac{1.05 \times 50 \times 6 \times 0.001}{5.1e^{-2.25|S+0.07|}} = \frac{0.315}{5.1e^{-2.25|S+0.07|}} \qquad (8)$$

Or if $S < -0.07$, then

$$E = \frac{1.05 \times 50 \times 6 \times 0.001}{5.1e^{-1.5|S+0.07|}} = \frac{0.315}{5.1e^{-1.5|S+0.07|}} \qquad (9)$$

6 CROSSCHECKING: THE LEAST-COST CORRIDOR

In order to crosscheck the new model with the historical context, Kisoji's least-cost corridors were calculated by adding the values of the outward and backward cumulative anisotropic cost surfaces and then extracting the lowest value zone (see figs. 7 and 8).[2] The authors prefer a "fuzzier" or less distinctly defined corridor as a zone of easy travel, rather than a strict linear path, because past roads were so unstable that they might frequently be altered, or different travelers might follow somewhat different routes. The cumulative anisotropic cost surface is created by the Spatial Analyst extension of ESRI ArcGIS 9.2 with expressions (8) and (9).
In the macroscopic view, the least-cost corridor between both ends of Kisoji (Ochiai and Sakurazawa) includes most parts of the historical road (see fig. 7). As mentioned above, pre-modern travelers used to take three or four days to pass through Kisoji. As the calorie index tells us, this was quite a strenuous journey. Interestingly enough, the Fukushima *sekisho* (checkpoint) was located outside the least-cost zone, which implies some political intention on the part of the authorities to control the movement of travelers.

In the microscopic view, the Kisoji trail between Yabuhara and Narai over the Torii path is also comprised of the local least-cost corridor (see fig. 8). The model estimates 510 kilocalories for the trip from Narai to Yabuhara. This figure is larger than that given by the experimental data (443 kilocalories). At present, it is difficult to determine which figure is closer to the physiological reality because the digital pedometer also estimates energetic expenditure by employing a similar algorithm based on accelerated velocity.

7 CONCLUSION AND FUTURE TASKS

This paper has presented a way to customize the parameters of an energy-based travel cost model using the empirical data collected in a part of the study area, in a manner that reflects the historical context with as much fidelity as possible. The customized models presented were then used to extrapolate friction values in the rest of the area. We plan to further apply this method to other cultural entities in different regions and time periods. The model should be regularly revised and improved in order to provide more accurate and realistic simulation. As a first step in this direction, the authors will attempt to develop a method to estimate MET values directly from the slope of the terrain without making any time/speed-related calculations.

---

[1]James Conolly and Mark Lake, *Geographic Information Systems in Archaeology*, Manuals in Archaeology (Cambridge: Cambridge University Press, 2006) 218.

[2]Yasuhisa Kondo et al., "FIELDWALK@KOZU" (see above, p. 158n4).

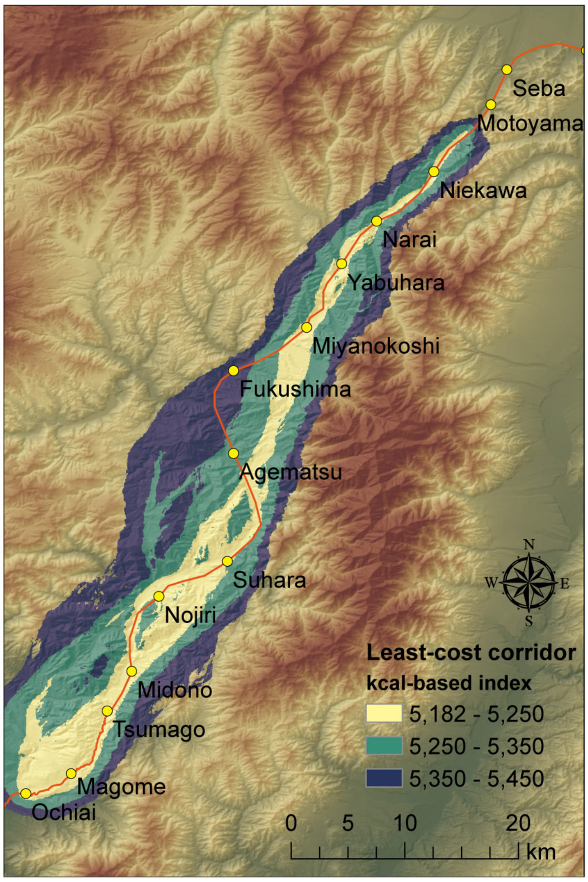

Figure 7. *Least-cost corridor between both ends of Kisoji (Ochiai and Sakurazawa).*

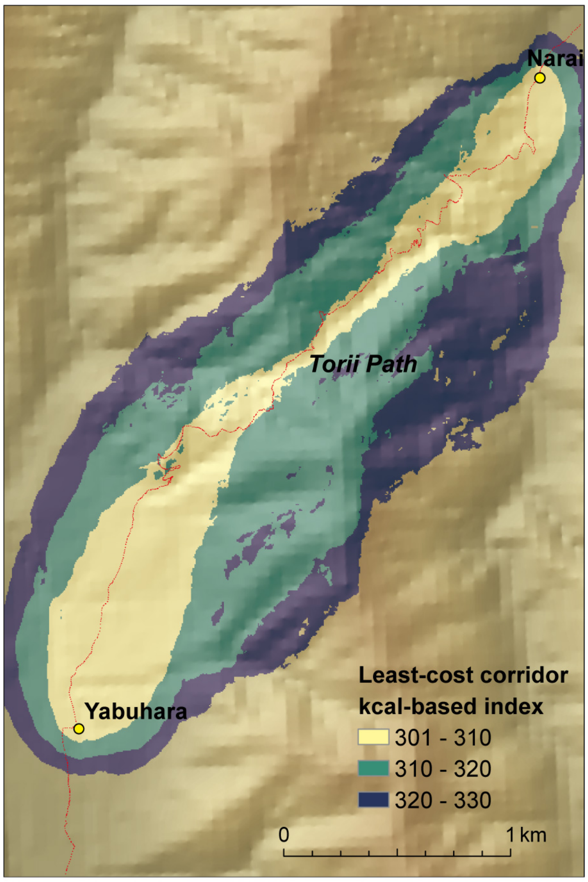

Figure 8. *Least-cost corridor between both ends of the Torii path (Yabuhara and Narai).*

ACKNOWLEDGEMENTS

This research was financially supported by a Scientific Grant-in-Aid of the Japan Society for the Promotion of Science. The authors are grateful to Dr. Eriko Kadobayashi, the National Institute of Information and Communication Technology (NICT), and Mr. Akihiro Kaneda, the Nara National Research Institute for Cultural Properties, for providing the Geo Photo-logging system and the differential GPS receivers respectively.

BIBLIOGRAPHY

Ainsworth, Barbara E., William L. Haskell, Melicia C. Whitt, Melinda L. Irwin, Ann M. Swartz, Scott J. Strath, William L. O'Brien, David R. Bassett, Jr., Kathryn H. Schmitz, Patricia O. Emplaincourt, David R. Jacobs Jr., and Arthur S. Leon. "Compendium of Physical Activities: An Update of Activity Codes and MET Intensities." *Medicine and Science in Sports and Exercise* 32 (2000): S498–504. http://personal.uncc.edu/jtlightf/classmats/assessment/ainsworth_MSSE_32_2000.pdf (accessed May 15, 2009).

Conolly, James, and Mark Lake. *Geographic Information Systems in Archaeology*. *Cambridge Manuals in Archaeology*. Cambridge: Cambridge University Press, 2006.

Gorenflo, Larry J., and Nathan Gale. "Mapping Regional Settlement in Information Space." *Journal of Anthropological Archaeology* 9 (1990): 240–73.

Kadobayashi, Rieko. "Public Involvement in Multiple Interpretation of Cultural Heritage Through 3D Blog and Photo-logging," paper presented at CAA 2009, Williamsburg, VA, USA, March 22–26, 2009. Also in *37th CAA 2009 Computer Applications and Quantitative Methods in Archaeology*, edited by Lisa Fischer et al., 39–40 Williamsburg, VA: The Colonial Williamsburg Foundation, 2009.

Kondo, Yasuhisa, Takayuki Ako, Inne Heshiki, Go Matsumoto, Yoichi Seino, Yoshimasa Takeda, and Hiroshi Yamaguchi. "FIELDWALK@KOZU: A Preliminary Report of the GPS/GIS-aided Walking Experiments for Re-modeling Prehistoric Pathways at Kozushima Island (East Japan)," paper presented at CAA 2008, Budapest, Hungary, April 2–6, 2008. Also in *On the Road to Reconstructing the Past*, edited by Erzsébet Jerem et al., 151. Budapest: Archaeolingua, 2008.

Neteler, Markus, and Helena Mitasowa. *Open Source GIS: A GRASS GIS Approach*, 3rd ed. New York: Springer, 2008.
Tobler, Waldo. "Three Presentations on Geographical Analysis and Modeling." *Technical Report 93-1*. Santa Barbara: National Center for Geographic Information and Analysis, University of California, 1993. www.ncgia.ucsb.edu/Publications/Tech_Reports/93/93-1.PDF (accessed May 8, 2009).
Undō Shoyōryō Undō Shishin no Sakutei Kentōkai [The Investigation Committee for Exercise Needs and Guideline], *Kenkō Dukuri no tameno Undō Shishin 2006 [Exercise Guide for Fine Health 2006]*. Tokyo: Ministry of Health, Labour and Welfare, 2006. www-bm.mhlw.go.jp/bunya/kenkou/undou01/pdf/data.pdf (accessed May 15, 2009).
van Leusen, Pieter Martijn. *Pattern to Process: Methodological Investigations into the Formation and Interpretation of Spatial Patterns in Archaeological Landscapes*. Ph.D. diss., University of Groningen, 2002. http://dissertations.ub.rug.nl/faculties/arts/2002/p.m.van.leusen/ (accessed May 27, 2009).