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A Markov Model for Analyzing Polytomous Outcome Data

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Abstract

This paper highlights the estimation and test procedures for multi-state Markov models with covariate dependences in higher orders. Logistic link functions are used to analyze the transition probabilities of three or more states of a Markov model emerging from a longitudinal study. For illustration purpose the models are used for analysis of panel data on Health and Retirement Study conducted in USA during 1992-2002. The applications use self reported data on perceived emotional health at each round of the nationwide survey conducted among the elderly people. Useful and detailed results on the change in the perceived emotional health status among the elderly people are obtained.

Keywords: Markov Models; Covariate Dependence; Logistic Regression; Multiple States; Higher Order; Emotional Health.

1. Introduction

In a longitudinal study, we observe correlated outcomes over time which may pose difficulty in modelling such data. These outcomes may be categorical ordinal and the correlations among the repeated measures have to be considered in analyzing these data. A popular choice is the use of generalized estimating equations (GEE) which is a marginal model with specification of underlying correlation structure. However, the choice of a correlation structure under a GEE framework is arbitrary. The specification of correlation structure is more complex in case of polytomous outcomes (Yu et al., 2003). A first order Markov transition model was proposed by Yu et al. (2003). A model for the first order binary outcomes was introduced by Muenz and Rubinstein (1985) and higher order models were proposed by Islam and Chowdhury (2006) and Islam et al. (2009).

It is noteworthy that Regier (1968) introduced a two state transition matrix for estimating odds ratio, Prentice and Gloeckler (1978) proposed a grouped data version of the proportional hazards regression model for estimating computationally feasible estimators of the relative risk function, Korn and Whittemore (1979) proposed a model for incorporating the role of previous state as a covariate to analyze the probability of occupying the current state, and Muenz and Rubinstein (1985) introduced a discrete time Markov chain for expressing the transition probabilities in terms of function of covariates for a binary sequence of presence or absence of a disease. The readers are referred to Albert (1994), Albert and Waclawiw (1998), Raftery and Tavare (1994) for some estimation procedures for transition probabilities. In recent years, there is a great deal of interest in the development of multivariate models based on the Markov Chains. In this paper, a Markov chain model for three or more intercommunicating states is proposed for analysis of covariate dependences of the transition probabilities. For illustration purpose, the model is used for analysis of panel data on Health and Retirement Study conducted in USA during 1992-2002. The risk factors that contribute to specific transitions can be identified from the proposed model.

2. The First Order Model

Let us consider $(Y_{i1}, Y_{i2}, ..., Y_{ij})$ represents the past and present responses for subject i (i= 1,.2,…,n) at follow-up j (j=1,2,…, n_i). Y_{ij} is the response at time t_{ij}. The multiple outcomes defined by $Y_{ij} = s$, s=0,1,2,…,m-1 if an event of level s occurs for the ith subject at the jth follow-up where y_{ij}=0 indicates that no event occurs. Then the first order Markov model can be expressed as

$$P(y_{ij} \left| y_{ij-q}, ..., y_{ij-1}\right.) = P(y_{ij} \left| y_{ij-1}\right.)$$

and the corresponding transition probability matrix is given by

$$\pi = \begin{bmatrix} \pi_{00} & \cdots & \pi_{0\text{m-1}} \\ \pi_{10} & \cdots & \pi_{1\text{m-1}} \\ . & & \\ . & & \\ . & & \\ \pi_{m-10} & \cdots & \pi_{\text{m-1m-1}} \end{bmatrix}$$

where $\pi_{us} = P(Y_j = s| \;\; Y_{j-1} = u)$. For any s,

$$\sum_{s=0}^{m-1} \pi_{us} = 1, \text{ u=0,…, m-1.}$$

Let $X_i = \left[1,\ X_{i1},\ \ldots\ldots,\ X_{ip}\right]$ = vector of covariates for the ith person, and $\beta'_{us} = \left\lfloor \beta_{us0}, \beta_{us1}, \ldots\ldots, \beta_{usp} \right\rfloor$ = vector of parameters for the transition from u to s. Then the transition probabilities are (see Hosmer and Lemeshow, 2000, pp.260-264 and Yu et al., 2003) as follows:

$$\pi_{us}(Y_j = s \mid Y_{j-1} = u, X) = \frac{e^{g_{us}(X)}}{\sum_{k=0}^{m-1} e^{g_{uk}(X)}}, \qquad u=0,\ldots,m-1$$

where

$$g_{us}(X) = \begin{cases} 0, & \text{if } s = 0 \\ \ln\left[\dfrac{\pi_{us}(Y_j = s \mid Y_{j-1} = u, X)}{\pi_{us}(Y_j = 0 \mid Y_{j-1} = u, X)}\right], & \text{if } s = 1,\ldots,m-1. \end{cases}$$

Hence

$$g_{us}(X) = \beta_{us0} + \beta_{us1}X_1 + \ldots + \beta_{usp}X_p.$$

Then the likelihood function for n individuals with each individual having n_i (i=1,2,….n) follow-ups can be expressed as

$$L = \prod_{i=1}^{n}\prod_{j=1}^{n_i}\prod_{u=0}^{m-1}\prod_{s=0}^{m-1}\left[\{\pi_{us}\}^{\delta_{usij}}\right]$$

where n_i = total number of follow-up observations since the entry into the study for the ith individual; δ_{usij}=1 if a transition type $u \to s$ is observed during jth follow-up for the ith individual, δ_{usij}=0, otherwise, u,s=0,…,m-1. The log likelihood function for the u-th component is given by

$$\ln L_u = \sum_{i=1}^{n}\sum_{j=1}^{n_i}\left[\sum_{s=0}^{m-1}\delta_{usij}\, g_{ms}(X_i) - \ln\left(\sum_{k=0}^{m-1} e^{g_{uk}(X_i)}\right)\right].$$

Differentiating with respect to the parameters and solving the following equations we obtain the likelihood estimates for m(m-1)(p+1) parameters.

3. Multi-State Markov Model of Higher Order

The multiple outcomes defined by Y_{ij}=s, s=0, 1, 2,…, m-1, if an event of level s occurs for the ith subject at the jth follow-up where Y_{ij}=0 indicates that no event occurs. Islam and Chowdhury (2006) showed the model for binary outcomes (s=0,1). If we consider the rth order Markov model for polytomous outcomes then the probabilities can be expressed as

$$P(y_{ij} \mid y_{ij-r}, \ldots, y_{ij-1})$$

Here, 0,1,…,m-1 are the m possible outcomes of a dependent variable, Y. The probability of a transition from $u_1,...,u_r$ ($u_1,...,u_r$=0,…,m-1) at times $t_{j-1},\ldots,t_{j-r}$ respectively to s (s=0,…,m-1) at time t_j is $\pi_{u_r....u_1 s} = P(Y_j = s \mid Y_{j-r} = u_r,..., Y_{j-1} = u_1)$. It is evident that for any combination of $u_r....u_1$, $\sum_{s=0}^{m-1} \pi_{u_r...u_1 s} = 1$, $u_1,...,u_r$=0,…,m-1 .

Define the following notations:

$X_i = \left[1,\ X_{i1},\ ....,\ X_{ip}\right]$ = vector of covariates for the ith person;

$\beta'_{u_1,...,u_r} = \left[\beta_{u_1,...,u_r s0}, \beta_{u_1,...,u_r s1}, ..., \beta_{u_1,...,u_r sp}\right]$ = vector of parameters for the transition type $u_1...u_r$ to s.

We can express the transition probabilities from state $u_1...u_r$ to states as follows in terms of conditional probabilities:

$$\pi_{u_1...u_r s}(Y_j = s \mid Y_{j-r} = u_r,....,Y_{j-1} = u_1, X) = \frac{e^{g_{u_1...u_r s}(X)}}{\sum_{k=0}^{m-1} e^{g_{u_1...u_r k}(X)}}$$

, $u_1,...,u_r$=0,…,m-1

where

$$g_{u_1...u_r s}(X) = \begin{cases} 0, & \text{if s} = 0 \\ \ln\left[\dfrac{\pi_{u_1...u_r s}(Y_j = s \mid Y_{j-r} = u_r,....,Y_{j-1} = u_1, X)}{\pi_{u_1...u_r s}(Y_j = 0 \mid Y_{j-r} = u_r,....,Y_{j-1} = u_1, X)}\right], & \text{if s} = 1,...,\text{m-1}. \end{cases}$$

Hence,

$$g_{u_1...u_r s}(X) = \beta_{u_1...u_r s0} + \beta_{u_1...u_r s1} X_1 + ... + \beta_{u_1...u_r sp} X_p .$$

Then the likelihood function for n individuals with each individual having n_i (i=1,2,….n) follow-ups can be expressed as

$$L = \prod_{i=1}^{n} \prod_{j=1}^{n_i} \prod_{u_1=0}^{m-1} \cdots \prod_{u_r=0}^{m-1} \prod_{s=0}^{m-1} \left[\left\{\pi_{u_1...u_r s}\right\}^{\delta_{u_1...u_r sij}}\right]$$

where n_i = total number of follow-up observations since the entry into the study for the ith individual; $\delta_{u_1...u_r sij}$ =1 if a transition type $u_1 \to ... \to u_r \to s$ is observed during jth follow-up for the ith individual, $\delta_{u_1 \ldots u_r sij}$=0, otherwise, $u_1,\ldots,u_r$,s=0,…,m-1. The log likelihood function is

$$\ln L = \sum_{u_1,\ldots,u_r=0}^{m-1} \ln L_{u_1 \ldots u_r} ,$$

where $L_{u_1 \ldots u_r}$ corresponds to the $u_1 \ldots u_r$-th component of the likelihood function.

Hence,

$$\ln L_{u_1 \ldots u_q} = \sum_{i=1}^{n} \sum_{j=1}^{n_i} [\sum_{s=0}^{m-1} \delta_{u_1 \ldots u_r sij} g_{u_1 \ldots u_r s}(X_i) - \ln\left(\sum_{k=0}^{m-1} e^{g_{u_1 \ldots u_r k}(X_i)} \right)]$$

Differentiating with respect to the parameters and solving the following equations we obtain the likelihood estimates for $m^r(m-1)(p+1)$ parameters:

$$\frac{\partial \ln L_{u_1 \ldots u_r}}{\partial \beta_{u_1 \ldots u_r sq}} = \sum_{i=1}^{n} \sum_{j=1}^{n_i} X_{qi}(\delta_{u_1 \ldots u_r sij} - \pi_{u_1 \ldots u_r sij}) ,$$

q=0,1,2,….,p; $u_1,\ldots,u_r$=0,…,m-1. The observed information matrix can also be obtained from following second derivatives.

4. Testing for the Significance of Parameters

There are some inference procedures developed for the models based on first-order Markov chains (see Anderson and Goodman 1957 and Kalbfleisch and Lawless 1985). Here we propose a test procedure for the r-th order Markov model. Let us consider that the vectors of $m^r(m-1)$ sets of parameters for the r-th order Markov model, can be represented by the following vector:

$$\beta = \left[\beta_1, \beta_2, \ldots\ldots\ldots, \beta_{m^r(m-1)} \right],$$

where $\beta_v' = \lfloor \beta_{v0}, \beta_{v1}, \ldots\ldots., \beta_{vp} \rfloor$, v=1,2,….., $m^r(m-1)$.

To test the null hypothesis $H_0 : \beta = 0$, we can employ the usual likelihood ratio test

$$-2[\ln L(\beta_0) - \ln L(\beta)] \sim \chi^2_{m^r(m-1)p}$$

To test the significance of the qth parameter of the v-th transition model, the null hypothesis is $H_0 : \beta_{vq} = 0$ and the corresponding Wald test is

$$W = \frac{\hat{\beta}_{vq}}{se(\hat{\beta}_{vq})} .$$

5. Application

For this study, an application using the Health and Retirement Study (HRS) data is given. The HRS (Health and Retirement Study) is sponsored by the National Institute of Aging (grant number NIA U01AG09740) and conducted by the University of Michigan. This study was conducted nationwide for individuals over age 50 and their spouses. The panel data from the six rounds of the study conducted on individuals over age 50 years in 1992, 1994, 1996, 1998, 2000 and 2002 is used. This study uses data documented by RAND. Also, the panel data on emotional health for the period, 1992-2002, is used. The self reported data on perceived emotional health among the elderly people in the USA is considered. The five categories of self-reported emotional health, used in this study, are: excellent, very good, good, fair and poor. Three categories as three states of emotional health: State 1: Poor, State 2: Fair/Good, and State 3: Very Good/Excellent are considered. From the panels of data, 9772 respondents in 1992 for analyzing emotional health among the elderly are used. The numbers of respondents in subsequent follow-ups are: 8039 in 1994, 7823 in 1996, 7319 in 1998, 6824 in 2000 and 6564 in 2002.

To analyze the self-reported mental health states, we considered the following explanatory variables: gender (male=1, female=0), marital status (unmarried=0, married=1), vigorous physical activity (3 or more days per week) (yes=1, no=0), ever drank any alcohol (yes=1, no=0), ever smoked (yes=1, no=0), felt depressed during the past week (yes=1, no=0), felt lonely during the past week (yes=1, no=0), race (white=1, else 0; black=1, else 0; others= reference category), age (less than or equal to 60 years=0 and more than 60 years=1).

Table 1 demonstrates the distribution of respondents' by status of perceived health and the selected variables in 1992. It is observed that most of the respondents were in the state of very good/excellent, followed by fair/good. It appears that only 8 percent were in the poor status of perceived mental health at the baseline, 42 percent in the fair/good states and about 50 percent in the very good/excellent states. The poor status of perceived emotional health was prevalent at a higher proportion among unmarried respondents, those not involved with vigorous physical activity for 3+ days/ week, those do not drink alcohol, smokers, feeling depressed and lonely, non-whites, blacks, and respondents aged more than 60 years (non-significant).

The transition counts and transition probabilities for the study period (1992-2002) are shown in Table 2. We have considered all the transitions made by all the respondents during the study period. About 57 percent remained in the poor state starting from poor, while 40 percent made transition from poor to good/fair and 3 percent moved from poor to very good/ excellent status of perceived mental health. Similarly, during the same period, 7 percent reported a move from fair/good to poor health status, 72 percent remained as fair/good, and 21 percent made a transition from good/fair to very good/excellent. It is also noteworthy that less than 1 percent made transition from very good/ excellent to poor status of perceived mental health, 25 percent to good/fair, while 75 percent remained in the perceived health status of very good/excellent.

The estimates of parameters for the first-order covariate dependent Markov models for three states are shown in Table 3. Higher order models could not be fitted due to lack of adequate cell frequencies. We have fitted m(m-1) models (3*2=6), where m is the number of states. The models are for transition of types: (i) poor $\rightarrow$ fair/good, (ii) poor $\rightarrow$ very good/excellent, (iii) fair/good $\rightarrow$ poor, (iv) fair good/ excellent $\rightarrow$ very good/ excellent, (v) very good/excellent $\rightarrow$ poor, and (vi) very good/ excellent $\rightarrow$ fair/good.

Transition of the type, poor $\rightarrow$ fair/good, is positively associated with physical activity and drinking alcohol, and negatively associated with feeling depressed. As the data are based on self reported perceived emotional health, the relationship with some selected explanatory variables such as drinking alcohol should be interpreted carefully. Similarly, transition of the type poor $\rightarrow$ very good/excellent is statistically associated positively with physical activity and elderly black.

A reversal is observed for transition of the type, fair/good $\rightarrow$ poor, which appears to have negative association with marital status, physical activity, drinking alcohol, whites and blacks as compared to Asians or other races while there is evidence of positive association with smoking, feeling depressed and feeling lonely. However, a transition from good/fair to an improved status of very good/excellent appears to increase with marital status ($p<0.10$), physical activity, drinking alcohol, but decreases with age, smoking, feeling depressed and feeling lonely.

A reversal in the impact is also observed for the transition from very good/excellent status of perceived emotion health to poor status and appears to have positive association with smoking and feeling depressed whereas negative association is observed with marital status, physical activity and drinking alcohol. Similarly, a reverse transition from very good/excellent to good/fair status of perceived emotional health is associated positively with gender, smoking, feeling depressed, feeling lonely, blacks compared to Asians and other groups but negatively associated with marital status, physical activity and drinking alcohol.

6. Conclusion

This paper illustrates some theoretical elaborations on the multi-state covariate dependent Markov models of first and higher orders. These models can provide very useful results for analyzing longitudinal data emerging from the studies on lifetime data analysis. The estimation and test procedures are discussed. We have used the logistic link functions for demonstrating relationships between transition probabilities and risk factors. An example is shown from the panel data on Health and Retirement Study conducted in USA during the period 1992-2002. The application uses the self reported data on perceived emotional health at each round of the nationwide survey conducted among the elderly people. We have obtained useful and detailed results on the change in the perceived emotional health status among the elderly people.

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Table 1: Distribution of Subjects by Their Status of Perceived Emotional Health and Selected Characteristics at the Baseline

Perceived Emotional Health

Variables	Poor		Fair/good		V good/Excellent		Total	
	N	%	N	%	N	%	N	%
Gender								
Female	427	8.3	2224	43.0	2524	48.8	5175	53.0
Male	376	8.2	1897	41.3	2323	50.5	4596	47.0
Marital Status**								
Unmarried	327	13.6	1099	45.8	972	40.5	2398	24.5
Married	476	6.5	3022	41.0	3875	52.6	7373	75.5
Vigorous physical activuty 3+ /wk**								
No	723	9.2	3419	43.5	3710	47.2	7852	80.4
Yes	80	4.2	702	36.6	1137	59.2	1919	19.6
Ever drinks any alcohol**								
No	495	12.8	1862	48.1	1515	39.1	3872	39.6
Yes	308	5.2	2259	38.3	3332	56.5	5899	60.4
Smoke ever**								
No	226	6.3	1407	39.5	1930	54.2	3563	36.5
Yes	577	9.3	2714	43.7	2917	47.0	6208	63.5
Felt depressed**								
No	596	6.5	3871	41.9	4770	51.6	9237	94.5
Yes	207	38.8	250	46.8	77	14.4	534	5.5
Felt lonely**								
No	650	7.0	3883	41.9	4738	51.1	9271	94.9
Yes	153	30.6	238	47.6	109	21.8	500	5.1
White**								
No	264	12.7	1128	54.2	690	33.1	2082	21.3
Yes	539	7.0	2993	38.9	4157	54.1	7689	78.7
Black**								
No	584	7.2	3188	39.5	4299	53.3	8071	82.6
Yes	219	12.9	933	54.9	548	32.2	1700	17.4
Age (in years)								
<= 60	751	8.2	3856	42.0	4573	49.8	9180	94.0
60+	52	8.8	265	44.8	274	46.4	591	6.0
Total	803	8.2	4121	42.2	4847	49.6	9771	100.0

* Significant at 5% level; ** Significant at 1% level.

Table 2: Transition Count and Transition Probability Matrix

Perceived Health	Transition Count			Transition Probability			
	Poor (0)	Fair/ Good (1)	Very Good/ Excellent (2)	Poor (0)	Fair /Good (1)	Very Good/ Excellent (2)	Total
Poor (0)	1463	1002	74	0.576	0.395	0.029	2539
Good/Fair(1)	1131	11862	3465	0.069	0.721	0.211	16458
Excellent/ Very Good(2)	149	4364	13059	0.008	0.248	0.743	17572

Table 3:Estimates of Three State Markov Model for Perceived Emotional Health

Variables	Coeff.	Std. err.	t-value	p-value	95% C.I.	
					LL	UL
Transition Type Poor -> Fair/Good						
Constant	-0.520	0.189	-2.76	0.006	-0.890	-0.151
Gender	-0.141	0.092	-1.53	0.127	-0.322	0.040
Marital Status	0.157	0.090	1.74	0.082	-0.020	0.333
Physical Activity	0.326	0.115	2.84	0.005	0.101	0.551
Drink	0.288	0.095	3.03	0.002	0.102	0.474
Smoke	0.000	0.094	0.00	0.999	-0.184	0.184
Felt Depression	-0.310	0.098	-3.18	0.001	-0.502	-0.119
Felt Lonely	-0.080	0.103	-0.77	0.439	-0.282	0.122
White	0.264	0.171	1.54	0.123	-0.071	0.599
Black	0.221	0.182	1.21	0.225	-0.136	0.578
Age	-0.031	0.087	-0.35	0.724	-0.202	0.140
Transition Type Poor -> Very Good/Excellent						
Constant	-4.674	1.054	-4.44	0.000	-6.739	-2.609
Gender	0.212	0.267	0.80	0.426	-0.310	0.735
Marital Status	0.264	0.269	0.98	0.327	-0.264	0.793
Physical Activity	1.076	0.272	3.96	0.000	0.544	1.609
Drink	0.307	0.274	1.12	0.263	-0.231	0.845
Smoke	0.143	0.288	0.50	0.618	-0.420	0.707
Felt Depression	-0.380	0.280	-1.36	0.175	-0.928	0.168
Felt Lonely	-0.145	0.300	-0.48	0.628	-0.733	0.443
White	1.666	1.023	1.63	0.103	-0.338	3.670
Black	1.992	1.031	1.93	0.053	-0.030	4.014
Age	0.266	0.245	1.08	0.278	-0.215	0.747
Transition Type Fair/Good -> Poor						
Constant	-1.602	0.147	-10.87	0.000	-1.891	-1.313
Gender	0.006	0.070	0.08	0.933	-0.130	0.142
Marital Status	-0.155	0.070	-2.22	0.027	-0.292	-0.018
Physical Activity	-0.293	0.075	-3.92	0.000	-0.440	-0.147
Drink	-0.375	0.067	-5.60	0.000	-0.507	-0.244
Smoke	0.308	0.071	4.33	0.000	0.169	0.448
Felt Depression	0.586	0.081	7.26	0.000	0.427	0.744
Felt Lonely	0.262	0.086	3.02	0.002	0.092	0.431
White	-0.502	0.132	-3.81	0.000	-0.761	-0.244
Black	-0.439	0.142	-3.10	0.002	-0.717	-0.161
Age	-0.230	0.067	-3.45	0.001	-0.360	-0.099
Transition Type Fair/Good -> Very Good/Excellent						
Constant	-1.362	0.117	-11.62	0.000	-1.592	-1.132
Gender	0.008	0.042	0.19	0.847	-0.074	0.090
Marital Status	0.183	0.047	3.85	0.000	0.090	0.276
Physical Activity	0.247	0.041	6.03	0.000	0.167	0.328
Drink	0.150	0.040	3.75	0.000	0.072	0.229
Smoke	-0.161	0.042	-3.87	0.000	-0.243	-0.080
Felt Depression	-0.221	0.065	-3.38	0.001	-0.349	-0.093
Felt Lonely	-0.176	0.069	-2.56	0.010	-0.311	-0.041
White	0.185	0.109	1.69	0.091	-0.029	0.399
Black	-0.030	0.117	-0.25	0.800	-0.258	0.199
Age	-0.106	0.041	-2.61	0.009	-0.186	-0.026

Table 3 (Continues): Estimates of Three State Markov Model for Perceived Emotional Health

Transition Type Very Good/Excellent -> Poor						
Constant	-3.603	0.468	-7.70	0.000	-4.520	-2.685
Gender	0.225	0.174	1.29	0.197	-0.117	0.567
Marital Status	-0.700	0.186	-3.76	0.000	-1.065	-0.335
Physical Activity	-0.262	0.171	-1.54	0.124	-0.597	0.072
Drink	-0.847	0.170	-4.98	0.000	-1.181	-0.514
Smoke	0.958	0.197	4.86	0.000	0.572	1.345
Felt Depression	1.149	0.260	4.42	0.000	0.639	1.659
Felt Lonely	0.355	0.273	1.30	0.194	-0.180	0.889
White	-0.463	0.429	-1.08	0.280	-1.303	0.378
Black	0.450	0.457	0.98	0.325	-0.446	1.346
Age	0.004	0.178	0.03	0.980	-0.345	0.354
Transition Type Very Good/Excellent -> Fair/Good						
Constant	-0.786	0.114	-6.89	0.000	-1.010	-0.562
Gender	0.126	0.037	3.39	0.001	0.053	0.199
Marital Status	-0.161	0.044	-3.66	0.000	-0.247	-0.075
Physical Activity	-0.231	0.036	-6.33	0.000	-0.302	-0.159
Drink	-0.419	0.037	-11.35	0.000	-0.492	-0.347
Smoke	0.223	0.037	5.96	0.000	0.150	0.297
Felt Depression	0.468	0.075	6.24	0.000	0.321	0.614
Felt Lonely	0.146	0.073	2.00	0.046	0.003	0.290
White	-0.183	0.107	-1.71	0.087	-0.392	0.026
Black	0.462	0.116	3.99	0.000	0.235	0.689
Age	0.172	0.037	4.60	0.000	0.099	0.246
Model Chi-square (p-value)	12382.1644 (0.000)					
LRT	17039.4682 (0.000)					